The Journal of Agricultural Science

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Optimisation of irrigation and sowing methods on carrot productivity

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Crops and Soils Research Paper

Cite this article: Prikxit , Sharma JC, Babal B, and Sharma A (2026). Optimisation of irrigation and sowing methods on carrot productivity. *The Journal of Agricultural Science* **164**(e33), 1–12. https://doi.org/10.1017/S0021859626100707

Received: 4 March 2025
Revised: 23 March 2026
Accepted: 30 March 2026

Keywords:
irrigation scheduling; nutrient availability; soil fertility; soil health; water productivity

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Abstract

Although carrot productivity is influenced by irrigation scheduling and planting techniques, however their interactive effects on soil properties and consequent crop performance in hilly agro-ecosystem remain insufficiently explored. It was hypothesised that optimised irrigation levels, combined with an appropriate sowing method would significantly improve soil nutrient availability, carrot yield and water productivity. A field experiment was carried out for two consecutive years (2021–22 and 2022–23) using a factorial Randomised Block Design with two sowing methods, Flat-bed (S_1) and Ridge (S_2) and four irrigation regimes based on irrigation water (IW)/cumulative pan evaporation (CPE) ratios of 0.6 (I_1), 0.8 (I_2), 1.0 (I_3) and 1.2 (I_4). Ridge sowing (S_2) consistently outperformed over flat-bed sowing (S_1) with respect to nutrient availability, yield and water productivity. The highest carrot yield (34.2 t/ha) was recorded under the combination of ridge sowing and the highest irrigation level (S_2I_4). Moderate irrigation level provides the balance between yield and water use, resulting in higher total water productivity, whereas the highest irrigation level (I_4) improved crop water productivity and soil nutrient dynamics although it was less efficient in crop production per unit water applied. The findings demonstrate that ridge sowing, in combination with optimised irrigation regimes (I_3), offer a practical strategy to enhance soil health and resource use efficiency while sustaining the carrot productivity hilly region. These findings offer a practical guidance for farmer and planners seeking to improve water management and crop performance in comparable agro-ecological environment.

Introduction

Carrot (*Daucus carota* L.) is an economically and nutritionally important cool-season root crop belongs to family *Apiaceae* (Rolbiecki *et al.*, 2025). Carrots are native to Central Asia, with Afghanistan as its Centre of origin, cultivated widely across temperate and tropical regions including the mid-hills of NW Himalayas (Philippe *et al.*, 2018). Its high content of antioxidants, minerals, vitamins and dietary fibre contributes to its dietary significance and increasing consumer demand (Boadi *et al.*, 2021). Carrot consumption is associated with improved immunity and reduced risk of chronic diseases such as hypertension, atherosclerosis and cardiovascular disorders (Razzaq *et al.*, 2017). Ensuring yields and quality under resource-limited environments is therefore an important production objective.

Carrot growth is highly sensitive to soil moisture, aeration and nutrient availability, making irrigation management a critical factor influencing root development, productivity and quality (Harasim *et al.*, 2025). Both deficit and excessive irrigation can constrain physiological processes, limit nutrient uptake and reduce water productivity (Schiattone *et al.*, 2018; Sharma *et al.*, 2023). Water deficiency significantly disrupts physiological processes in plants, including food accumulation, photosynthesis, carbohydrate and protein metabolism and the oxidative defensive system (Mankotia *et al.*, 2024). Precise irrigation scheduling is thus essential to balance water use with crop requirements and to minimise nutrient losses from leaching (Elshamly and Nassar, 2023).

Sowing method also plays a significant role in determining seedling establishment, soil-root interaction and resource use efficiency (Prikxit *et al.*, 2025). Planting layouts such as flat-beds, ridges and furrows differ markedly in their effects on soil aeration, drainage, moisture distribution and nutrient assimilation (Solanki *et al.*, 2020). These factors are particularly important in the mid-hill agroecosystems of NW Himalayas, where slope terrain, limited arable land and erratic rainfall create inherent production constraints. Selecting an appropriate sowing method may therefore enhance soil conditions, reduce erosion risk and improve overall crop performance (Singh *et al.*, 2017).

Although irrigation and sowing methods are individually well recognised as determinants of root crop productivity, their combined influence on soil chemical properties, microbial activity, water productivity and carrot yield under mid-hill conditions has not been adequately examined. Therefore, the objectives of this study were to evaluate (i) the effects of IW/CPE-

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based irrigation regime and sowing method on soil chemical properties, microbial activity and water productivity and (ii) the subsequent influence on the productivity and quality of carrot (*Daucus carota* L.). In line with these objectives, it was hypothesised that ridge sowing, under optimal irrigation regime, would improve soil nutrient availability and microbial activity, thereby improving water productivity as well as the yield and quality of carrot under mid hill conditions.

Materials and methods

Experimental site and soil type description

The study was conducted at the experimental farm of Department of Soil Science and Water Management Dr. YS Parmar University of Horticulture and Forestry, Nauni, India during 2021–22 and 2022–23. The experimental site is located at 30° 52′ N and 77° 11′ E, 1175 m above mean sea level with an average slope of 7–8%. The average annual precipitation in this region is 1100 mm with an annual moisture deficit of around 420 mm and considering an annual PET of 1520 mm. According to USDA soil taxonomy classification, the study area belongs to the *Typic Haplustepts* subgroup. The initial soil characteristics of the experimental site during course of investigation are provided in Table 1. The surface and subsurface soil of experimental site was sandy loam in texture, neutral in soil pH, higher to medium in organic carbon content, low in available nitrogen, higher to medium in available phosphorus and medium in available potassium, respectively. Available calcium and magnesium were moderate and sulphate sulphur content was adequate in both the depths.

Table 1. Analysis of soil properties before conducting the experiment

Properties	Depth (cm)	
	0–15	15–30
Sand, silt and clay (%)	57.7, 28.2, 14.1	59.2, 28.8, 12.0
Textural class	Sandy loam	Sandy loam
pH (1:2)	6.72	6.90
EC (dS/m)	0.26	0.29
Organic carbon (g/kg)	12.6	8.70
Available N, P and K (kg/ha)	245.4, 26.3, 265.5	224.5, 19.8, 219.7
Available Ca and Mg (cmol (p^+)/kg)	3.71, 3.80	3.05, 3.14
Sulphate Sulphur (kg/ha)	31.8	28.0
Bulk density (Mg/m^3)	1.29	1.32
Particle density (Mg/m^3)	2.53	2.61
Moisture content at the time of ploughing (%)	8.28	14.2
Moisture retention at 0.33 bar (w,%)	23.9	21.0
Moisture retention at 15 bar (w,%)	7.20	6.80

EC, electrical conductivity; N, nitrogen; P, phosphorus; K, potassium; ca, calcium; Mg, magnesium.

