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Research Article

Evaluation of Root Zone Behavior and Cucumber Yield under Different Mulch Materials and Irrigation Schedules under Tunnel Farming

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Water plays a crucial role in better agricultural production. The situation of irrigation water in Pakistan is getting worse day by day. New sowing techniques for high-value agriculture are the only solution to increasing water and crop productivity. Drip irrigation coupled with mulch in tunnel farming can be an effective tool for better agricultural production. Therefore, this study was designed to check the impact of different mulch materials coupled with various irrigation schedules on cucumber yield and its root zone behavior. Three types of mulch, i.e., black, transparent, and wheat straw, each under two different levels of deficit irrigation (DI) of 20% DI and 40% DI, were compared with farmer practice as a control. The experiment was conducted at a farmer's field and laid out under a randomized complete block design. The effect of treatments was checked on the number of leaves per plant, plant height, number of fruits per plant, fruit weight per plant, and crop yield. Moreover, the effect of treatments was checked on the crop root zone. The Hydrus-1D model was calibrated to successfully simulate soil moisture in the root zone. The study's results revealed that among all treatments, the total yield of the cucumber was higher under 20% DI than 40%. The treatment T3 (transparent mulch + 20% DI) had a maximum yield of 47.31 tons/ha, whereas the minimum yield of 31.86 tons/ha was obtained under control. There was little difference between the yield of black plastic mulch and wheat straw mulch. Maximum root length was found in the case of black mulch with 20% DI (86.9 cm), and the maximum diameter of the root zone canopy was observed under wheat straw mulch. Hydrus-1D proved its ability and was recommended for simulating root zone moisture, with the lowest value of $R^2 = 0.894$. It was concluded that cucumber production with 20% DI is viable for drip irrigation with mulch applications.

1. Introduction

Food demand is increasing with each passing day and is expected to be twice as high by 2050 [1]. On the other hand, the water availability situation is more critical in Pakistan, represented by per capita water availability reduced to 1,000 m^3/annum, internationally considered the water shortage threshold value [2]. The agriculture sector utilizes almost 90% of the available water, and the remaining water is utilized for household and industrial purposes [3]. In order to produce enough food, there is a need to develop technologies that can produce more crops with higher water productivity [4]. In this scenario, with the daily food demand of the population and limited water availability, high crop production can be produced only by attempting the best use of precious resources through high-value agriculture [5, 6]. High-value agriculture primarily relates to the production of off-season vegetables like cucumber. The cucumber is an annual herbaceous plant commonly grown in many types of

