Techno-economic analysis of irrigation systems for efficient water use in the backdrop of climate change

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In view of the growing water scarcity, particularly in the backdrop of climate change the adoption of water-efficient irrigation systems is becoming indispensable. The study of efficient irrigation systems is lacking in the developing countries like India, which is in turn responsible for the low values of water-use efficiency in agriculture. Therefore in this article, different irrigation systems studied for the developing countries, including the water-efficient and traditional ones, are reappraised. The irrigation systems are assessed on the basis of various factors such as economic parameters, water productivity, water saving and crop yield. Among water-efficient irrigation systems, drip irrigation system (DS) is considered to be the most successful method for water conservation and increased agricultural output. DS not only reduces the cost of supplied water, but also those incurred in the activities such as human labour and other cultivation costs. DS is found suitable for a variety of crops, including cereals, vegetables and cash crops in different regions of the world. Water saving and electricity saving is in the range 40–54% and 26–47% respectively, when DS is compared with the surface irrigation methods. For most of the crops, drip irrigation is found to be the most robust, profitable and cost-effective method of irrigation and could be a possible solution to the growing water shortage in the backdrop of climate change.

Keywords: Climate change, crop yield, irrigation systems, water saving, water-use efficiency.

WITH the increasing population and elevation in economic standards, water consumption is constantly increasing. The effect of climate change has resulted in erratic rainfall distribution across the globe leading to scarcity of available freshwater resources, which further adds to the problem. This issue is more for the developing countries with a large population. For instance, India is home to around 18% of the world's population but has only about 4% of the total global freshwater reserves[1]. Also, out of the total available water resources in India, more than 85% is consumed by the agriculture sector. Therefore, water saving in agriculture is the need of the hour for addressing the critical issues of water and food security, particularly in the developing countries such as India. In view of this, new perspectives, initiatives and proactive research in the area of efficient water use in agriculture is important for mitigating the effects of climate change and water stress conditions on agriculture.

Using water-efficient irrigation systems, such as drip irrigation, is one method of conserving water in agriculture. The drip system is an irrigation methodology where water is delivered directly to the root zone of the sown crop through a systematic assembly of pipes and emitters. This is totally different from conventional irrigation methods like flood irrigation or other surface irrigation methods where water is supplied to the entire land. There are two main pressurized high-efficiency irrigation systems: sprinkler and drip irrigation systems. However, the suitability of each method is dependant on certain farming conditions[2]. For instance, for a geographical area having an undulating terrain the most suitable method of irrigation is the sprinkler system as it will assist in easy water application, which would otherwise be difficult through gravity-driven irrigation. On the other hand, drip irrigation is suitable for point application of irrigation water. One of the main reasons for low crop yield is the inadequate and erratic supply of irrigation water. In the absence of appropriate rainfall, a lack of irrigation water results in low soil moisture, which leads to a lack of water or water stress in the crops. Different types of crops have different responses to water stress conditions[3]. For instance, vegetables are sensitive to water stress and thereby require irrigation at fixed intervals and at critical growth stages[4]. To improve the water saving of different crops, we can opt for at least one of the two alternatives, increase the crop yield for a fixed amount of water supplied or minimize the water loss for a fixed crop yield. Traditional irrigation systems are inexpensive to install, but they result in significant water loss and low crop water-use efficiency. With the advent of globalization, urbanization and climate change scenarios, it is important to use cost-effective water-saving irrigation technologies[5].

According to Pachauri and Meyer[6], the climate change impacts can be observed in changing precipitation patterns, excessive snow melting and alteration in the

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hydrological systems, thus severely affecting the water resources on earth, both in terms of quantity and quality (medium confidence). Temperature rise of 2°C are expected to have a negative impact on wheat, maize and rice production in tropical and temperate regions. It is also projected that climate change will lead to reduction of surface water and groundwater resources in most of the dry subtropical regions (robust evidence, high agreement). This leads to urgent water-saving measures amongst all the sectors of the water economy. According to the Falkenmark scale, which is the most widely used water stress indicator, India is a highly water-stressed region[7]. The irrigation sector consumes more than 80% of the total water in India. In 2015, the net area sown was 140 million hectares (m ha), of which only 68.4 m ha was irrigated. All of these evidences indicate the necessity for water conservation in agriculture, as well as the use of water-saving irrigation systems. The main emphasis of this article is to manage the adverse impacts of climate change on the already scarce water resources and in particular agricultural water. As the impacts of climate change cannot be reversed overnight, it requires persistent and long-term work to implement water conservation irrigation approaches, particularly in developing nations such as India, where there is an obvious shortage of water-efficient irrigation infrastructure.

Here, we have done an extensive review on different irrigation systems, viz. drip, furrow, perforated pipes, channel-lined, sprinkler, flood irrigation and other farm irrigation methodologies used in the developing countries (including India). This study summarizes the analysis and comparison of various irrigation systems based on several parameters such as economic factors, agricultural production, water-use efficiency, and other miscellaneous factors.

