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Comparative Study of Crop and Water Productivity Under Drip and Furrow Irrigation Systems for Plastic Tunnel-Grown Off-Season Vegetables

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Abstract

This study evaluates crop and water productivity of drip and furrow irrigation systems for off-season vegetables under plastic tunnels on farmer's fields. Drip and furrow irrigation systems were tested on capsicum, cucumber and hot papers in this study. A permanent tunnel of 60 × 3 × 2 m was erected. Each crop was planted on 0.8 × 0.4 m raised beds under drip and furrow irrigation systems. Water productivity was calculated as the ratio of total yield to total water consumed by the crop. Data collected for three off-season vegetables revealed that each crop consumed less water under drip irrigation as compared to the furrow irrigation system. Among crops, hot peppers consumed the least amount of water irrespective of irrigation systems in comparison to furrow irrigation system. In addition, the percent use of all inputs under drip irrigation was reduced: water by 30%-45%, fertilizers by 22%-30% and pesticides by 15%-20% (because of reduced temperature and humidity) for different crops. In comparison to furrow irrigation, yield under drip irrigation was increased by 20%-30% and net farm income by 19%-41% for different crops. Average water productivity (kg/m^3) was increased by 141% for capsicum, 165% for cucumber and 109% for hot papers under drip irrigation system compared to the furrow irrigation system. In conclusion, drip irrigation technology is effective in improving crop growth and water productivity, and reducing water scarcity while considerably reducing fertilizer and pesticide use. These results advocate for drip irrigation as an ideal technology to address the issue of freshwater resource scarcity in Pakistan.

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Introduction

Pakistan needs to increase crop production to meet the food and fiber requirements of its rising population and export earnings. Important challenges are environmental degradation, increasing water scarcity, injudicious use of fertilizers and conventional agronomic and post-harvest technologies [1]. In this context, the Government of Punjab is implementing a mega project "Punjab Irrigated-Agriculture Productivity Improvement Project, in all districts of the province, for a period of 12 years (2011-2022), with financial assistance from the World Bank. The overall objective of the project is to improve agriculture and water productivity to maximize farm incomes. The Government and people of Pakistan are showing great interest in addressing the immediate and future impact of water scarcity on their lives and livelihoods. The issue is extremely sensitive and broad in dimension, requiring multiple and long-term actions to deal effectively with water shortages confronting different regions and various segments of society. Agriculture is the biggest user (69% share) of water in Pakistan and, ironically, wastes the maximum amount of water as well [1]. The issues that need to be addressed immediately include an increase in water storage capacity, minimizing water wastage at various levels, and increasing water use efficiency. The water availability in Pakistan is already below the critical level of 1700 m^3/person and climatic changes in the region may worsen the situation further [2].

The Water Management Department, Government of Punjab, focused on improved irrigation technologies for sharing them with the end users, as a mission, since its inception. Several water-saving technologies were popularized among the farmers to this end with very successful outcomes. Precision land levelling, bed-furrow irrigation and most recently, installation of high-efficiency irrigation systems are cases in point. With this perspective, the Water Management Department, Government of Punjab envisaged and launched a mega project "Punjab Irrigated Agriculture Productivity Improvement Project (PIPIP)". Main interventions are increasing both delivery and application efficiency of water, adopting improved high-efficiency irrigation systems, soluble fertilizers promoting crop diversification / high-value crops and effective application of non-water inputs, off-season vegetables in tunnels, non-pesticide or organic control of insect pests, bio-degradable Plastic mulch and fertigation with soluble fertilizers through drip irrigation. Vegetable crops are the eminent source of human nutrition. Production of vegetable crops in greenhouses is steadily increasing throughout the Punjab. The efficient use of irrigation water in greenhouses allows flexibility in planting time, establishing a more uniform plant stand, influencing soil temperature, and reducing the use of pesticides due to control outré & temperature [3]. Moreover, improving crop and water productivity will put the prices of vegetables within the reach of urban and rural poor [4].