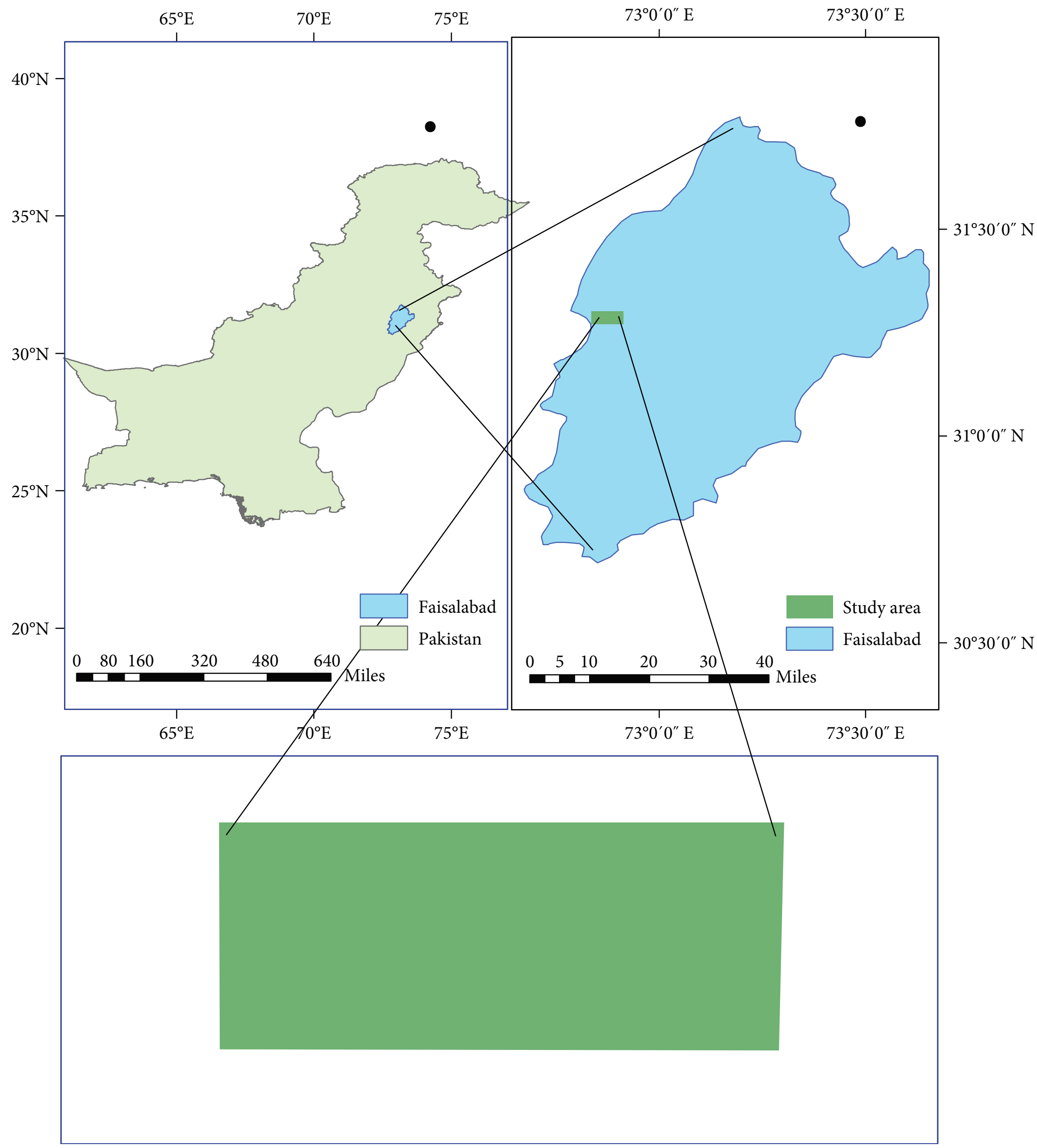

Figure 1: Geological location of the study area.

soil rich in humus and areas with better light conditions. Cucumbers can only grow in moist and temperate regions. It is usually grown in the summer and requires watering for better quality and production. To produce the cucumber in winter, tunnel farming and mulch applications can be adopted to maintain the temperature for optimum crop growth. Mulches are the films used to cover the soil surfaces to conserve water and reduce soil erosion [7, 8]. Different types of mulches are available in different colors, and literature has reported that the mulch color or its transparency has a substantial effect on soil hotness and, ultimately, on crop growth [9–12].

Pakistan is suffering from the effects of climate change, and its consequences can be seen from the fact that the climate patterns have been shifted significantly from their original period. The requirement for vegetable production exists despite the climate variation. So, the best way to produce vegetables is using artificial environmental conditions that could be achieved using tunnel farming. Tunnels are greenhouse structures used for crop production when there can be no production outside the tunnel [13]. Under the tunnel, excessive water use creates a suffocating environment that can spread diseases; therefore, the best way to apply minimum water in tunnel farming is to use deficit irrigation

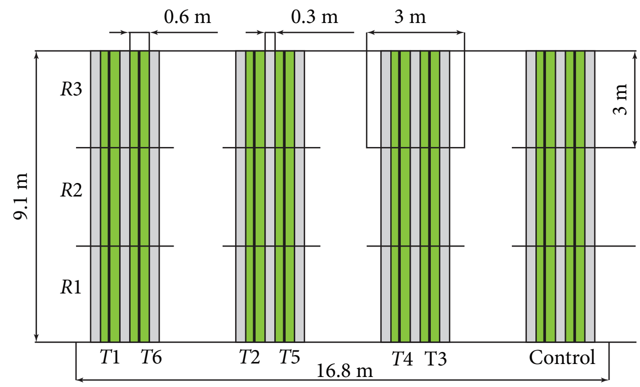

Figure 2: Experimental layout.