The economic viability of an irrigation project depends on a number of factors like the total irrigation equipment installation cost, operation and maintenance cost, water-saving cost, energy-saving cost, revenue earned from crop yield, etc. All these factors depend on a set of conditions which is region-specific – topography, land use, soil type, socio-economic policy; crop-specific – water-sensitive quotient, nature of crop (cash crop, vegetable crop, fruit trees, etc.) and irrigation-specific[8]. The interaction of these factors leads to economic effectiveness assessment of a crop with a specific irrigation methodology. The present study aims to quantify the trends of cost-effectiveness, crop yield and water productivity for various crops under different irrigation methodologies at different geographical locations and under varied climatic conditions. It will provide an insight into the water-use efficiency of various irrigation systems globally with respect to different agro-climatic parameters. This study was conducted with the understanding that developing nations with a large population are the most susceptible to the harmful effects of climate change on agricultural output and water availability. Also, the literature lacks a thorough review and comparison of irrigation systems used in the developing countries where water-efficient irrigation methods are most required. Hence, different aspects of the irrigation systems studied in the developing countries, are critically reviewed here. Finally, the adverse impacts of climate change on water availability as well as crop yield are also reappraised.

Economic analysis of irrigation systems

Narayanamoorthy *et al.*[9] performed research on the drip system (DS) and flood system (FS) type of irrigation on brinjal in the Sivagangai district, Tamil Nadu, India. The authors performed economic assessment on two parameters, net present worth (NPW) and benefit–cost ratio (BCR) at a discount rate of 10% and 15% (ref. 9). NPW is defined as the difference between the sum of the present value of benefits and the costs incurred during the life of a drip set. BCR is defined as the ratio of the annual benefits and annual costs incurred in a project. The number of hours of irrigation of a unit land area was 1.02 and 5.47 h/acre for drip and flood irrigation respectively. Also, 40% water saving and 41% electricity saving was observed in drip irrigation over the flood system. Another advantage of DS over FS is the overall reduction by 20% in the cost of cultivation in tasks like irrigation, weeding, ploughing and other preparatory works[10–14]. BCR was reported to be 4.8 by drip irrigation. Brinjal cultivation using drip irrigation generates 54% more profit than the conventional method of irrigation. This large margin of profit helps the farmers to easily meet the capital cost of the drip system, which is rated to be Rs 36,928/acre in Tamil Nadu.

Bakhsh *et al.*[15] used the following three sites for their study: Chiniot (31.72°N, 72.97°E), Hafizabad (32.03°N, 73.11°E) and Samundri (30.48°N, 71.52°E), located in Rachna doab, Pakistan, to compare four methods of irrigation (one conventional and three high-efficiency irrigation – drip and two different types of perforated pipe systems). They performed an economic analysis on three cropping zones of rice–wheat (Hafizabad), mixed (Chiniot) and cotton–wheat (Samundri). To evaluate the economic efficiency of drip irrigation and perforated pipe irrigation systems, the most appropriate tool is that of internal rate of return (IRR), because it does not depend on the application of an arbitrary discount factor[16]. IRR is the rate of interest at which net present value (NPV) is equal to zero. Using the IRR tool, Bakhsh *et al.*[15] estimated that the gross margins deduced from the conventional method for both farmer survey (Rs 22,053) as well as the experimental stations (Rs 19,199) were far below both the perforated pipe and drip irrigation systems. Among the three irrigation systems, the drip system has the highest gross margin of Rs 36,832. The drip system of irrigation was tested only in Samundri, where it was found to be advantageous over both perforated pipe and conventional systems. Analysis of various discount budgeting schemes reveals BCR rate to be 1.74 at 2% discount rate, which reduced to 1.69, 1.63 and 1.58 at 4%, 6% and 8% discount rates respectively. The IRR value was worked out to be 36%. BCR values for drip irrigation clearly shows that it is a good investment, but when compared to perforated pipe systems it is inefficient (whose BCR value ranges from 1.88 to 2.49 at 4% discount rate) across all project sites due to its high initial investment costs and discount rate.

Cotton is a water-intensive cash crop widely grown in India and about 33% of the cotton area is cultivated under surface irrigation method in the country[17]. Pawar *et al.*[18] reported that cotton in Sirsa district of Haryana cultivated under drip irrigation system reduced the cost of cultivation drastically in operations like irrigation (40%), weeding and intercultural (35%) and field preparatory works (26%), and 28% less quantity of seeds was required compared to flood irrigation system. However, the cost of fertilizers (7.23%) and harvesting cost (24.30%) were observed to be higher under drip irrigation system than flood irrigation system. The number of irrigations used for the drip method was 1.65 h/ha and for the flood method 19.75 h/ha. The consumption of electricity under DS was only 447.5 kWh/ha, while it was 667.5 kWh/ha under FS, giving an energy saving of 33% per hectare with DS.