Experimental setup

The present investigation was carried out during the month of November to February for consecutive two years with eight treatments comprised two sowing methods: Flat-bed (S_1) and Ridge (S_2), along with four irrigation schedules: I_1, I_2, I_3 and I_4 (0.6, 0.8, 1.0 and 1.2 IW/CPE ratios, respectively) replicated three times in Factorial Randomised Block Design. Irrigation scheduling was based on IW/CPE approach, where irrigation water depth (IW) was maintained 30 mm for each irrigation. The cumulative pan evaporation (CPE) was measured by summarising daily observed evaporation from USWB Class A open pan evaporimeter located 0.5 km away from the experimental site. The irrigation interval was determined when the ratio of IW to CPE reached the prescribed level of 0.6, 0.8, 1.0 and 1.2. Accordingly, irrigation was scheduled when the CPE reached 50, 37.5, 30 and 25 mm for the 0.6, 0.8, 1.0 and 1.2 IW/CPE ratios, respectively. Surface irrigation was applied using measured amounts of water through 2-inch PVC pipes equipped with a water flow metre.

Cultivation practices

The investigation was carried out with *Pusa Yamdagni* variety of carrot (*Daucus carota* L.) in 3 m × 2 m plots with 30 cm × 10 cm spacing. There was 1 m and 3 m buffer zone between plots and replications, respectively. The recommended doses of FYM (10 t/ha), N (50 kg/ha), P_2O_5 (50 kg/ha) and K_2O (40 kg/ha) nutrients were applied as per the package of practices for vegetable crops (Anonymous, 2014). The full dose of P and K fertilisers were applied at the time of field preparation. The nitrogen was applied into three split doses *viz.* half as basal and rest in two splits at one month interval. After sowing, a light irrigation was given at alternate days until proper germination of seeds. Before the execution of irrigation schedule, 30 mm irrigation was applied in all plots. Then subsequent irrigations were applied as per schedules of irrigation.

Soil analysis

Representative soil samples of each treatment were collected from 0–15 and 15–30 cm depths at the time of harvesting during both years of the study. After collection, samples were dried in shade and ground with the help of pestle, passed through 2 mm sieve and then analysed for soil available N, P, K, Ca, Mg and sulphate sulphur. Available nitrogen (N) was determined by alkaline potassium permanganate method (Subbiah and Asija, 1956). Available phosphorus (P) was examined by bicarbonate extraction method (Olsen *et al.*, 1954). Available potassium (K), calcium (Ca) and magnesium (Mg) were measured by ammonium acetate extraction method (Merwin and Peech, 1951). Sulphate sulphur (SO_4^{2-} S) was determined by turbidimetric method (Williams and Steinbergs, 1959).

Total microbial count

Microbial populations (Bacteria, fungi and actinomycetes) were assessed using the serial dilution technique of Salle (1973). One gram of soil was mixed with 10 ml sterile water to prepare the initial dilution, followed by a series of tenfold dilution up to 10^{-6}. Aliquots of 0.1 ml from 10^{-6}, 10^{-5} and 10^{-4} dilutions were plated for bacteria, actinomycetes and fungi, respectively. Plating was carried out on nutrient agar (bacteria), kenknight and munaier's medium (actinomycetes) and potato dextrose agar (fungi). The inoculum was evenly spread using a sterile spreader, and plates were incubated at 30°C for 2–5 days. Microbial populations were calculated as per Equation (1) and expressed as cfu/g soil (colony-forming units per gram of soil).

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$$\text{Viable cell per g of dry soil} = \frac{\textit{Mean plate count} \times \textit{dilution factor}}{\textit{Dry weight of soil}} \quad (1)$$

Water use indices

Profile water use was estimated by moisture deficit in the root zone before and after irrigation at different depths and water requirement was determined by the total amount of water applied at each schedule and effective rainfall (Waqas *et al.*, 2021). Reference evapotranspiration (ET_o) and effective rainfall was calculated by FAO CROPWAT 8.0 software. Crop evapotranspiration (ET_c) was calculated by multiplying reference evapotranspiration (ET_o) by crop coefficient (K_c) Equation (2). Crop coefficients were different for different growth stages and these were obtained from FAO (Allen *et al.*, 1998).

$$ET_c = ET_o \times K_c \quad (2)$$

Water productivity

Water productivity is a measure of how much agricultural production is achieved for each unit of water consumed. Crop water productivity (CWP) is a measure of water productivity expressed in terms of yield per unit amount of water consumed by the crop during evapotranspiration. CWP was calculated as per Equation (3):

$$CWP\,(kg/ha/mm) = \frac{Yield(kg/ha)}{ET_c(mm)} \quad (3)$$

Total water productivity (TWP) is also a measure of water productivity stated in terms of yield per unit of total water supplied (TWS) including irrigation and rainfall (Biswas *et al.*, 2021). TWP was calculated as per Equation (4)

$$TWP\,(kg/ha/mm) = \frac{Yield\,(kg/ha)}{Total\ water\ supplied\,(mm)} \quad (4)$$

Profile water use

Profile water use (PWU) was estimated based on the depletion of soil moisture from the crop root zone between two successive sampling dates. Soil samples were collected from different depths within the effective root zone, and soil moisture content was determined by the gravimetric method (Allen *et al.*, 1998). The profile water use was calculated using the following Equation (5):

$$PWU = \sum_{n=1}^{\infty}\left(\frac{M1 - M2}{100} \times BD \times D\right) \quad (5)$$

Where,
PWU = Profile water use (mm)
M_1 = Soil moisture content (%) at the first sampling
M_2 = Soil moisture content (%) at the second sampling
BD = Bulk density of soil (Mg/m^3)
D = Depth of soil layer (mm)

Harvest index (HI)

Economic yield (kg/ha) was determined by taking the fresh weight of the roots. Fresh leaf and root weights were used to estimate biological yield (kg/ha). Harvest index (%) was determined from below listed in Equation (6).

$$\textit{Harvest index}\,(\%) = \frac{\textit{Economic yield}}{\textit{Biological yield}} \times 100 \quad (6)$$

Analysis of data

The experimental data were analysed using factorial randomised block design and three-way analysis of variance (ANOVA) as described by OPSTAT. Treatments means were compared using the critical difference (CD) at 5% significance level. ANOVA of recorded parameters are presented in Table S1–S12.