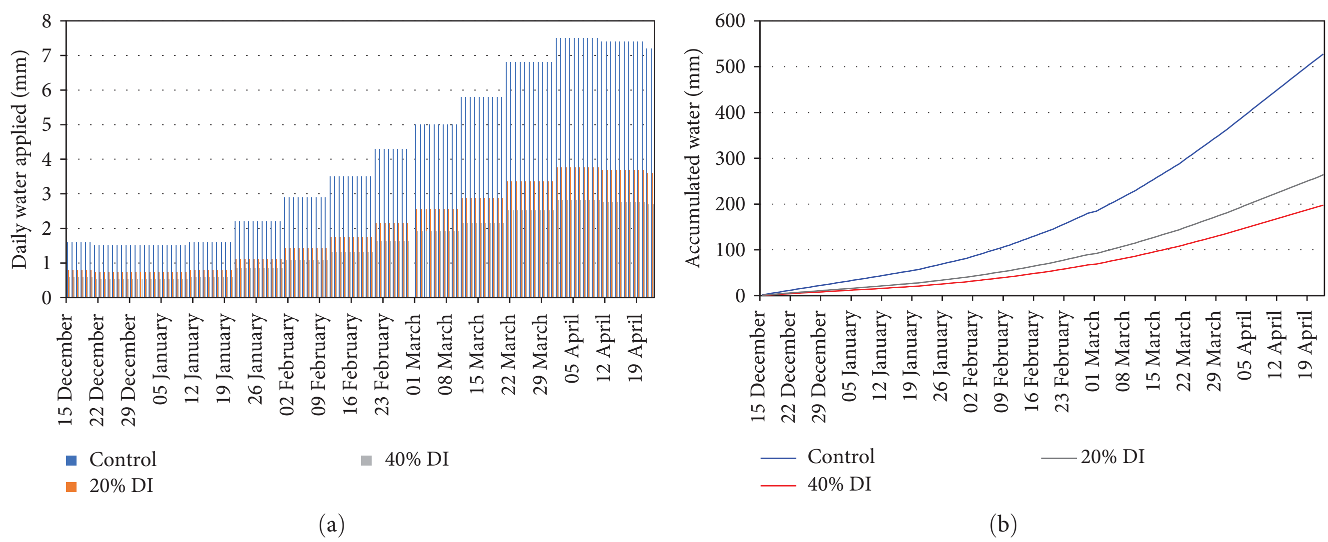

Figure 3: Water applications under different treatments (a) daily and (b) accumulative.

(DI). Using mulch can reduce evaporation, which could further decrease water applications. This study has been designed to examine the potential of tunnel farming for cucumber production and to analyze the combined effects of DI with mulch applications on crop as well as rote zones. The study aimed to evaluate the effects of different mulch types on crop production and root zone behavior and to optimize irrigation deficit for enhanced cucumber growth in tunnel farming.

2. Materials and Methods

To check the cucumber response under different mulch colors and levels of DI, an experimental study was carried out at a farmer's field in District Faisalabad with 31.418715°N, 73.079109°E (Figure 1). The study area bears light winds, and summers are moist and hot, while winters have cool and dry climates. The maximum/minimum average temperature was 40.5°C /26.9°C in the summer and 19.4°C/4.1°C during winter. The average rainfall found in the area on an annual basis is 375 mm. The soil of the study area is primarily silty loam and very fine. Mixed-wheat cropping system with wheat as a significant rabi crop followed by almost all kinds of vegetables.

The soil and water samples were collected and analyzed to examine irrigation water quality and soil fertility using standard procedures. The tubewell is mostly used for irrigation due to limited canal water availability.

2.1. Field Preparation. After the rotavator, cultivator, and planker applications, the beds (0.6 m wide bed and 0.3 m wide furrow) (Figure 2) were formed using a mounted bed planter. Later, the walk-in tunnel was installed 3 m apart along the bed. The width and height of the tunnel were 3 m and 2 m, respectively. The drip laterals were placed in the center of the beds, and the beds were covered using different kinds of mulches as per the designed layout of the experiment (Figure 2). Three kinds of mulches were used, including white plastic, black plastic, and wheat straw (organic). The white and black plastic mulches were 1.21 m in width, while 0.60 m laid on the beds and 0.10 m were buried under soil at both sides of the bed. The thickness of the plastic mulches was 0.8 mm. The wheat straw was placed on beds up to 15 mm thickness to cover barren soil completely.