Baranchuluun *et al.*[19] used three parameters, namely NPV, BCR and IRR to assess the economic worth of three modernized irrigation technologies, viz. furrow, sprinkler and drip systems on vegetable crops like potato, radish, head cabbage and tomato in Mongolia. The net benefits of drip irrigation were higher compared to other methods, and contributed to labour and water saving. For instance, drip irrigation saved 0.7 persons/day and 915.8 m^3/ha water in potato production, 3.5 persons/day and 507 m^3/ha water in radish and 4.9 persons/day and 2830 m^3/ha water in headed cabbage, 2.6 persons/day and 1700 m^3/ha in tomato, whereas sprinkler irrigation saved 49.5 m^3/ha water in potato production and 26 m^3/ha in radish, 141 m^3/ha in headed cabbage and 85 m^3/ha in tomato. BCR drip irrigation for potato, radish, cabbage and tomato was 3.6, 3.5, 3.2 and 9.2 respectively. In the case of sprinkler irrigation it was 2.7, 2.7, 2.3 and 6.7 for potato, radish, cabbage and tomato respectively. BCR for furrow irrigation was 2.12, 2.21, 1.78 and 6.22 for potato, radish, cabbage and tomato respectively. Thus, drip irrigation was the most economically viable option for all of the vegetable crops considered in this research, followed by sprinkler and furrow irrigation.

To estimate the mitigation cost of the impact of climate change on rice in three different regions of Asia (the Philippines, China and India), Wassmann and Pathak[20] used a standard tool of marginal abatement cost curves (MACCs)[21] employing different irrigation technologies and scenarios. An inter-comparison of different types of agro-topographical regions across different countries of Asia in terms of mitigation potential and economic returns was taken up in Wassmann and Pathak[20]. Net return with various irrigation technologies ranged from US$ 36.77/ha to US$ 120.55/ha, while the yield ranged from 3.13 to 4.17 t/ha in Haryana. Net return in Ilocos Norte in the Philippines ranged from US$ 84.78 to 186.68 per hectare, which is about three times higher than that in Haryana. This can be attributed to lower economic costs in the Philippines due to high rainfall of 1200 mm compared to 400 mm in Haryana. Net return was highest (US$ 216–310/ha) in Zhejiang, China, because of the high yield. Irrigation cost was also low in Zhejiang compared to Haryana because of higher rainfall of 660 mm. Different types of greenhouse gas emissions (methane, nitorus oxide, carbon dioxide) can be aggregated under global warming potential (GWP). It has been expressed as carbon dioxide equivalent. While Haryana represented a medium-productive, low-return and low-GWP region, Ilocos Norte represented a medium-productive, medium-return and high-GWP region, whereas Zhejiang reflected a highly productive, high-return and high-GWP region[22].

Rajak *et al.*[23] performed on economic analysis by comparing the BCR values between drip and furrow irrigation systems on the white gold crop of cotton in the northeastern dry region of Karnataka. The study area was divided into four zones on the basis of salinity and water table depth from the soil. BCR was 1.61 and 2.0 for drip and furrow system respectively, when applied water was 1.2 ET for zone 1. Zone 4 was the only block where BCR of the drip system was 0.79, which was higher than that of furrow irrigation at 0.66. This can be attributed to the fact that in most places the initial investment of drip structures is higher compared to furrow irrigation. However, the gross income from drip system was higher than that of the furrow system as the revenue generated from saved water, energy and enhanced crop yield in the drip method is far more than the furrow system. The highest value of gross income from the drip and furrow systems was noted for zone 1 with US$ 689.8 and US$ 545 respectively. The gross income (US$ 223–690/ha) of drip irrigation was more than that of furrow irrigation (US$ 67–545/ha).

Gorain *et al.*[24] performed an economic analysis between drip irrigation and traditional flood irrigation on the water-intensive crops of sugarcane and banana in Maharashtra, by studying the Cobb–Douglas production function (that uses marginal value product). The social BCR at 10% discount rate for drip irrigation was 2.08. Social BCR is a process of identifying, measuring and comparing the social benefits and costs of an investment project. Mathematically,

$$\text{Social benefit (per hectare)} = 1/n \sum B_i,$$

where B_i is the discounted benefit (social rate of discounting is 10% for the ith crop).

Social costs (per hectare) = $C_1 + C_2$,

where C_1 is the cost of subsidy per hectare and C_2 is the investment for rejuvenation of failed or less water-yielding wells.

This represents the importance of drip technology not only as a water-saving method, but also having both economic and social benefits (with a reported net social benefit of Rs 1.10 lakh/ha/yr and net social cost of Rs 97,000/ha/yr). The number of irrigation events for drip and flood irrigation methods per season per crop for sugarcane was reported to be 217 and 48 respectively. The same for banana was 54 and 21 respectively. However, the number of hours of irrigation was low for drip system (2.5) and high for flood system (8.0). It was found that drip farms require considerably lesser units of electricity to produce per quintal of sugarcane and banana crops. The electricity use efficiency in sugarcane was found to be 7.45 and 16.32 kWh per quintal yield for drip and flood method of irrigation respectively, amounting to 54% saved electricity using the drip method. For banana, the saving amounted to 26% using the drip system.