Results

Available NPK

Available NPK at 0–15 and 15–30 cm soil depths during the 2021–22 and 2022–23 growing seasons are presented in Tables 2–4. Pooled data across both seasons on soil nutrient status (NPK) revealed a significant effect of irrigation regimes and sowing methods on nutrient availability, with notable trends at 0–15 and 15–30 cm soil depths (Tables 2–4). Nutrient availability decreased with increasing soil depth, except for available N, which showed higher concentrations in 15–30 cm as compared to 0–15 cm depth.

Across irrigation regimes, NPK was consistently higher under higher IW/CPE ratio of 1.0 and 1.2. However, among sowing methods ridge sowing recorded significantly higher NPK than flat-bed sowing at both depths. Among irrigation schedules, maximum available N (302.2 and 325.5 kg/ha), P (62.6 and 34.3 kg/ha) and K (306.5 and 243.4 kg/ha) were observed under I_4, while the lowest was under I_1 at 0–15 and 15–30 cm, respectively. Among sowing methods, ridge sowing method outperformed the flat-bed method, recording maximum available N (296.0 and 315.7 kg/ha), P (57.4 and 30.1 kg/ha) and K (297.7 and 235.1 kg/ha) at 0–15 and 15–30 cm, respectively.

The interaction S×I showed a consistent pattern across primary available nutrients, with ridge sowing combined with higher irrigation levels (IW/CPE ratio of 1.0 and 1.2) resulting in maximum available N, P and K at both depths. The interaction was significant for available N and P at both soil depths and for available K at 15–30 cm. Contrarily at 0–15 cm, the interaction for K exhibited statistically equivalence. Furthermore, flat-bed sowing under IW/CPE ratio of 0.6 recorded minimum nutrient availability. Year had a non-significant effect on available N whereas, significant effect was observed for available P at 0–15 cm and 15–30 cm depths. Year found to be non-significant for available K at 0–15 cm and non-significant at 15–30 cm soil depth.

Available Ca, Mg and SO_4^{2-} S

Data on Secondary nutrient availability (Ca, Mg, SO_4^{2-}) at the 0–15 cm & 15–30 cm is summarised in Tables S4-a, S5-a and S6-a, respectively. The pooled analysis revealed that year, sowing methods and irrigation regimes had a significant effect on the availability of available Ca (Figure 1a,b), Mg (Figure 1c,d) and SO_4^{2-}S (Figure 1e,f) at 0–15 cm soil depth except for available Mg, where sowing method had a non -significant effect at both the depths. Among irrigation regimes, I_4 recorded the highest available Ca, measuring 5.14 cmol (p^+)/kg at 0–15 cm depth and 4.10 cmol

https://doi.org/10.1017/S0021859626100707 Published online by Cambridge University Press

https://doi.org/10.1017/S0021859626100707 Published online by Cambridge University Press

Table 2. Effect of different irrigation regimes and sowing methods on available N (kg/ha) at 0–15 cm and 15–30 cm soil depths (Pooled data)

	Available *N*																	
	0–15 cm									15–30 cm								
	Y_1			Y_2			S*I			Y_1			Y_2			S*I		
Depth	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
I_1	275.3	281.8	278.6	282.1	280.4	281.3	278.7	281.1	279.9	292.9	302.5	297.7	298.3	301.3	299.8	295.6	301.9	298.8
I_2	288.8	295.3	292.1	282.9	285.6	284.3	285.9	290.5	288.2	303.6	310.7	307.1	302.7	306.2	304.5	303.1	308.5	305.8
I_3	292.9	305.2	299.1	296.5	312.4	304.5	294.7	308.8	301.8	318.3	318.4	318.4	315.2	324.4	319.8	316.7	321.4	319.1
I_4	303.0	302.2	302.6	298.8	304.9	301.9	300.9	303.6	302.2	317.8	328.7	323.3	322.2	333.1	327.7	320.0	330.9	325.5
Mean	290.0	296.1		290.1	295.8		290.0	296.0	–	308.2	315.1		309.6	316.3		308.9	315.7	–
$CD_{0.05}$																		
Y	NS									NS								
S	2.27									1.32								
I	3.21									1.94								
Y*S	3.21									NS								
Y*I	4.54									2.74								
I*S	4.54									2.74								
Y*S*I	NS									3.88								

Y_1- 2021–22, Y_1- 2022–23, S_1- Flat bed, S_2- Ridge, I_1 -IW/CPE 0.6, I_2 -IW/CPE 0.8, I_3 -IW/CPE 1.0, I_4 -IW/CPE 1.2, CD-critical difference, NS-Non-significant.

Table 3. Effect of different irrigation regimes and sowing methods on available P (kg/ha) at 0–15 cm and 15–30 cm soil depths (Pooled data)

	Available *P*																	
	0–15 cm									15–30 cm								
	Y_1			Y_2			S*I			Y_1			Y_2			S*I		
Depth	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
I_1	46.5	47.3	46.9	52.3	53.8	53.0	49.4	50.6	50.0	20.0	22.0	21.0	24.4	26.2	25.3	22.2	24.1	23.2
I_2	52.3	51.6	52.0	57.8	57.2	57.5	55.1	54.4	54.8	23.7	25.7	24.7	28.3	29.1	28.7	26.0	27.4	26.7
I_3	54.4	55.7	55.0	59.8	63.8	61.8	57.1	59.7	58.4	26.5	31.6	29.0	32.3	33.8	33.1	29.4	32.7	31.0
I_4	57.7	62.9	60.3	62.7	66.9	64.8	60.2	64.9	62.6	29.7	34.9	32.3	34.7	37.9	36.3	32.2	36.4	34.3
Mean	52.8	54.4		58.1	60.4		55.5	57.4	–	25.0	28.6		29.9	31.7		27.5	30.1	–
$CD_{0.05}$																		
Y	0.86									0.55								
S	0.86									0.55								
I	1.22									0.78								
Y*S	NS									0.78								
Y*I	NS									NS								
I*S	1.72									1.10								
Y*S*I	NS									NS								

Y_1- 2021–22, Y_1- 2022–23, S_1- Flat bed, S_2- Ridge, I_1 -IW/CPE 0.6, I_2 -IW/CPE 0.8, I_3 -IW/CPE 1.0, I_4 -IW/CPE 1.2, CD-critical difference, NS-Non-significant.

(p^+)/kg at 15–30 cm. Magnesium availability was also maximised under I_4, with 3.61 cmol (p^+)/kg and 3.36 cmol (p^+)/kg at 0–15 and 15–30 cm, respectively, these values being statistically at par with I_3. Similarly, $SO_4^{2-}S$ was substantially higher under I_4, recording 36.4 kg/ha at 0–15 cm and 32.3 kg/ha at 15–30 cm, the latter being statistical at par with I_3.