Table 1: Crop agronomic parameters.

Treatments	Number of leaves/plant	Plant height (cm)	Number of fruits/plant (nos.)	Fruit weight/plant (g)	Total yield (tons/ha)
*T*1 (black mulch + 20% deficit irrigation)	31.99^{d}	172.67^{d}	30.67^{b}	1610^{b}	44.54^{b}
*T*2 (black mulch + 40% deficit irrigation)	$41.16^{a,b}$	181.5^{b}	$21.92^{d,e}$	1358.67^{e}	37.59^{e}
*T*3 (transparent mulch + 20% deficit irrigation)	35.50^{c}	$178.5^{b,c}$	36.17^{a}	1710.33^{a}	47.31^{a}
*T*4 (transparent mulch + 40% deficit irrigation)	44.16^{a}	185.33^{a}	$28.67^{b,c}$	1491.83^{c}	41.26^{c}
*T*5 (wheat straw + 20% deficit irrigation)	28.64^{e}	168.33^{e}	$25.5^{c,d}$	1405^{d}	38.87^{d}
*T*6 (wheat straw + 40% deficit irrigation)	$38.23^{b,c}$	$175.5^{c,d}$	19.25^{e}	1260.67^{f}	34.87^{f}
Control (without mulch + furrow irrigation)	25.48^{e}	164.33^{f}	15.33^{f}	1151.67^{g}	31.86^{g}
Significance value	3.50	3.82	3.17	100.33	1.27

[a,b,c,d,e,f,g]Different superscript alphabets denote the significance between various values of a particular parameter.

2.2. Experiment Description. The experiment comprised six treatments, including *T*1: Black mulch with 20% DI level under drip irrigation, *T*2: Black mulch with 40% deficit level under drip irrigation, *T*3: Transparent mulch with 20% deficit level under drip irrigation, *T*4: Transparent mulch with 40% deficit level under drip irrigation, *T*5: Wheat straw mulch with 20% deficit level under drip irrigation, and *T*6: Wheat straw mulch with 40% deficit level under drip irrigation [14]. The experiment also included a control plot as farmer practice. The experiment was laid under a randomized complete block design, as suggested by Zhou et al. [15] for small-scale studies. The total experiment area was $30 \times 55\,\text{ft} = 1{,}650\,\text{ft}^2$ or $153.290\,\text{m}^2$ in four tunnels. The layout of the trial is given in Figure 2. The crop was cultivated in a farmer's (Sami Ahmed) field in the Sarshamir area of Faisalabad.

2.3. Irrigation Scheduling. The irrigation schedules were developed according to 20% and 40% deficit crop water requirements using Cropwat software. The past 10 years' climate data (maximum, minimum temperature, wind speed, humidity, and sunshine hours) was used to calibrate the model for predicting crop water requirements during the current season.

2.4. Data Collection and Analysis. The soil moisture contents at different time intervals (30, 60, 90, and 131 days after sowing) at 0.3 m depth were measured using time domain reflectometer (TDR) meter (Spectrum Launches 350). Different plants from each treatment and replicates were selected and tagged for onward data collection. At maturity, the number of leaves and fruits per plant was counted. The plant height was measured by measuring tape of the same plants. Afterward, the total weight of fruits per plant was measured and multiplied by the number of plants to determine the total yield. The water productivity was calculated by using the following equation:

$$\text{Water productivity} = \frac{\text{Total yield}}{\text{Total water applied}} \left(\text{kg ha}^{-1}\text{m}^{-3}\right). \tag{1}$$

Table 2: Change in root length with time.