Kheira and Abdrabbo[25] performed a simple cost analysis study on corn crop cultivated in the area of Nile valley and delta, Ethiopia under subsurface drip, surface drip and furrow irrigation using gated pipes. The total cost of producing corn was estimated to be US$ 545.43/ha/season for subsurface irrigation. Due to the additional expense spent for concealing the assembly of lateral lines in the soil utilized in drip subsurface systems, this was the highest value observed among the three irrigation systems. Furrow irrigation gave the lowest cost of US$ 443.02/ha/season, which was lower than that surface of drip irrigation by 18.63%; but furrow irrigation (using gated pipes) gave the highest value of gross margin, including fixed cost (US$ 925.84/ha/season), which was 156.3% and 166.3% higher than surface drip irrigation and subsurface drip irrigation systems respectively. BCR for surface drip system, subsurface drip system and furrow system was 1.7, 1.6 and 3.1 respectively. When economic reasons were considered, the furrow system worked best for corn crops, but for locations with waterlogging issues, the surface drip method was preferable[26].

Darouich *et al.*[27] used three attributes for economic cost analysis – fixed investment cost (FIC), variable irrigation cost (VIC) and economic water productivity (EWPR), on cotton crop in Ras-El-Ain district, northeast of Syria. The authors worked out the best alternatives among the drip system, furrow system and border system of irrigation using the DSS model of SADREG for the surface system and MIRRIG for the drip system. The investment cost for drip system varied from 1313 to 2320 euro/ha, which is much higher compared to modernized surface irrigation (furrow and border systems). A huge gap was observed between the two systems on comparing the EWPR values of 1.3–2.1 for drip system and up to 4.9–7.1 for surface irrigation. All the data clearly indicate that surface irrigation is preferred over drip irrigation when economic factors are considered.

Hasan[28] deduced that furrow irrigation has the lowest cost and highest farmer return, whereas drip irrigation provides 25–45% lower economic results than surface irrigation in cotton crop sown in Syria.

Kumar and Palanisami[29] performed an economic assessment on banana, grapes and cotton crop grown in the Coimbatore district, Tamil Nadu. For cultivation of banana crop, the drip method gave a saving (in weeding labour) of 71% over the flood method. This led to cost saving under operation and maintenance expenses, reducing the cost of cultivation significantly under drip system of irrigation over the flood method. The gross margin was Rs 200,232/ha in drip-irrigated farms and Rs 163,048/ha in control farms. Grapes, which is sensitive to water stress, showed huge savings in weeding and labour costs. In the cultivation of grapefruit, the cost incurred on human labour was Rs 17,324/ha and Rs 29,433/ha in drip farms and flood farms respectively, which showcases an average reduction of 41% in drip-supported farms. Similarly, for cotton cultivation, the cost saving observed due to reduction in labour in drip irrigation was 69%. The drip system was found to be more economical based on the savings from cultivation practice; however, the cost of installation was not considered[30].

Khalifa and Mahmoud[31] used eight economic bases to study drip irrigation efficiency on 12 long-life fruit trees – apple, apricot, banana, citrus, date-palm, fig, grape, guava, mango, olives and pears in a cropped area of Egypt. The TISD (trickle irrigation system design) model gave different results for different fruit trees; all the fruit trees had BCR value >1, thus making all of them economically viable. The notable values were for apricots, pears and dates with the highest BCR value of 2.14, 2 and 2 respectively, followed by 1.8 and 1.6 for mangoes and grapes respectively. The net return for apricots and dates was found to be US$ 2188/ha and US$ 2588/ha, and the lowest BCR was for figs (0.97).

Mandal *et al.*[32] reported the highest production cost, highest net profit and highest BCR of Rs 68,764/ha, Rs 82,346/ha and 2.20 respectively, for a 5 × 5 m guava farm (compared to a 6 × 6 m farm) in Abohar, Punjab, by drip irrigation. For the same farm the highest production cost, highest net profit and highest BCR were Rs 63,912/ha, Rs 19,306/ha and 1.30 respectively, under flood system of irrigation.

Narayanamoorthy and Devika[33] studied okra in Tamil Nadu and found that drip irrigation system led to a reduction in cultivation cost by 15% and 47% saving of water resources and electrical energy, and augmented about 49% of productivity with the same crop (okra) cultivated under conventional flood method of irrigation (FMI). The drip farmers earned an additional farm business income of Rs 72,711 per acre over non-drip farmers.

The literature reveals application of a multitude of parameters for economic assessment of irrigation measures like that of BCR, IRR, cost-effectiveness analysis (CEA), NPV, maximum net return, maximum net cultivated area, minimum fixed cost, minimum total annual cost, minimum annual energy cost, minimum annual labour cost, minimum annual maintenance cost, FIC, VIC and EWPR, Cobb–Douglas production function and MACCs. Figures 1 and 2 prepared with the help of data collected from different literature sources, present results for water and electrical energy (in percentage) savings respectively, with respect to different types of crops. It can be seen that the drip system gives water saving of about 40–55% for most of the crops compared to surface irrigation method (Figure 1), while electrical energy saving due to drip irrigation ranges from 26% to 47% compared to surface irrigation system (Figure 2). Table 1 provides the crop references for Figures 1–4.