Sowing methods significantly influenced Ca and $SO_4^{2-}S$ at both depths (0–15 and 15–30 cm), whereas, their effect on Mg at both depths and Ca at 15–30 cm was non-significant. Among sowing methods, ridge sowing resulted in notably higher available Ca (5.04 and 4.04 cmol (p^+)/kg) and higher SO_4^{2-} S at both depths (34.6 and 31.2 kg/ha). However, sowing method effects on Mg at both depths, as well as the interaction effects between year, sowing methods and irrigation regimes, were not statistically significant for available Ca, Mg and $SO_4^{2-}S$.

Microbial count, yield and HI

Microbial count under different irrigation regimes and sowing methods across the 2021–22 and 2022–23 seasons are summarised in Supplementary Table S7-a, S8-a & S9-a. The pooled analysis (Figure 2) revealed that soil microbial populations (bacteria and actinomycetes) were significantly influenced by year, sowing methods and irrigation regimes, showing a trend similar to that observed for soil-available nutrients. The highest microbial counts were recorded under the I_4 irrigation regime, with bacteria at 85.0×10^6 cfu/g soil, actinomycetes at 44.0×10^5 cfu/g soil and fungi at 39.0×10^4 cfu/g soil. Among sowing methods, ridge sowing supported significantly greater population of bacteria (78.2×10^6 cfu/g soil), actinomycetes (39.6×10^5 cfu/g soil) and fungi (36.0×10^4 cfu/g soil. Microbial count was found to be higher during 2022–23. However, the interaction effect between year, sowing methods and irrigation regimes (Y*S*I) was statistically non-significant.

Harvest index and crop yield under varying irrigation and sowing methods during the 2021–22 and 2022–23 seasons are detailed in Table 5. Pooled analysis of harvest index and yield data showed significant variation across irrigation regimes and sowing methods (Table 5). Year had a non-significant effect on harvest index and yield. Irrigation regimes, sowing methods and their interaction also had a significant effect on HI (Table 5). Among irrigation regimes, maximum HI (70.7%) was observed under I_3, which was statistically at par with I_4 (70.2%), while the lowest HI occurred in I_1. Among sowing methods, ridge (S_2) demonstrated superior performance with the highest HI (69.0%). The interactions of treatments revealed that combination of S_2I_3 resulted maximum HI (72.0%), which was statistically at par with S_2I_4. Interaction effect among year, sowing methods and irrigation regimes found to be non-significant.

The maximum yield (32.4 t/ha) was achieved under I_4 irrigation regime, which was 74.2% higher than the yield obtained under I_1. Among sowing methods, ridge sowing method exhibited superior efficacy for achieving considerably higher yield (27.9 t/ha), corresponding to 13.0% increase over flat-bed sowing. The interaction between sowing method and irrigation regime was also significant, with S_2I_4 achieving the highest yield (34.2 t/ha), 103.1% higher than the lowest yielding S_1I_1. Similarly, S_2I_3 (32.4 t/ha) produced 92.0% more yield than S_1I_1, highlighting the synergistic benefits of higher irrigation coupled with ridge sowing. Year had a non-significant effect on yield of crop, while interaction effect found to be significant among year, sowing methods and irrigation methods.

Water use indices

Crop water productivity and total water productivity data under varying irrigation and sowing methods during the 2021–22 and 2022–23 seasons are detailed in Table 6. Pooled data presented in Table 6 indicated that TWP and CWP was significantly influenced

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https://doi.org/10.1017/S0021859626100707 Published online by Cambridge University Press

Table 4. Effect of different irrigation regimes and sowing methods on available K (kg/ha) at 0–15 cm and 15–30 cm soil depths (Pooled data)

	Available *K*																		
	0–15 cm									15–30 cm									
	Y_1			Y_2			S*I			Y_1			Y_2			S*I		
Depth	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
I_1	278.3	285.1	281.7	280.1	284.0	282.0	279.2	284.6	281.9	213.0	221.4	217.2	216.8	223.7	220.3	214.9	222.6	218.7
I_2	284.0	293.9	289.0	288.6	296.5	292.6	286.3	295.2	290.8	216.4	228.7	222.5	225.4	232.5	229.0	220.9	230.6	225.7
I_3	302.5	300.8	301.7	299.0	304.9	301.9	300.7	302.9	301.8	235.0	234.4	234.7	242.4	245.5	244.0	238.7	239.9	239.3
I_4	304.3	306.1	305.2	305.5	310.1	307.8	304.9	308.1	306.5	232.9	243.9	238.4	246.6	250.5	248.6	239.8	247.2	243.5
Mean	292.3	296.5		293.3	298.9		292.8	297.7	–	224.3	232.1		232.8	238.0		228.6	235.1	–
$CD_{0.05}$																		
Y	NS									2.22								
S	3.01									2.22								
I	4.26									3.13								
Y*S	NS									NS								
Y*I	NS									NS								
I*S	NS									NS								
Y*S*I	NS									NS								

Y_1- 2021–22, Y_1- 2022–23, S_1- Flat bed, S_2- Ridge, I_1 -IW/CPE 0.6, I_2 -IW/CPE 0.8, I_3 -IW/CPE 1.0, I_4 -IW/CPE 1.2, CD-critical difference, NS-Non-significant.