Despite high returns, the non-availability of irrigation water is hindering the expansion of the area under vegetables. The drip irrigation system is an expensive, but efficient system of irrigating high-value crops, such as off-season vegetables. Combined use of drip irrigation with mulches for tunnel farming should be taken into consideration. Drip irrigation increased yield considerably with a substantial decrease in water, fertilizer, and energy inputs [5]. The net increase in income with drip than with furrow irrigation system was 23%, 34%and 41% higher in capsicum, cucumber and hot pepper, respectively as earlier reported [3, 6]. Drip irrigation improved marketable yield and fruit quality in the case of cucumber [7]. Keeping in view the above discussion, a comparison was made between drip irrigation and furrow irrigation methods to assess the potential of drip irrigation technology and investigate its effect on yield and water productivity of three off-season vegetables (capsicum, cucumber, hot pepper) at farmer fields in a controlled environment.

Materials and Methods

Study area, and soil characteristics

The study was conducted under the domain of four districts *viz*., Faisalabad, Jhang, Chiniot and Toba Tek Singh of Faisalabad division, Punjab, Pakistan. Faisalabad division is situated at latitude 31' 15" N, and longitude 72^o 48" E with an altitude of 149 m. The climate in Division Faisalabad is dry and sub-tropical. Mean maximum and mean minimum temperatures in summer (April-October) are 49^{o}C and 27^{o}C, respectively. In winter temperature ranges between 6^{o}C and 21^{o}C (November - March). The average normal rainfall is around 350 mm, most of which falls during summer. The study area has an acute shortage of canal water with brackish underground water. The field study was conducted on three off-season vegetables, capsicum, cucumber, and hot pepper with participation of farmers during 2016-2022 to determine crop growth and water use

Table 1 Sowing methodology of off-season vegetables grown in plastic tunnels.

Crop	Nursery sowing / sowing date	Transplanting date	Harvesting date	Row × Row (cm)	Plant × Plant (cm)	Variety
Capsicum	25th September	15th Nov	March-April	60	30	Orible
Cucumber	15th October	-	May-Mid June	67	30	Yala
Hot peppers	15th October	30th Nov	March-June	90	45	Golden Hot

efficiency by three off-season vegetables irrigated through drip and furrow systems to study the relative water productivity of two irrigation systems. Soils consist of young alluvial deposits with plain topography, mostly structure-less, predominantly sandy clay loam to clay loam in texture and are potentially productive. Water scarcity is, however, a chronic problem since the area is located at the tail ends of canals. The water table is deep. The use of brackish groundwater is, therefore, a necessary evil. Almost 35% of soils are suffering from moderate to severe, primary or secondary salinity (Soil Survey of Pakistan, Non-saline sites were, however, selected for this study, with chemical characteristics ranging from EC 1.70-1.90 dSm^{-1}, pH 7.5-7.8, organic matter 0.48-0.61% and Olsen-P 21-22.7 ppm.

Crop cultivation and management

Nursery of the capsicum and hot pepper plants was grown in trays filled with Peat Max soil at day and night temperatures of 30°C and 12°C, respectively. Nursery plants were protected from diseases and insects. At 35–40 days of age, seedlings were transplanted onto the beds, made with specially designed bed planters; on leveled land. Cucumber seeds were sown directly on the beds. The bed soil was covered with biodegradable black polythene mulch made of polyhydroxyalkanoates (PHAs)-biodegradable polymer material to suppress weed growth. Fourteen plastic tunnels (height 2.134 m, width 3.2 m and length 60 m) were erected at each site. And each tunnel, on three beds, was covered with plastic sheets. The distance between laterals was 1.067 m, and the number of emitters in 64.008 meters long lateral was 168 and the spacing between them was 15 cm. Nitrogen, phorophorous & potash (NPK) fertilizers were applied as per the recommendation of the Agriculture Department. The sowing methodology of off-season vegetables is given in Table 1. The plants were irrigated with the help of drip and furrow (as flood) systems as per requirement. The amount of water applied for drip irrigation was recorded with a water meter and for furrow irrigation by using standard procedures. Plant protection measures were adopted to avoid insect and disease attacks as and when needed.