The major advantage of drip irrigation can be seen in cost savings in cultivation practices like weeding and labour costs. Savings in cultivation ranged from 20% in brinjal (in Tamil Nadu) to 26–40% in cotton crop (in Haryana), to 41% in grapes to 69% in cotton (in Tamil Nadu) to 71% in banana. The profit margin of drip over conventional systems was approximately 54%. BCR values ranged from 1.58 to 9.2 for different types of crops, of which maximum BCR was 9.2 for tomato. BCR depends upon the social and economic parameters of the area as well as cultivation and nature of the crops. Results from different economic assessments concluded that the drip system of irrigation is economically efficient compared to the others in majority of case studies. Figure 3 shows the trend on the basis of statistics observed from different literature for BCR values. It reveals the BCR of wheat, vegetables, fruits and cash crops like cotton and sugarcane for different modernized methods of irrigation. It can be seen that BCR of a drip system is more than 1 for all types of crops and more than the BCR values of other systems, except for wheat, where BCR of drip is 1.74 which is less than that of perforated pipe systems (1.9). Similarly, in cotton and corn BCR of drip irrigation is 1.61 and 1.66 respectively, which is less than that of furrow irrigation (2 and 3.09 respectively).

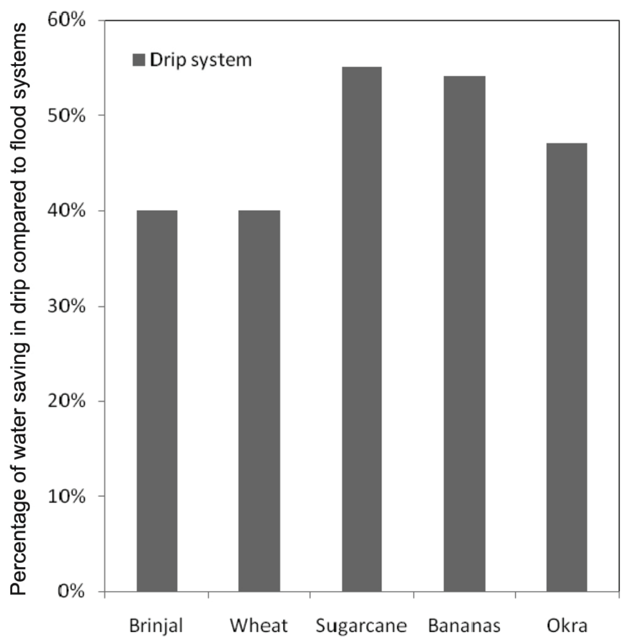

Figure 1. Water saving by drip irrigation over flood systems.

Analysis of water productivity and crop yield for different irrigation systems

Bakhsh *et al.*[15] studied different irrigation systems for wheat crop grown in Samundri, Pakistan. It was found

Table 1. Reference of the crops, studied in the literature, summarized in Figures 1–4

Crop	Location	Reference
Brinjal (Figures 1–4)	Tamil Nadu, India	9
Wheat (Figures 1, 3 and 4)	Rachnadoab, Pakistan	15
Sugarcane (Figures 1–4)	Maharashtra, India	24
Bananas (Figures 1, 2 and 4)	Maharashtra, India	24
Okra (Figures 1, 2 and 4)	Tamil Nadu, India	33
Cotton (Figures 2 and 4)	Haryana	18
Cotton (Figure 3)	Karnataka	23
Potato (Figure 3)	Mongolia	19
Guava (Figure 3)	Punjab	32
Radish (Figure 3)	Mongolia	19
Cabbage (Figure 3)	Mongolia	19
Tomato (Figure 3)	Mongolia	19
Apricot (Figure 3)	Egypt	31
Pear (Figure 3)	Egypt	31
Mango (Figure 3)	Egypt	31
Grapes (Figure 3)	Egypt	31
Dates (Figure 3)	Egypt	31
Corn (Figure 3)	Ethiopia	25

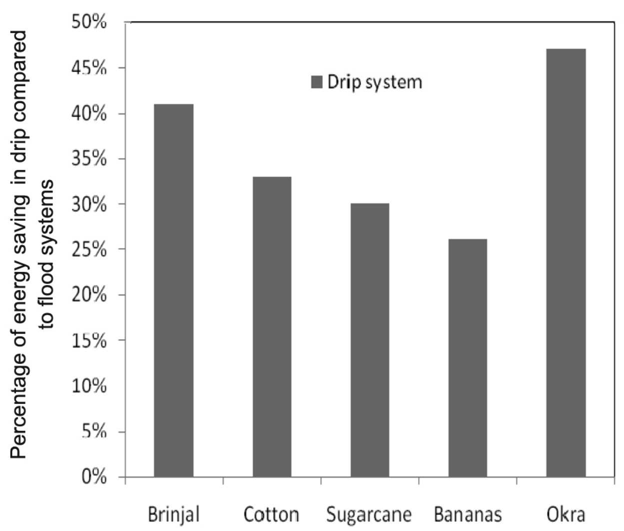

Figure 2. Electrical energy saving in drip system over conventional system.

that the drip irrigation, perforated pipe irrigation and conventional irrigation gave water productivity of 2.26, 1.46, and 0.90 kg-m^3 respectively. The average water productivity (crop yield per unit volume of water applied) for drip irrigation and conventional methods was 2.26 and 0.98 kg-m^3 respectively. Compared to conventional irrigation methods, perforated pipe irrigation and drip irrigation reflected a 39% and 25% increase in wheat yield respectively. Yohannes and Tadesse[34] reported a significantly higher tomato yield (50% higher) and water-use efficiency under drip irrigation compared to furrow irrigation. This may be attributed to the frequent application of smaller amounts of water in drip irrigation. Also, drip irrigation using inline emitters resulted in higher yield compared to self-compensating emitters. Fruit size was significantly higher in drip irrigation using inline emitters in comparison to furrow irrigation. The highest values of water-use efficiency were observed with self-compensating emitters (0.43 Mt/ha/cm), which is 44% higher than that of the furrow system.