Treatments	Days	Root length (cm)			
–	–	*R*1	*R*2	*R*3	*R*
*T*1: Black mulch + 20% deficit irrigation					
	30	13.4	13.7	12.6	13.2
	60	38.3	36.7	35.9	36.9
	90	66.3	64.2	65.3	65.3
	131	88.2	86.3	86.4	86.9
*T*2: Black mulch + 40% deficit irrigation					
	30	12.6	12.1	11.5	12.1
	60	34.0	36.3	35.2	35.2
	90	64.2	64.9	65.3	64.8
	131	85.3	84.6	84.2	84.7
*T*3: Transparent mulch + 20% deficit irrigation					
	30	12.1	12.3	12.9	12.4
	60	35.5	32.6	33.6	33.9
	90	65.7	64.8	66.2	65.6
	131	86.3	84.2	85.8	85.4
*T*4: Transparent mulch + 40% deficit irrigation					
	30	11.2	11.6	11.0	11.3
	60	33.5	31.3	31.4	32.1
	90	62.4	63.9	62.8	63.0
	131	83.2	82.8	84.3	83.4
*T*5: Wheat straw mulch + 20% deficit irrigation					
	30	13.1	11.4	10.3	11.6
	60	34.6	35.1	33.2	34.3
	90	61.3	62.2	61.7	61.7
	131	78.3	79.2	78.8	78.8
*T*6: Wheat straw mulch + 40% deficit irrigation					
	30	12.7	10.9	11.2	11.6
	60	35.4	33.2	32.8	33.8
	90	60.9	59.8	59.3	60.0
	131	76.1	74.9	74.1	75.0
Control: Without any mulch under furrow irrigation					
	30	10.2	9.6	10.8	10.2
	60	30.2	28.3	29.2	29.2
	90	55.6	58.7	56.7	57.0
	131	68.5	67.0	67.9	67.8

The same methodology to calculate water productivity was adopted by Bakhsh et al. [16] and Chauhdary et al. [17–19]. The root length and diameter were measured 30, 60, 90, and 131 days after sowing. For this purpose, three plants were tugged from each replication of every treatment, and the root length was measured with the MyROOT android application [20]. Similarly, root canopy diameter was determined using a vernier caliper near the soil surface. Later, the average of three plants will be used as a single value.

2.5. Simulation of Moisture Profile. The Hydrous-1D has the ability to analyze the flow of water, solute transport, and heat flow in variably saturated porous media (soils). Hydrous-1D software was used to simulate the moisture profile in the cucumber root zone under different irrigation schedules for the present work. The root growth was used as an input, and root water uptake was also considered to check the water flow in the root zone. Uniform soil depth was taken up to 90 cm as recommended for cucumber. The incremental time steps were taken as 131, equal to the total crop period in days. The default value for iteration criteria was used, which was 10. Van Genuchten–Mualem, with no hysteresis, was used as a soil hydraulic model. Similarly, the water flow parameters were taken from the model database for sandy loam soil. The upper and lower boundary conditions were taken as "atmospheric BC with surface runoff" and "free drainage," respectively. As the cucumber was in the tunnel, the precipitation was taken as irrigation depth in time-variable boundary conditions.

3. Results and Discussion

3.1. Irrigation Scheduling and Crop Water Requirement. Two DI techniques were designed and applied to cucumber at two DI levels of 20% DI and 40% DI. The irrigation requirement revealed by CROPWAT showed that 20% DI level had more water applications compared to 40% DI; the total water applied was 248 mm. The irrigation amount was 186 mm under 40% DI, less than 20% DI. Conversely, the control treatment with furrow irrigation had the highest amount of water applied at 529.9 mm. The daily and accumulative water application at different deficit levels and controls are presented in Figure 3.

The results revealed that the number of leaves per plant and plant height were more significant under white mulch than the treatments of black and wheat straw mulches. This happened due to the difference in soil temperature under different mulch conditions. The soil temperature was maximum under white mulch conditions due to higher soil temperature as the white mulch has the capacity for maximum transmission of sunlight and heat. Results showed that the high temperature of soil allowed the early germination of plants and better vegetative growth of plants than all other mulch types. These results are in strong agreement with the results of [21, 22]. The overall crop performance was observed to be better under 40% DI as compared to 20% DI. The number of fruits per plant showed a maximum number with white mulch + 20% DI and a minimum with wheat straw + 40% DI.