Data collection

Data were collected on early spring yield and quality of produce, total water used per acre, number of irrigations, water used per irrigation, saving of inputs, increased incomes and farm profitability, reduced incidence of pest and diseases and some environmental benefits, in participation of farmers. Water productivity was calculated as the ratio of total yield (kg) to total water consumed by each crop as follows:

Water Productivity (WP) = Fruit yield (kg/acre) /volume of applied water (m^3/scre)

The CROPWAT program [8] was used to calculate crop water requirements by combining different climatic, crop and soil data. Benefit/cost was calculated by considering various inputs used with drip and surface irrigation systems. The net income per acre for all crops was calculated by subtracting the planting costs from the total income. The benefits to costs ratio (B:C) was calculated using the formula:

Benefit/cost ratio = gross returns (USD$)/cost of cultivation USD$.

Statistical analysis

All data were statistically analyzed using SPSS 25.0 [9] for one-way ANOVA, and multiple mean comparisons using the least significant difference (LSD) test ($\alpha = 0.05$).

Results and discussion

Crop productivity

It is observed the yield of off season drip irrigated vegetables was significantly higher than that under furrow irrigation (Table 2). Drip irrigation increased the yield by 25%, 20% and 30% in case of capsicum, cucumber and hot pepper, respectively, compared to conventional furrow irrigation. The higher yield obtained under drip irrigation treatments might be due supply of moisture and nutrients in adequate proportion, which resulted in triggering the production of healthy fruits as reported by Mazher et al. [10]. Other investigators also stated similar results that the increase in yield was most likely due to improved water relations of plants grown under drip irrigation than with furrow irrigation [11], where higher moisture renders crops more susceptible to insects, diseases and environmental damage [12]. These findings for yield increase under drip irrigation are in close agreement with the works of other researchers who reported 13% more yield under drip irrigation in comparison to that under conventional furrow irrigation [13]. The quality of produce as visually observed by the farmers, project staff and customers was also better with drip than with the furrow irrigation system, which enabled farmers to sell the produce at a relatively higher price. Improved yields with drip irrigation may have been due to improved water management, reduced incidence of diseases, insects, environment damage and fine-tuning of fertilizer applications [14].

Fertilizers used by capsicum, cucumber and hot pepper were higher by 30%, 22% and 24%, respectively, when grown under furrow irrigation compared with drip irrigation (Table 2). This is logical since drip irrigation uses soluble fertilizers to provide essential nutrients to plant roots, on per need basis, at different growth stages. It is suggested that some water in furrow irrigation escapes the root zone along with fertilizer, contributing to the loss of resources. Findings of other researchers are also following our results regarding considerable savings in fertilizer with drip irrigation as it allows site-specific application of NPK [15, 16]. These results are also in line as reported by Hashim et al. [17] and Paul et al. [18] regarding better crop yield. It can be seen from Table 2 that 22% to 30% higher fertilizer use under furrow irrigation compared with drip irrigation. The results are quite in line with Hashim et al. [17] that vegetable crops in Punjab are generally unevenly watered and fertilized, either due to their poor availability or mass applications, and drip irrigation is likely to mitigate these problems.

Water productivity

Water productivity is the standard for comparing the economy of agricultural water use under different irrigation methods. It can be seen in Table 3 that the average irrigation depth under furrow irrigation was quite high to fulfill its crop water requirement (CWR). The capsicum, cucumber and hot peppers saved 45%, 30% and 31% irrigation water, respectively, with drip irrigation method compared to that with furrow irrigation. The water productivity of capsicum, cucumber and hot papers was 32, 29 and 25 kg/m^3, respectively, under drip irrigation which was significantly better than that (13, 11, 12 kg/m^3, respectively) under furrow irrigation. Similarly, Paul et al. [18] compared drip irrigation and furrow irrigation methods and found that 24% of irrigation water was saved under drip irrigation. The research work of Greenwood et al. [19] has shown that drip

Table 2 Crop productivity and fertilizer use for off-season vegetables grown under drip and furrow irrigation systems (averaged 7 years of data).