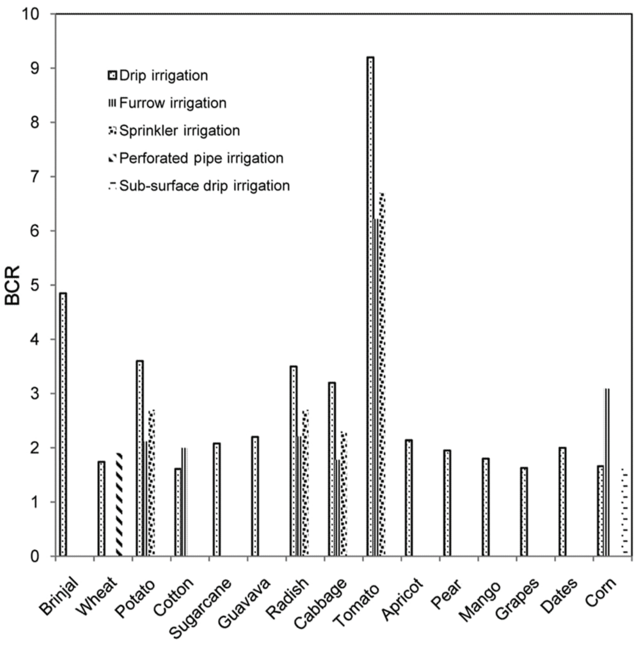

Figure 3. Benefit–cost ratio (BCR) of various irrigation systems for different crop types.

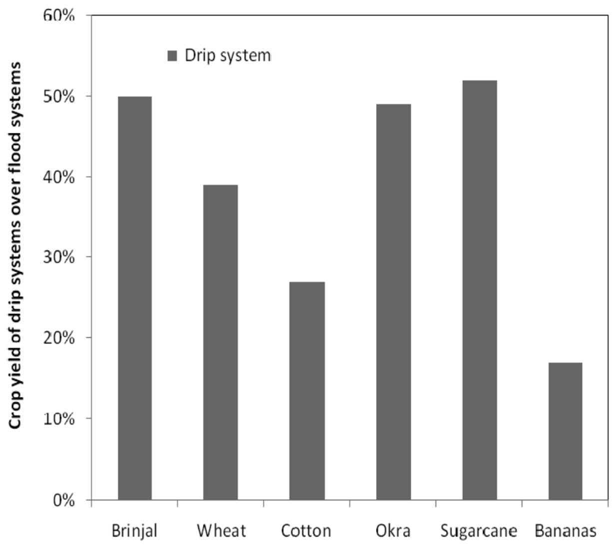

Figure 4. Excess crop yield by drip irrigation over flood systems.

Rajak *et al.*[23] reported that the net saving in irrigation water with drip irrigation was 21.5%, 16.3%, 12.3% and 9.1% at irrigation levels of 0.8, 1.0, 1.2 and 1.4 ET respectively, when compared with the same levels for furrow irrigation. Water productivity for each zone was higher in the drip method compared to the furrow method. The highest productivity for drip and furrow was in zone 1 with 1.2 ET applied water, with values of 22.7 and 17.9 kg/ha/cm respectively. High savings in water help in the support of extra crop harvest contributing to higher crop yield. Gorain *et al.*[24] deduced the quantity of water saved with drip irrigation in monetary terms to be Rs 1.1 lakhs and Rs 69,900 per hectare for sugarcane and banana respectively, and in physical terms using drip irrigation over flood irrigation for banana as 3659 m^3/ha and for sugarcane as 5941 m^3/ha, accounting for 54% and 55% of saved water respectively. The higher yield in sugarcane and banana with drip compared to flood irrigation was 420.2 and 100.82 q/ha respectively, in which drip farms yielded significantly higher than the flood farms.

Kheira and Abdrabbo[25] reported the highest value of corn ears yield (11.59 Mg/ha) at 1.0 ET water application followed by 7.43 and 7.33 Mg/ha with furrow irrigation (using gated pipes), surface drip irrigation and subsurface drip irrigation respectively. Water productivity estimates were made by deducing irrigation water-use efficiency, which was the highest (2.44 kg/m^3) for furrow irrigation using gated pipes at 1.0 ET followed by surface drip irrigation (1.77 kg/m^3) at 0.8 ET and the lowest value (0.97 kg/m^3) recorded with subsurface drip irrigation at 0.6 ET water application. The higher productivity of water using surface drip irrigation over subsurface drip irrigation was attributed to uniform water distribution in the effective root zones of corn in the soil profile[35]. The highest plant height, leaf area, number of steps per plant and number of leaves per plant of 244.3 cm, 862.4 cm^2, 18 and 18 respectively, was achieved with the surface drip irrigation system at 100% of ET. Darouich *et al.*[27] reported that drip irrigation requires 350–700 mm less water use than surface irrigation, thereby giving higher water productivity over surface irrigation by 0.13–0.29 kg/m^3.