Table 3: Change in root canopy diameter with time.

Treatments	Days	Root length (cm)			
–	–	*R*1	*R*2	*R*3	*R*
*T*1: Black mulch + 20% deficit irrigation					
	30	1.15	1.21	1.12	1.16
	60	2.64	2.59	2.56	2.59
	90	4.76	4.81	4.71	4.76
	131	5.78	5.83	5.76	5.79
*T*2: Black mulch + 40% deficit irrigation					
	30	1.23	1.31	1.22	1.25
	60	2.87	2.85	2.82	2.85
	90	4.88	4.67	4.82	4.79
	131	5.89	5.83	5.91	5.88
*T*3: Transparent mulch + 20% deficit irrigation					
	30	1.24	1.32	1.35	1.30
	60	2.73	2.79	2.84	2.79
	90	4.85	4.73	4.82	4.80
	131	5.75	5.81	5.84	5.80
*T*4: Transparent mulch + 40% deficit irrigation					
	30	1.30	1.36	1.27	1.31
	60	2.85	2.89	2.91	2.88
	90	4.91	4.85	4.87	4.88
	131	5.85	5.88	5.95	5.89
*T*5: Wheat straw mulch + 20% deficit irrigation					
	30	1.16	1.12	1.20	1.16
	60	2.72	2.70	2.81	2.74
	90	4.83	4.80	4.87	4.83
	131	5.82	5.96	5.93	5.90
*T*6: Wheat straw mulch + 40% deficit irrigation					
	30	1.25	1.24	1.29	1.26
	60	2.89	2.84	2.86	2.86
	90	4.91	4.99	5.05	4.98
	131	5.92	5.95	6.02	5.96
Control: Without any mulch under furrow irrigation					
	30	1.13	1.18	1.05	1.12
	60	2.45	2.49	2.40	2.45
	90	4.56	4.27	4.45	4.43
	131	5.24	5.38	5.38	5.33

However, a worse number of fruits were observed in the control treatment due to poor vegetative growth compared to others. There was a little difference in the number of fruits between black and white mulch treatments. The highest fruit weight (1,733.33 g) and crop yield (47.31 tons/ha) of cucumber were obtained with T3 treatment (white mulch + 20% DI) relative to other treatments. The minimum fruit weight (1,151.67 g) and yield (31.86 tons/ha) were observed under control treatment. The white mulch was identified as the best mulch technique due to better vegetative growth of crops with maximum yield due to higher heat absorption by soil, creating a favorable environment for crop production. The black mulch was identified as less efficient due to the above adverse phenomenon. These results are in strong agreement

Table 4: Change in moisture content under different irrigations.

Depth (cm)	Moisture under 40 DI Observed	Moisture under 40 DI Model	Moisture under 40 DI Percentage difference	Moisture under 20 DI Observed	Moisture under 20 DI Model	Moisture under 20 DI Percentage difference	Moisture under furrow Observed	Moisture under furrow Model	Moisture under furrow Percentage difference
Moisture after 30 days of sowing									
5	0.067	0.064	4.580	0.07	0.075	6.897	0.137	0.131	4.478
10	0.084	0.078	7.407	0.083	0.082	1.212	0.15	0.157	4.560
15	0.094	0.101	7.179	0.094	0.104	10.101	0.165	0.176	6.452
20	0.118	0.11	7.018	0.117	0.114	2.597	0.23	0.224	2.643
25	0.122	0.119	2.490	0.122	0.125	2.429	0.242	0.245	1.232
30	0.128	0.124	3.175	0.128	0.131	2.317	0.271	0.267	1.487
Moisture after 60 days of sowing									
5	0.071	0.065	8.824	0.071	0.078	9.396	0.142	0.139	2.135
10	0.078	0.068	13.699	0.082	0.088	7.059	0.152	0.155	1.954
15	0.094	0.102	8.163	0.104	0.106	1.905	0.169	0.169	0.000
20	0.112	0.113	0.889	0.118	0.116	1.709	0.23	0.222	3.540
25	0.119	0.118	0.844	0.123	0.131	6.299	0.255	0.249	2.381
30	0.126	0.123	2.410	0.132	0.136	2.985	0.274	0.271	1.101
Moisture after 90 days of sowing									
5	0.072	0.074	2.740	0.076	0.081	6.369	0.137	0.142	3.584
10	0.091	0.092	1.093	0.096	0.098	2.062	0.151	0.154	1.967
15	0.104	0.101	2.927	0.112	0.109	2.715	0.169	0.172	1.760
20	0.117	0.115	1.724	0.12	0.119	0.837	0.225	0.231	2.632
25	0.122	0.121	0.823	0.132	0.134	1.504	0.256	0.25	2.372
30	0.128	0.129	0.778	0.142	0.139	2.135	0.277	0.273	1.455
Moisture after 131 days of sowing									
5	0.083	0.081	2.439	0.084	0.084	0.000	0.152	0.147	3.344
10	0.093	0.095	2.128	0.1	0.101	0.995	0.161	0.157	2.516
15	0.101	0.106	4.831	0.11	0.112	1.802	0.179	0.168	6.340
20	0.112	0.112	0.000	0.122	0.124	1.626	0.223	0.225	0.893
25	0.116	0.119	2.553	0.129	0.132	2.299	0.258	0.253	1.957
30	0.122	0.126	3.226	0.137	0.14	2.166	0.278	0.271	2.550