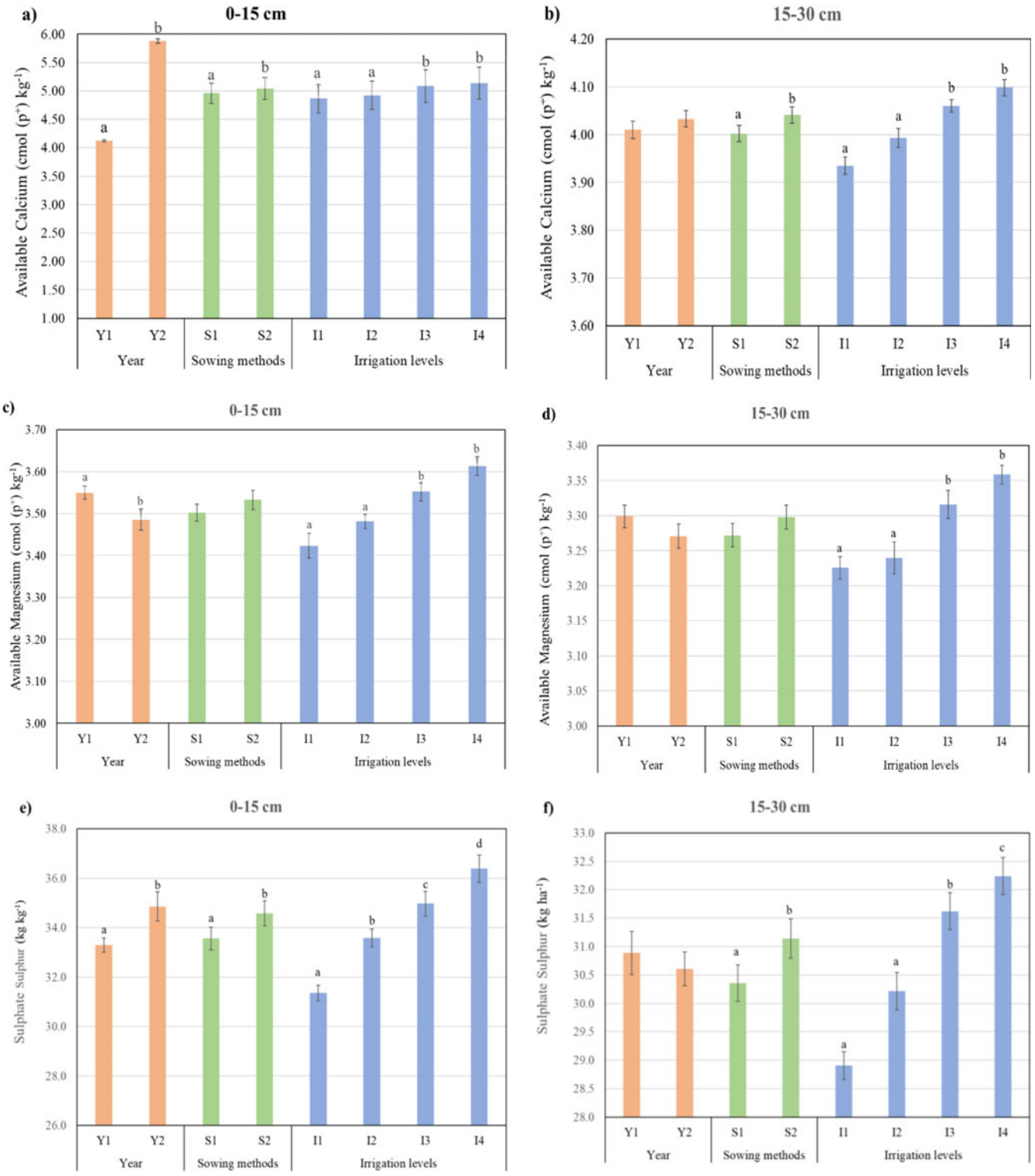


Figure 1. Effect of years, sowing methods and irrigation regimes on (a and b) available Ca cmol (p+)/kg), (c and d) available Mg (cmol (p+)/kg and (e and f) sulphate sulphur (kg/ha) at 0–15 and 15–30 cm depth, respectively. Error bars indicate the standard error of mean (SEM), and different uppercase and lowercase letters above bars denote significant differences among sowing methods and irrigation regimes, respectively ($p < 0.05$) (Mean data). Bars without letters indicate non-significant differences among treatments.

by different year, sowing methods and irrigation regimes. Among irrigation regimes, maximum TWP was recorded under I_3 (113.7 kg/ha/mm), which was higher than I_4 (97.7 kg/ha/mm), indicating that I_3 achieved approximately 14.1% water saving compared to highest irrigation level. However, the maximum CWP was recorded under I_4 (201.1 kg/ha/mm) followed by I_3 (188.5 kg/ha/mm). Interactions among sowing methods and irrigation regimes revealed that highest TWP and CWP was under S_2I_3 (121.6 kg/ha/mm) and S_2I_4 (212.3 kg/ha/mm), respectively.

Detailed data on irrigation water inputs under different IW/CPE regimes during the 2021–22 and 2022–23 growing seasons are provided in Supplementary Table S12. Data pertaining to the total

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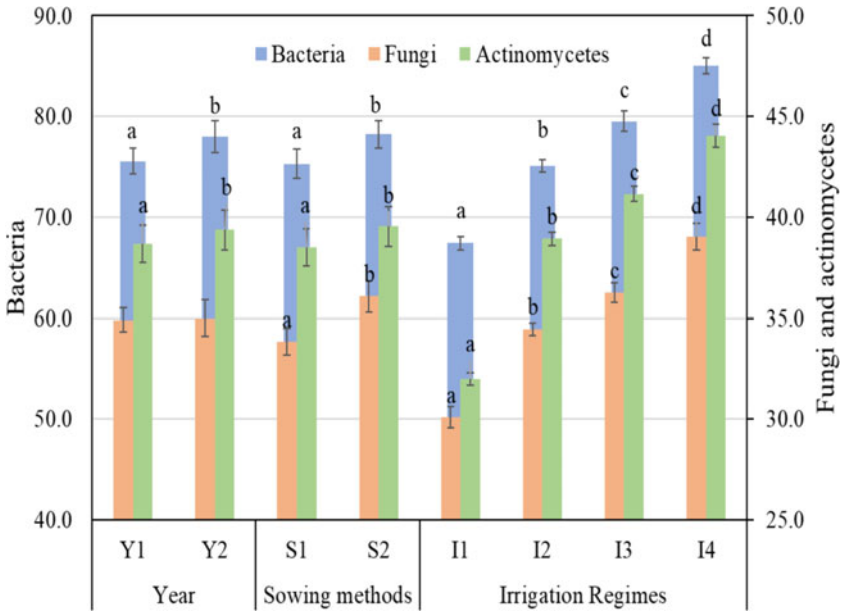


Figure 2. Effect of years, sowing methods and irrigation regimes on total microbial count- Bacteria (10^6 cfu/g soil), Fungi (10^4 cfu/g soil) and Actinomycetes (10^5 cfu/g soil). Error bars indicate the standard error of mean (SEM), and different uppercase and lowercase letters above bars denote significant differences among sowing methods and irrigation regimes, respectively.

amount of water applied, profile water use and total water requirement are described in Table 7. Data indicated that maximum amount of water applied (23 and 26 cm) was under I_4 irrigation regime during 2021–22 and 2022–23, respectively, resulting in maximum profile water use under S_2I_4 being negative (−1.69 and −2.19 cm), which reflects high amount of water applied under I_4, which exceeds the crop requirement. Our study revealed that total water requirement was higher during 1st season because there was more effective rainfall (21.70 cm) in 2021–22 as compared to 2022–23 (4 cm).

Discussion

Soil nutrient availability

This study highlights the combined efficacy of optimal irrigation scheduling and an appropriate sowing method in enhancing nutrient availability and soil health, offering valuable insights for sustainable crop production. Water movement and distribution showed a strong correlation with nitrogen (N) dynamics, consistent with previous findings (Santos *et al.*, 1997). Maximum available N was observed in the sub-surface layer (15–30 cm), likely due to less frequent but heavier irrigation events that induced a higher hydraulic gradient (Singh *et al.*, 2018). This gradient increased soil moisture content, facilitating the downward movement of applied N into deeper layer (Xu *et al.*, 2020). The high mobility of nitrate-N (NO_3^-N) allowed it to move readily with percolating water and accumulating at lower depths (Thakur, 2020; Wang *et al.*, 2021).