Water productivity was deduced to be 7.4 and 4.9 kg/m^3 in drip and flood farms respectively, accounting for 50% more productivity in drip systems over flood systems[29]. The cropping intensity, irrigation intensity and net sown area per crop had improved tremendously under drip irrigation compared to conventional flood irrigation[30].

Mandal *et al.*[32] found that drip-irrigated guava produced 8.31 and 15.0 t/ha with a land configuration of 6 m × 6 m, and 12.0 and 21.60 t/ha for 5 m × 5 m in the third and fourth year of planting. The results indicate that drip irrigation has a significant role in increasing productivity as well as the economic return of guava in saline soil at the planting distance of 5 m × 5 m spacing.

Narayanamoorthy and Devika[33] showed that the application of drip irrigation system led to saving 47% water and electrical energy. There was an increase in okra productivity by 49% when compared with the traditional irrigation system. Brinjal yield with DMI was 1.5 times more than with FMI[9]. The productivity of cotton under DMI (23.35 q/ha) was found to be 27% higher than FMI (18.37 q/ha)[18].

Figure 4 shows the crop yield of sugarcane to be the highest compared to other crops, 52% more yield by drip system over flood system of irrigation. The yield of drip irrigation ranges from 17% to 52% over the flood system for various crops as discussed below.

Effect of climate change on water availability and crop yield

According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the mean temperature of the earth had increased by 0.85°C for the period 1880–2012, leading to significant challenges like accelerated melting rate of Arctic ice, sea-level rise, ocean acidification and change in wind currents[6]. If the above-mentioned climate change trend continues, it will lead to a 4°C rise in temperature by 2100 (ref. 36). IPCC has developed four different representative concentration pathways (RCPs) that depend upon the future concentration of greenhouse gases in the atmosphere until 2100 (ref. 6). Climate change is a global issue, but its ill-effects are significant in the under-developed and developing nations like India, Pakistan, etc. Pakistan[37], for example, has been the seventh most severely impacted country by climate change over the past three decades. A large degree of spatial discrepancy due to climate change in agricultural production has been observed globally in the simulations of Rosenzweig and Parry[38]. Crop yields are more negatively affected in most tropical and subtropical zones, such as Asia, than in temperate regions of America. Among the many sectors affected by climate change, the agricultural sector is extremely threatened[39]. The impact of climate change can be witnessed in agriculture by observing the change in run-off, stream flow and spatial distribution of water availability across the world[7]. The effect on economy in India is prevalent, as the country has an agrarian economy. The 700 billion-plus population is dependent on agriculture, directly or indirectly, leading to issues like food security in the future, if appropriate measures to combat the impact of climate change on crop yield and water productivity are not undertaken using latest irrigation methodologies like drip irrigation, sprinkler irrigation, etc. The three climatic variables used as reference to study the change in crop yield are precipitation, maximum temperature and minimum temperature. Temperature increase has the most likely negative impact on crop yields[40,41]. Temperature changes can be projected with more precision than precipitation changes at the regional level using a variety of climate models and concentration pathways.

In most crops, the effect of an increase in temperature reflects as a decrease in crop yield. For example, an increase in 1.5°C temperature led to 20% reduction in soybean crop yield[42]. In India, a decrease in wheat yield up to 20% because of an abrupt rise in temperature during grain-filling stage was noted by Gupta *et al.*[43]. Matthews *et al.*[44] used simulation models for rice production to show a decrease in yield by 5% for 1°C rise in mean temperature above 32°C. The aggregated yield of five different crops of the African continent was reported to be more sensitive to temperature changes compared to precipitation changes[45]. By 2050, the global food production would reduce by 10% due to global warming with a potential to substantially worsen the global food production[46].

The decrease in precipitation has led to an increase in aridity globally. The increment has been observed to be from 17% in the 1950s to about 27% in the 2000s (ref. 46). The increase in aridity has led to a decrease in crop yield. Maize has seen a decrease in yield by 1.7% at a temperature of 30°C or more under drought conditions[47,48].

The impact of climate change was observed through not only the change in precipitation which further influences water availability in agriculture practices, but also due to increase in evapotranspiration of crops due to larger growing seasons and rise in temperatures. These will enhance the crop irrigation requirements globally ranging from 5% to 20%, by 2080 (refs 49–51). Due to an increase in evapotranspiration, the crop water requirement increases leading to a decrease in overall yield of a fixed amount of applied water. For example, for sugarcane and cotton (grown in southeast Punjab), the yield reduced by 16% and 6% annually respectively, compared to the baseline in the far future (2070–99)[52].