with the literature published in [23–26]. The details of results regarding crop agronomic parameters are given in Table 1.

3.2. Effect of Mulches and Irrigation Scheduling on Root Length (cm). Results of irrigation scheduling techniques and different mulch materials on cucumber crop root length are presented in Table 2. The results showed the maximum root length under black mulch with 20% DI (86.9 cm) followed by transparent mulch with 20% DI (85.4 cm) compared to different treatments (Table 2). Higher root length under black mulch may be due to the black mulch trapping more heat than transparent mulch, which caused more root development. The wheat straw mulch conserved more moisture and hence had a low temperature at the soil surface and lower temperature in the root zone; therefore, the root development was less under wheat mulch than black and transparent mulches. Similarly, the root length was higher in 20% DI due to excessive moisture availability at a lower soil profile than that under 40% DI.

3.3. Effect of Mulches and Irrigation Scheduling on Root Canopy Diameter. The results showed the maximum root diameter with wheat straw mulch under 40% DI (5.96 mm) followed by wheat straw + 20% DI (5.90 mm) compared to other treatments with different mulch materials, as presented in Table 3. The value of the root canopy diameter was found to be opposite to the length of the root zone. The major cause of this change in diameter was moisture content near the soil surface. Wheat straw absorbed the moisture content and conserved it for a long time near the soil surface, resulting in the lateral movement of roots with a greater diameter than other mulch treatments. Transparent mulch also showed more diameter than black mulch as black mulch absorbs more heat than transparent mulch; it can cause the removal of moisture near the soil surface, ultimately causing less lateral movement of the root compared to downward movement.

3.4. Change in Moisture Content under Different Levels of Deficit. Results of the Hydrous-1D model and observed values showed that the model is an excellent alternative to TDR values; hence, the model can be used to simulate soil moisture. Values obtained from the model and observed using TDR are given in Table 4, and their graphical representations are shown in Figure 4(a)–4(l).