Higher available P under I_4 regime was attributed to increased activity of specific P-solubilising microbes, enhanced mineralisation of organic matter and greater conversion of fixed P in available forms under adequate moisture (Singh *et al.*, 2008). The distribution of available K is primarily influenced by diffusion and adsorption onto the soil exchange complex, resulting in higher K accumulation in the surface layer (0–15 cm). Lower values of available P and K in sub surfaces (15–30 cm) may be due to restricted movement and fixation in soil (Badr, 2007). Optimal moisture and aeration also promote mineralisation of organic fractions and thereby increasing nutrient availability (Sharma *et al.*, 2023).

Among sowing methods, ridge sowing method showed superior nutrient retention due to reduced leaching and denitrification losses under better controlled irrigation. Increased nutrient availability under ridge sowing was linked to improved soil moisture, which stimulated microbial activity and accelerated nutrient mineralisation and transformation processes (Elshamly and Nassar, 2023).

Yield and water use indices

Higher irrigation frequency reduces soil strength in the root zone and improves nutrient availability, thereby creating conducive conditions for growth and development of carrot (Ciza *et al.*, 2022). Carrot yield increased with higher irrigation regimes, likely due to greater photosynthetic activity and improved assimilate partitioning under uniformly supplied soil moisture (Alam *et al.*, 2010; Sarkar *et al.*, 2024). Compared with flat-bed sowing, ridge sowing provides better temperature regulation, aeration and drainage, ensuring optimal oxygen availability in the root zone (Carvalho *et al.*, 2023). It also facilitates the maintenance of balanced soil moisture-nutrient environment throughout the growing season, thereby promoting improved root and shoot growth (Anozie and Baiyeri, 2022; Solanki *et al.*, 2020).

Seasonal variability in water requirements was evident, with higher demands in 2021–22 due to greater effective rainfall, emphasising the dynamic relationship between rainfall and irrigation. Yield and the amount of irrigation are key determinants of water productivity (Patel *et al.*, 2005; Tlig *et al.*, 2023). The improved TWP under the I_3 regime with ridge validates that optimised irrigation regime provides maximum production per unit of water use by maintaining adequate water availability, while minimising excess water and evaporative losses (Pal *et al.*, 2020).

CWP directly associated with yield and ET_c, as it excludes effective rainfall and reflects the crop water demand required to produce one unit yield under different irrigation regimes. Highest yield or per unit production was achieved under I_4 irrigation level, which consequently resulted in the maximum in CWP (Maida *et al.*, 2020 and Singh *et al.*, 2021). However, these findings are more specific to mid hill conditions and based on two growing

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Table 5. Effect of sowing methods and irrigation regimes on harvest index (%) and yield of carrot (t/ha) (Pooled data)

	Harvest index									Yield								
	Y_1			Y_2			S*I			Y_1			Y_2			S*I		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
I_1	61.733	64.933	63.3	60.767	67.5	64.1	61.3	66.2	63.7	17.3	19.3	18.3	16.5	21.4	18.9	16.9	20.4	18.6
I_2	68.067	66.333	67.2	67.9	65.9	66.9	68.0	66.1	67.1	22.9	25.0	23.9	23.2	24.5	23.9	23.0	24.8	23.9
I_3	69.567	70.233	69.9	69.267	73.8	71.5	69.4	72.0	70.7	29.0	31.9	30.5	27.9	32.8	30.3	28.4	32.4	30.4
I_4	69.133	71.267	70.2	68.267	72	70.1	68.7	71.6	70.2	30.5	34.2	32.3	30.7	34.3	32.5	30.6	34.2	32.4
Mean	67.1	68.2		66.6	69.8		66.8	69.0	–	24.9	27.6		24.6	28.3		24.7	27.9	–
$CD_{0.05}$																		
Y	NS									NS								
S	0.94									0.263								
I	1.33									0.372								
Y*S	1.33									0.372								
Y*I	NS									NS								
I*S	1.88									0.527								
Y*S*I	NS									0.745								

Y_1- 2021–22, Y_1- 2022–23, S_1- Flat bed, S_2- Ridge, I_1 -IW/CPE 0.6, I_2 -IW/CPE 0.8, I_3 -IW/CPE 1.0, I_4 -IW/CPE 1.2, CD-critical difference.

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Table 6. Effect of sowing methods and irrigation regimes on total water productivity (kg/ha/mm) and crop water productivity (kg/ha/mm) (Pooled data)

	Total water productivity (TWP)									Crop water productivity (CWP)								
	Y_1			Y_2			S*I			Y_1			Y_2			S*I		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
I_1	48.4	54.2	51.3	94.6	123.2	108.9	71.5	88.7	80.1	113.0	126.6	119.8	96.4	125.5	110.9	104.7	126.1	115.4
I_2	64.0	70.1	67.1	133.4	141.1	137.3	98.7	105.6	102.2	149.6	163.8	156.7	135.9	143.7	139.8	142.8	153.8	148.3
I_3	74.9	82.5	78.7	136.7	160.7	148.7	105.8	121.6	113.7	189.7	208.9	199.3	163.3	192.0	177.7	176.5	200.5	188.5
I_4	68.3	76.4	72.4	116.3	130.0	123.1	92.3	103.2	97.7	199.8	223.7	211.8	179.7	201.0	190.4	189.8	212.4	201.1
Mean	63.9	70.8		120.2	138.7		92.1	104.8	–	163.0	180.8		143.8	165.6		153.4	173.2	–
$CD_{0.05}$																		
Y					1.07									1.59				
S					1.07									1.59				
I					1.51									2.25				
Y*S					1.51									2.25				
Y*I					2.14									3.18				
I*S					2.14									3.18				
Y*S*I					3.03									4.50				

Y_1- 2021–22, Y_1- 2022–23, S_1- Flat bed, S_2- Ridge, I_1 -IW/CPE 0.6, I_2 -IW/CPE 0.8, I_3 -IW/CPE 1.0, I_4 -IW/CPE 1.2, CD-critical difference.