Crop	Irrigation system	Yield (kg/acre)	Yield increase (%)	NPK (kg/acre)	NPK use increase (%)
Capsicum	Drip	58403a	25	281c	30
	Furrow	43802c	-	402a	-
Cucumber	Drip	62011a	20	367b	22
	Furrow	49680b	-	467a	-
Hot pepper	Drip	38012d	30	269d	24
	Furrow	26650e	-	356b	-
LSD		52.57		31.27	

Table 3 Waster use efficiency and pesticide use for off-season vegetables grown under drip and furrow irrigation systems (averaged 7 years of data).

Crop	Irrigation system	Water used (m^3/ acre)	Water use increase (%)	WP (kg/m^3)	WP Increase (%)	No. of pesticide sprays	Pesticide use increase (%)
Capsicum	Drip	1802d	-	32.0a	-	17c	-
	Furrow	3284b	45	13.3c	141	20b	15
Cucumber	Drip	3081b	-	29.7a	-	21b	-
	Furrow	4422a	30	11.2d	165	25a	16
Hot pepper	Drip	1542e	-	25.0b	-	8.0e	-
	Furrow	2219bc	31	12.0c	109	10d	20
LSD		11.14		0.46		1.32	

WP = Water productivity

irrigation has better water productivity than furrow irrigation. Likewise, other researchers compared drip and furrow irrigation and found that although frequency and total number of irrigations for crops were much higher with drip than with furrow irrigation system, the percentage of water applied to capsicum was much higher under furrow [20, 21]. A perusal of Table 2 revealed that increased water productivity under drip irrigation varied from 109% to 165% for different crops. It is emphasized that drip irrigation increases the consumptive use of water because plants grown under drip irrigation are never allowed to go into water deficit stress [22]. Drip irrigation drips water and fertilizer directly and slowly into the soil of crop roots through high-frequency irrigation, forming ellipsoidal or spherical wet bodies in the root zone, which is beneficial for crops to absorb water from the soil and can effectively reduce deep percolation [23]. Through high-frequency irrigation, drip irrigation slowly applies a small amount of water to the root of the crop, so that the crop is always under better water, avoiding the periodic excessive water and water deficit caused by traditional furrow irrigation. Drip irrigation improves the water productivity of vegetables and plays a significant role in saving water [24, 25]. In addition, the biodegradable plastic mulch played a vital role in weed control by reducing the evaporation of moisture from the bed surface and moderating soil; temperature. Biodegradable plastic mulch has been shown to control weeds, ensure early growth and higher yield, and increase water and fertilizer use efficiency in several other studies [26, 27]. Insect pest and disease attacks were considerably reduced on crops grown under drip irrigation due to lower relative humidity than furrow irrigation, which reduced 16-20% less pesticide uses under drip irrigation compared to furrow irrigation.

Economic benefits

After deducting the total cost, the net income of drip irrigation is significantly higher than furrow irrigation (Table 3). However, the gross cost of drip irrigation was higher due to cost of the drip irrigation system. However, gross return, net returns and benefit/cost ratio (B:C) of drip irrigation were significantly higher (6.72, 4.75 and 5.07) for capsicum, cucumber, and hot peppers, respectively, than furrow irrigation. The net economic returns were calculated by subtracting the inputs from the outputs. The inputs include costs, seeds, chemical fertilizers, pesticides, machinery, and labor. The net income calculated for capsicum, cucumber and hot peppers under drip irrigation was higher than furrow irrigation. This study unequivocally confirms the earlier studies that while yield increased, water, fertilizer, energy, etc. (major cost of production), can be reduced, through drip irrigation. It is a very useful confirmation since the present study has been conducted on farmers' fields in the participation of a large number of farmers (Tables 2 and 3). The net percent increase in income with drip irrigation than with furrow irrigation system was 18%, 34%, and 41% in capsicum, cucumber and hot pepper, respectively as earlier reported by other researchers [28-30]. Table 3 also shows that the per kg sale price of vegetables under study was reasonably better when grown with drip (because of better appearance) than furrow irrigation system. The only exception was capsicum, which fetched a lower price for unknown reasons.