Climate change leads to a change in plant transpiration and soil evaporation, thus affecting the water productivity of crops in the future. A 35% increase in water productivity can decrease crop water requirement from 80% to 20% (ref. 53). This high conservation of water puts focus on the development of agronomic practices and new irrigation methodologies that will lead to moisture conservation and improvement in the water productivity of crops[54].

The impact of climate change on crop yield and water productivity can be analysed employing various crop models. The output of these models helps in deducing effective risk management strategies[55]. Robust strategies of smart irrigation methodologies like drip irrigation can be adopted in accordance with the economy and geography of the affected location.

Zou *et al.*[56] worked out the economics of four irrigation systems – micro-irrigation (MI), sprinkler irrigation (SI), channel lining (CI), low-pressure pipes (LI) by considering different parameters and CEA, in a cropped area of China, as a mitigation and adaptation response to the climate change scenario. CEA of mitigation-SI performance was the best, CEA of crop yield-MI performance was good, and CEA of water-saving and water productivity-MI performance was also good. Water saved (pumped), energy saved, greenhouse gas emissions (CO_2) prevented, and crop yield are the basis on which cost-effectiveness ratio has been calculated for different scenarios. Water-saving irrigation techniques are certainly better than conventional irrigation methods. Based on CEA definition, MI was effective in combating CO_2 with the highest magnitude. CI had a negative CEA due to high water and energy saving costs, and low cost of initial equipment. Most of the cultivated area in China is estimated to be 50% covered by CI techniques in the coming years. However, CI is not as effective as MI as a response to climate change mitigation and adaptation. Though compared to CI, MI is better as a response mechanism to climate adaptability. CI is not effective in increasing crop yield and hence not preferred as an adaptation strategy (although several Chinese provinces apply this due to its low installation costs). MI is sensitive to energy prices that are managed by the Chinese Government, but the global impact of water has a significant effect on EP and thus MI is influenced by global market scenarios. So its application as a WSI measure in China is subject to vulnerability in its CEA.

Discussion

The world is facing the critical issue of global warming which is leading to climate change, thus affecting the meteorological trends throughout the world and resulting in uneven distribution of water[57]. In the face of global warming and growing scarcity of water, developing countries having a large population, are more vulnerable to the adverse impacts of climate change. India is a global agricultural powerhouse with the largest cultivation area under rice, wheat and cotton, and the second largest producer of rice, wheat, cotton, sugarcane in the world[58]. With growing water demand and limited freshwater supplies, we must better our water management plan to optimize water usage across many sectors such as agriculture, industry, household uses, etc. The distribution of water in India for irrigation, municipal and industrial uses is 91%, 7% and 2% respectively[59]. This can be attributed to the poor water-use efficiency of irrigation systems in the country. India's water-use efficiency in agriculture is US\$ 0.3 m^3, whereas that of China and Israel is US\$ 1.7 and US\$ 2.1 m^3 (ref. 59) respectively. The water consumed to produce 1 kg of rice is 3030 l in India and 500 l in China[60]. In India, out of the total gross irrigated area, 27% is for rice which uses 47% of the total water consumption in agriculture. The national productivity of rice is 3.6 t/ha, which is much below the world average of 4.5 t/ha (ref. 60). Considering the above statistics, it is indispensable to adopt a water-efficient irrigation methodology on a large scale. One possible solution is the use of drip irrigation system, as it results in higher yields and larger water saving for different crop types and study regions (Figures 2 and 4). Various aspects like population growth and food security leading to demand for increased productivity will further augment water demand for the irrigation sector in India in the near future. The total water demand in India is expected to be 910 BCM in 2025 (ref. 61). Considering the current water resources (demand and supply), it is challenging to meet this demand. To avoid a future water crisis, it is much needed to take the right initiative for efficient use and conservation of water.

Conclusion

This article examines several irrigation methods based on various criteria such as economic analysis, water productivity and agricultural output. The drip irrigation gives an average water saving of 47% and average electricity saving of 37% for various crops under different agro-climatic conditions when compared to conventional surface irrigation methods.

The perceptible limitations pertaining to the application of the drip system that have emerged from a reappraisal of the literature are: (1) The drip system is advantageous over conventional and modernized surface irrigation systems in terms of water saving and crop yield; but if the economy is considered, drip is preferred over flood irrigation but not over modernized surface irrigation methods in a few cases. (2) The literature lacks research on drip irrigation effectiveness undertaken for grain crops like wheat and rice in India. Most of the irrigation studies have been conducted on cash crops like cotton and sugarcane, or vegetables and fruit crops. (3) The practical applications of the drip system needs more technical knowledge and intensive training for successful fabrication and operation in the farms. It has a high price of installation, but the Government is supporting the farmers by providing the drip system at subsidized rates. (4) The lack of knowledge about the water saving and cost-effectiveness of the drip system among farmers has led to its limited use compared to other conventional irrigation systems.

Despite these limitations, the drip system is a popular irrigation methodology in several continents considering its cost-effectiveness and water saving. Hence, it is a suitable adaptation and mitigation measure against climate change, particularly in the developing countries like India.

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