Table 7. Effect of sowing methods and irrigation regimes on water balance components and total water requirement

Year	Irrigation regimes	Sowing methods	Quantity of irrigation water applied (cm)	Effective rainfall (cm)	Profile water use (cm)	Total water requirement (cm) (IWA + ER + PWU)
2021–2022	IW/CPE 0.6	Flat-bed	14.0	21.7	−1.2	34.5
		Ridge	14.0	21.7	−1.3	34.4
	IW/CPE 0.8	Flat-bed	14.0	21.7	−1.4	34.3
		Ridge	14.0	21.7	−1.6	34.1
	IW/CPE 1.0	Flat-bed	17.0	21.7	−1.3	37.4
		Ridge	17.0	21.7	−1.3	37.5
	IW/CPE 1.2	Flat-bed	23.0	21.7	−1.6	43.1
		Ridge	23.0	21.7	−1.7	43.0
2022–2023	IW/CPE 0.6	Flat-bed	17.0	4.0	−1.3	19.8
		Ridge	17.0	4.0	−1.6	19.4
	IW/CPE 0.8	Flat-bed	17.0	4.0	−2.0	19.1
		Ridge	17.0	4.0	−2.2	18.8
	IW/CPE 1.0	Flat-bed	20.0	4.0	−1.9	22.1
		Ridge	20.0	4.0	−1.9	22.1
	IW/CPE 1.2	Flat-bed	26.0	4.0	−2.1	27.9
		Ridge	26.0	4.0	−2.2	27.8

IWA, Irrigation water applied; ER, Effective rainfall; PWU, Profile water use; IW/CPE, Irrigation water/Cumulative pan evaporation.

seasons, therefore multi location and long-term studies are needed to validate and generalise the recommendations.

Conclusions

This study demonstrated that conjoint use of ridge sowing and IW/CPE ratio of 1.0 (I_3) emerged as the most effective strategy for improving carrot yield, soil quality and increasing water use efficiency under mid-hill conditions. The optimal irrigation schedule (I_3) saved 15% more water than I_4, while producing comparable yields, highlighting its superior efficiency in optimising water use under water limited environment. This confirmed it as the most sustainable and viable option, thus, validating the research hypothesis that optimal irrigation scheduling combined with ridge sowing improves yield and water use efficiency without compromising soil health. Hence, based on results it can be recommended as a practical approach for carrot cultivation under similar agro-ecological conditions. To strengthen adoption and refine recommendation, future research should incorporate multi-locational trials, economic evaluation and comparison with micro-irrigation system across diverse environments.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0021859626100707.

Acknowledgements. The authors are thankful to the Department of Soil Science and Water Management, Dr. Yashwant Singh Parmar, University of Horticulture and Forestry, Nauni, Solan, H.P, India for providing necessary facilities to conduct this work.

Author contributions. Prikxit and JC Sharma conceived and designed the study. Prikxit, JC Sharma conducted the research experiment and recorded the data. Prikxit and Archna Sharma performed statistical analyses. Prikxit, JC Sharma, Bhawna Babal and Archna Sharma wrote the article.

Funding statement. The authors have not taken any assistance from any funding agency.

Competing interests. The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Ethical standards. Not applicable.

References

Alam MS, Malik SA, Costa DJ and Alam A (2010) Effect of irrigation on growth and yield of carrot (*Daucus carota* ssp. *sativus*) in hill valley. *Bangladesh Journal of Agriculture Research* **35**, 323–329. https://doi.org/10.3329/bjar.v35i2.5895.

Allen RG, Pereira LS, Raes D and Smith M (1998) Crop evapotranspiration: Guidelines for computing crop water requirements. FAO irrigation and drainage paper 56. FAO, Rome, Italy.

Anonymous (2014) *Package of Practices for Vegetable Crops. Directorate of Extension Education*. Nauni, Solan, HP: Dr YS Parmar University of Horticulture and Forestry, 202p.

Anozie CC and Baiyeri KP (2022) Effects of tillage methods and poultry manure rates on the production of carrot (*Daucus carota* L.) in Nsukka, Southeast Nigeria. *Journal of Horticulture and Forestry* **14**(4), 42–48. https://doi.org/10.5897/JHF2022.0691.

Badr MA (2007) Spatial distribution of water and nutrients in root zone under surface and subsurface drip irrigation and cantaloupe yield. *World Journal of Agricultural Sciences* **3**, 747–756. https://www.idosi.org/wjas/wjas3(6)/8.pdf.

Biswas A, Mailapalli DR and Raghuwanshi NS (2021) Consumptive water footprints, water use efficiencies and productivities of rice under alternate wetting and drying for Kharagpur, West Bengal, India. *Water Supply* **21**, 2935–2946. https://doi.org/10.2166/ws.2021.068.

Boadi NO, Badu M, Kortei NK, Saah SA, Annor B, Mensah MB, Okyere H and Fiebor A (2021) Nutritional composition and antioxidant properties of three varieties of carrot (*Daucus carota*). *Scientific African* **12**, e00801. https://doi.org/10.1016/j.sciaf.2021.e00801.

Carvalho ADD, Silva GOD, Guedes SF, Pereira EDC, Martins GP and Magalhães CDC (2023) Evaluation of summer carrot cultivars in bed and ridge systems. *Horticultura Brasileira* **41**, e2553. https://doi.org/10.1590/s0102-0536-2023-e2553.

Ciza A, Silungwe F and Kihupi N (2022) Carrot productivity under various levels of irrigation and fertilization. *Asian Research Journal of Agriculture* **15**(4), 56–68.

Elshamly AM and Nassar SM (2023) Stimulating growth, root quality, and yield of carrots cultivated under full and limited irrigation levels by humic and potassium applications. *Scientific Reports* **13**(1), 14260. https://doi.org/10.1038/s41598-023-41488-5.

Harasim E, Kwiatkowski CA and Buczek J (2025) Effect of farming system and irrigation on nutrient content and health-promoting properties of carrot roots. *Agronomy* **15**(6), 1289. https://doi.org/10.3390/agronomy15061289.

Maida P, Bisen BP and Dhakad U (2020) Effect of different irrigation levels on growth and yield of chilli (*Capsicum annum* L.). *Bulletin of Environment, Pharmacology and Life Sciences* **9**, 18–22.

Mankotia S, Sharma JC and Verma ML (2024) Impact of irrigation and fertigation schedules on physical and biochemical properties of apple under high-density plantation. *Communications in Soil Science and Plant Analysis* **56**(7), 985–993. https://doi.org/10.1080/00103624.2024.2440064.

Merwin HD and Peech M (1951) Exchangeability of soils potassium in the sand, silt and clay fractions as influenced by the nature of the complementary exchangeable cations. *Soil Science Society of the African Proceedings* **15**, 125–128.

Olsen SR, Cole CV, Watnabe FS and Deam LA (1954) Estimation of available phosphorus by extraction with sodium bicarbonate. *United States Department of Agriculture Circular* **939**, 1–19.