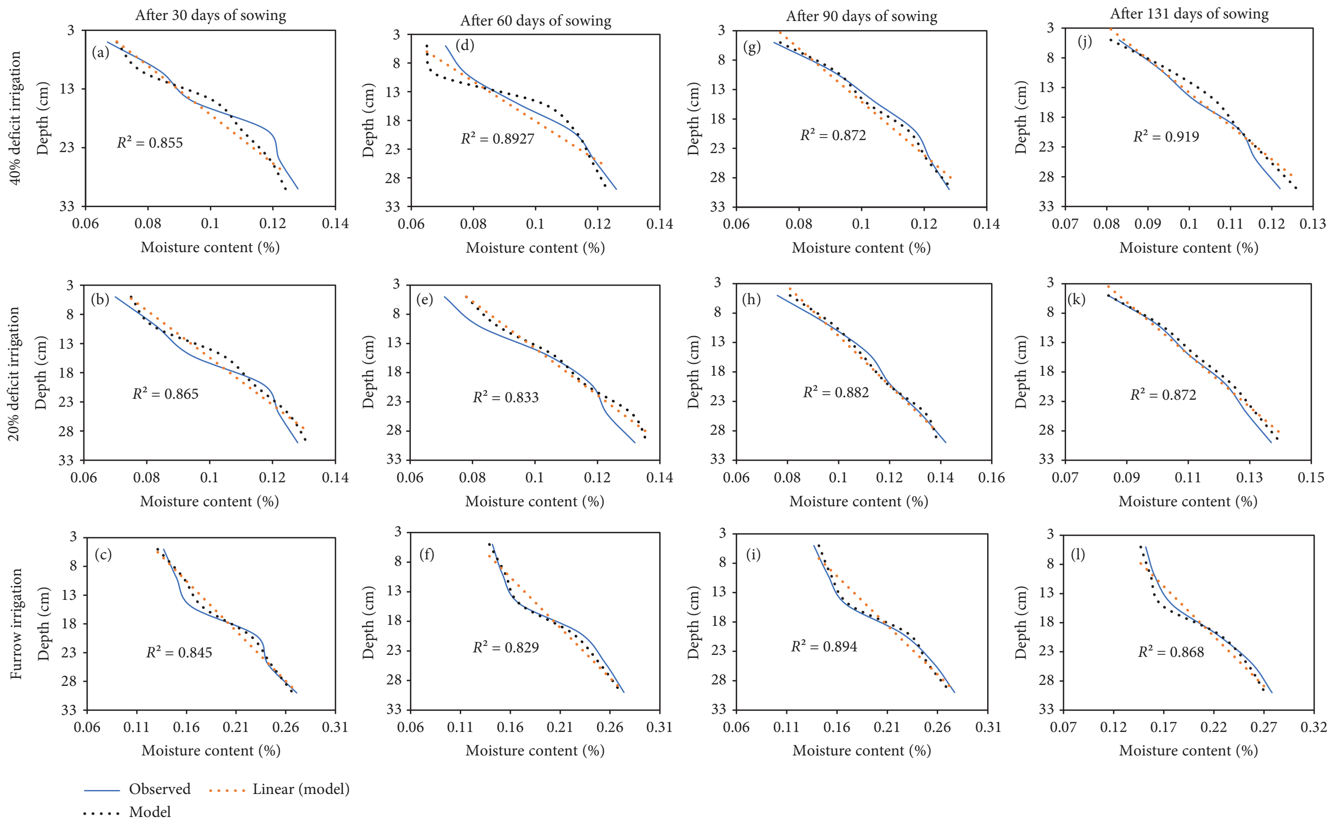

Figure 4: Variation in moisture content under different irrigation types (a–c) 30 days, (d–f) 60 days, (g–i) 90 days, and (j–l) 131 days.

A model run was performed using the input values from experiment data to simulate moisture content values. The moisture content at different depths was also measured with the help of a TDR, and values were compared with the moisture obtained from the model. It can be seen that moisture is increasing with each passing day. Moreover, moisture also increases with depth. At the last crop stage, the moisture decreased because the temperature during the last stage was higher than in the early stages of the crop.

By comparing the moisture values at a depth of 30 cm, it has been observed that maximum moisture is found for furrow irrigation after 90 days of sowing, followed by moisture at 60 and 131 days under furrow irrigation, which is the same because of the temperature difference. Minimum moisture content was observed at a depth of 5 cm with 40% DI after 60 days of sowing, which is very close to moisture at a depth of 5 cm with 40% DI after 30 days.

4. Conclusions

It was concluded that different irrigation scheduling techniques produced significantly different results regarding cucumber yield and its growth. The growth and yield were more under 20% DI than less water applications (40% DI). At the same time, the white mulch produced a higher cucumber yield than other mulch types under corresponding levels of DI. The behavior of root length was different as the deepest roots were found under transparent mulch/coconut fiber coupled with 40% DI. Overall, the highest yield was produced under drip irrigation compared with traditional furrow irrigation.

Data Availability

Data used to support the findings of this research will be available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All the authors equally contributed to this work.

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