Table 3 Economic analysis of off-season vegetables grown under drip and conventional furrow irrigation systems. The data is 7 years average of 12 sites.

Cost items/acre	Capsicum (US$)		Cucumber (US$)		Hot pepper (US$)	
	Furrow	Drip	Furrow	Drip	Furrow	Drip
Land preparation	50	54	45	50	54	58
Leveling	18	18	18	18	18	18
Seed	152	152	468	468	50	50
Fertilizer	502	480	669	576	456	369
Pesticide/insecticide	68	56	96.5	67.5	21	18
Irrigation	78	61	90.5	75.3	48	37
Tunnel	900	900	990	990	900	900
Drip system cost	-	818	0	818	-	818
Mulching	50	50	50	50	50	50
Transportation	360	371	320	380	246	271
Total seasonal cost	2178	2960	2747	3492.8	1843	2589
Total income	23733	29201	12845	18791	6662	10035
Net income	10787	13273	10098	15299	4937	8382
Yield/acre (kg)	43502	58403	49680	62011	26650	38012
Benefit-cost ratio (BCR)	4.46	6.72	3.67	4.75	2.86	5.07

Socioeconomic impact

The socioeconomic and environmental benefits of the project are visible now. Overall speaking, crop yield was 20%-30% higher under drip irrigation than under furrow irrigation. Drip irrigation was instrumental in reducing the percent use of all inputs by crops: water by 30%-45%, fertilizers by 22%-30%, and pesticides by 15%-20% (because of reduced temperature and humidity). Our results are quite in line with Iqbal et al. [27]. The use of brackish groundwater was also substantially reduced, with an overall reduced demand for water. The project farmers reported an increase in farm profitability, ranging from 49%-59%., with a multiplier effect on economic activities. A conservative estimate shows a reduction in unemployment by 5%. Increased water productivity can therefore contribute to improving socio-economic development and create opportunities for on-farm and off-farm employment in water-scarce areas, with a multiplier effect on the village economy, converting agriculture into industry. Not to mention, the main reason for migration from rural to urban areas in Punjab is the lack of employment opportunities for small farmers since the opportunity to work on farms is diminishing due to mechanization and technological development. Modernizing high-value crop production would reduce unemployment, which in turn would reduce rural poverty, and would also help them meet essential dietary nutrients at a lower price. Employment is also a key factor in population environmental sustainability. The horticulture sub-sector is more useful for small farmers since high-value crops can provide more income from small holdings. PRA also revealed an increase in employment opportunities and a reduction in migration of the urban population, in 90% of the project area and around. The overall impact studies in Division Faisalabad show almost 50% increase in farm profitability registered by the farmers, through saving in water and fertilizer application by about 25%. This suggests that drip irrigation has a greater scope for the production of off-season vegetables especially in water-scarce areas of Pakistan.

Conclusions

It concludes that under conditions of the greenhouse, drip irrigation can significantly enhance the crop growth and water productivity of off-season crops with a considerable reduction in fertilizer, pesticides and cost of production. Our analysis highlights the potential benefits of drip irrigation in terms of improving overall agricultural productivity and sustainability through its introduction on the landscape level. In conclusion, drip irrigation is primarily utilized in regions with low water availability, such as Thal and for crops grown in greenhouses, high-value crops, and intensive farming. Moreover, it can enhance crop production and quality, water productivity and NPK use efficiency while conserving water resources. Due to its numerous benefits, drip irrigation has emerged as a popular method of irrigation in modern agricultural practice. The introduction of high-efficiency irrigation systems is also likely to increase the quest for technology among youth in Punjab. New resource-efficient technologies as well as enhanced competitiveness and innovations are generating shifts in employment and qualitative changes in the workforce, all over the developing world. Governments can create policy frameworks to enable, support and reward such improvements in resource efficiency or productivity, bringing increased competitiveness, resilience, security and new sources of jobs and growth.

Conflict of interest

The authors claim no conflicts of interest.

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