Pal S, Kumar S, Pravesh K, Singh A and Gangwar HK (2020) Effect of moisture regime IW/CPE ratio on soil properties, yield and water use efficiency of wheat crop (*Triticum aestivum* L.). *International Journal of Current Microbiology and Applied Sciences* **9**, 2499–2506.

Patel IC, Patel BS, Patel MM, Patel AG and Tikka SBS (2005) Effect of varieties, levels of irrigation and dates of sowing on yield and monitory returns of summer cowpea under North Gujarat condition. *Indian Journal of Pulses Research* **18**, 217–218.

Philippe DH, Dominique D, Sophie BM, Maxime D, Franck V, Jacques D and François K (2018) Spatial variation of root yield within cultivated carrot fields is strongly impacted by plant spacing. *Scientia Horticulturae* **241**, 29–40. https://doi.org/10.1016/j.scienta.2018.06.072.

Prikxit S J C, Mahajan S and Sharma A (2025) Optimization of sowing methos and irrigation levels on carrot productivity (*Daucus carota* L.) in mid hills of North Western Himalayas, India. *Indian Journal of Ecology* **52**(5), 983–987. https://doi.org/10.55362/IJE/2025/4603.

Razzaq M, Akram NA, Ashraf M, Naz H and Al-Qurainy F (2017) Interactive effect of drought and nitrogen on growth, some key physiological attributes and oxidative defense system in carrot (*Daucus carota* L.) plants. *Scientia Horticulturae* **225**, 373–379. https://doi.org/10.1016/j.scienta.2017.06.055.

Rolbiecki S, Jagosz B, Rolbiecki R and Kuśmierek-Tomaszewska R (2025) Climate-induced water management challenges for cabbage and carrot in Southern Poland. *Sustainability* **17**(15), 6975. https://doi.org/10.3390/su17156975.

Salle AJ (1973) *Laboratory Manual on Fundamental Principles of Bacteriology*. New York, NY, USA: McFraw-Hill Book Company. pp. 176.

Santos DV, Sousa PL and Smith RE (1997) Model simulation of water and nitrate movement in a level-basin under fertigation treatments. *Agricultural Water Management* **32**, 293–306.

Sarkar MD, Akter S, Bakhashwain AA, Mousa MA and Ibrahim OH (2024) Influence of effective irrigation water usage on carrot root productivity and quality properties in soilless culture. *Journal of Soil Science and Plant Nutrition* **24**(1), 1042–1058. https://doi.org/10.1007/s42729-023-01608-6.

Schiattone MI, Vigiani R, Venere DD, Cantore V, Todorovic M, Perniola M and Candido V (2018) Impact of irrigation regimes and nitrogen rate on yield, quality and water use efficiency of wild rocket under greenhouse condition. *Scientia Horticulturae* **229**, 182–192. https://doi.org/10.1016/j.scienta.2017.10.036.

Sharma A, Sharma JC, Shukla YR, Verma ML, Singh U, Spehia RS, Sharma D, Gautam KL, Dogra R, Tecimen HB, Kumar M and Kumar A (2023) Nutrient management influences root characteristics and nitrogen use efficiency in the vegetable-based agroecosystem in the Northwestern Himalayas. *Sustainability* **15**, 10593. https://doi.org/10.3390/su151310593.

Singh A, Verma K, Kumar N, Lothe NB, Kumar A, Chauhdhary A, Kaur P, Singh KP, Singh AK, Kumar R, Anandakumar TM and Singh S (2021) Optimized irrigation and planting technique improve yield and economics in aloe vera [*Aloe vera* (Miller)]. *Industrial Crops and Products* **167**, 1–8. https://doi.org/10.1016/j.indcrop.2021.113539.

Singh KP, Hari Ram SK and Sonkar PR (2008) Effect of sowing techniques and irrigation methods on yield, yield attributes, net profit and water use efficiency of late sown chickpea. *Plant Archives* **8**, 711–712.

Singh YP, Tomar SS, Singh AK and Yadav RP (2018) Nutrient management and irrigation scheduling effect on blackgram (*Vigna mungo*) – Frenchbean (*Phaseolus vulgaris*) yield, economics, water productivity and soil properties. *Journal of Soil and Water Conservation* **17**, 58–64. https://doi.org/10.5958/2455-7145.2018.00009.7.

Singh AK, Meena RN, Kumar AR, Kumar S, Meena R, Hingonia K and Singh AP (2017) Effect of land configuration method and sulphur levels on growth, yield and economics of Indian mustard (*Brassica juncea* L.) under irrigated condition. *Journal of Oilseed Brassica* **81**, 151–157.

Solanki B, Kaswala AR, Dubey PK and Italiya AP (2020) Effect of land configuration and different organic sources on growth, yield and quality of carrot under organic farming. *The Bioscan* **15**, 357–362.

Subbiah BW and Asija GI (1956) A rapid procedure for estimation of available nitrogen in soils. *Current Science* **25**, 229–260.

Thakur J (2020) Standardization of irrigation and fertigation schedule for apple under high density plantation. Ph.D. Thesis. Department of Soil Science and Water Management, Dr. Y S Parmar University of Horticulture and Forestry, Nauni, Solan.

Tlig W, Mokh FE, Autovino D, Iovino M and Nagaz K (2023) Carrot productivity and its physiological response to irrigation methods and regimes in arid regions. *Water Supply* **23**(12), 5093–5105. https://doi.org/10.2166/ws.2023.304.

Wang GY, Hu YX, Liu YX, Ahmad S and Zhou XB (2021) Effects of supplement irrigation and nitrogen application levels on soil carbon–nitrogen content and yield of one-year double cropping maize in subtropical region. *Water* **13**, 1180. https://doi.org/10.3390/w13091180.

Waqas MS, Cheema MJM, Hussain S, Ullah MK and Iqbal MM (2021) Delayed irrigation: An approach to enhance crop water productivity and to investigate its effects on potato yield and growth parameters. *Agricultural Water Management* **245**, 106576. https://doi.org/10.1016/j.agwat.2020.106576.

Williams CH and Steinbergs A (1959) Soil sulphate fractions as chemical indices of available sulphur in some Australian soils. *Australian Journal of Agriculture Research* **10**, 340–352.

Xu JT, Cai HJ, Wang XY, Ma CG, Liu YJ, Ding YB, Wang XB, Chen H, Wang YF and Saddique Q (2020) Exploring optimal irrigation and nitrogen fertilization in a winter wheat summer maize rotation system for improving crop yield and reducing water and nitrogen leaching. *Agricultural Water Management* **228**, 105904. https://doi.org/10.1016/j.agwat.2019.105904.

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