Current rice farming, water resources and micro-irrigation

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Rice is the staple food for half of the world's population, and rice farming is a livelihood for millions of farmers in Asia. In India, it provides an individual with 32% of the total calorie and 24% of the total protein daily. This crop is mostly grown in puddled soil by transplanting, and flood irrigation is practised by farmers. Water or irrigation input to transplanted rice typically ranges from 1000 to 2000 mm depending upon the growing season, climatic condition, soil type and hydrological conditions. Facing water scarcity and climate change, reducing water requirement of this crop is a challenge. Out of 42.75 million hectare (m ha) rice area, only 25.12 m ha is under irrigation. Regarding water resources, depletion of groundwater is alarming in the north Indian states. On the other hand, it is under-utilized in eastern India. Micro-irrigation, i.e. sprinkler and drip methods have been used with the aim of minimizing water use and enhancing water use efficiency of rice. In addition, evidence-based scientific understandings on micro-irrigation for rice have been elucidated in this article. The potential of drip or sprinkler irrigation to rice on water saving as well as scientific insight and critical appraisal have been expounded on reasons of yield reduction. This comprehensive treatise would facilitate the formulation of strategies or policies on efficient management of water or irrigation for rice cultivation.

Keywords: Micro-irrigation, rice farming, water resources and availability, water use efficiency.

GLOBALLY, rice is the most important crop. It provides staple food for more than 3.5 billion people, i.e. about half of the world's population[1]. Worldwide, this crop is grown on an area of 162.72 million hectare (m ha) with an annual production of about 741.48 million tonnes (mt) in 2014. Asia accounts for 88% of the world's area and 90.5% of the world's production[2]. According to an estimate[3], about 114 mt of additional milled rice will be needed by 2035 to meet the global food demand. In India, rice is grown on 43.86 m ha, which is the largest area among all rice-growing countries, with paddy production of 157.2 mt (refs 2, 4) (Figure 1). With a rapid-growing population, India's food demand is increasing over the years and this will continue in the future. On the other hand, per capita water availability per year is declining (Figure 2). Therefore, rice production needs to be enhanced using less water in the coming years.

Rice provides 688 kcal/capita, i.e. ~32% of total calorie intake per day and protein intake of ~24% of the total per day in India[5]. Export–import trends showed that India had imported only 1323 tonnes of milled rice, whereas export was 11.3 mt with an export value of 8205 million USD in 2013 (ref. 2). Moreover, rice farming is the livelihood of millions of farmers in India and other Asian countries. Therefore, sustaining and improving the production of rice is essential to meet the global demands as well as for food security in India.

Water resources in India and rice irrigation

It has been estimated that, after accounting for losses due to evaporation, the total average annual water availability in India is 1869 billion cubic metre (BCM). Due to hydrological characteristics and topographical constraints, utilizable water is only 1123 BCM (690 BCM from surface, 433 BCM from groundwater), which is just 28% of the water derived from precipitation. About 85% of water usage (688 BCM) is being diverted for irrigation, which may increase to 1072 BCM by 2050 (refs 6, 7). A major source of irrigation is groundwater. Annual groundwater recharge is about 433 BCM, of which 212.5 BCM is used for irrigation and 18.1 BCM for domestic and industrial purposes[6,8]. However, there are considerable spatial and temporal variations in the availability of water as in case of rainfall. Depletion of groundwater and limitation of surface water imply that not all of the net sown area is amenable to irrigation.

In India, net irrigated area is 66.1 m ha (2012–13). Rice-irrigated area is only 25.12 m ha, which is 58% of the rice area of 42.75 m ha (Figure 1). With regard to different sources of irrigation, canal-irrigated area in the country has remained constant at 16.63 m ha for the last 20 years; tank irrigation has decreased 2.25 m ha; whereas tube-well irrigation is steadily increasing and has reached about 29.17 m ha; area under other wells has remained almost constant with an average of 11.91 m ha (2010–11)[4]. Indiscriminate use of groundwater irrigation has caused alarming depletion in the North Indian states such as Rajasthan, Punjab and Haryana; a reliable estimate

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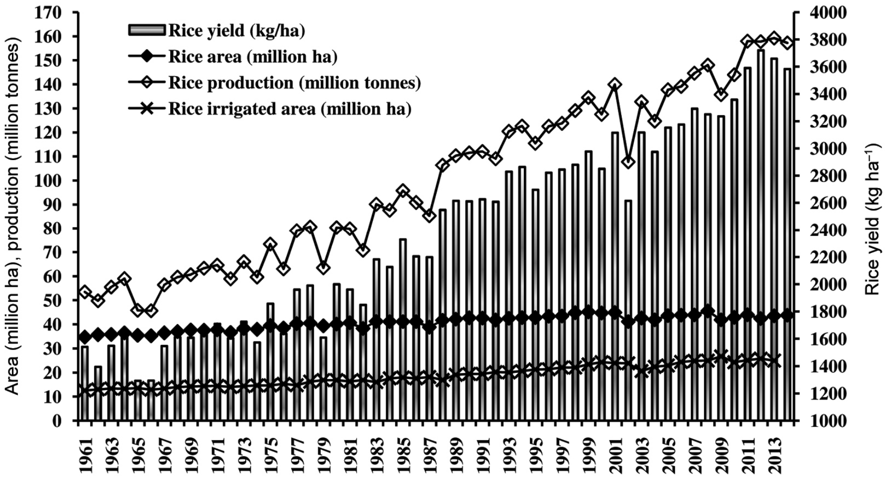

Figure 1. Trends in rice area, production, yield and irrigated area under this crop in India (1961–2014)[4].

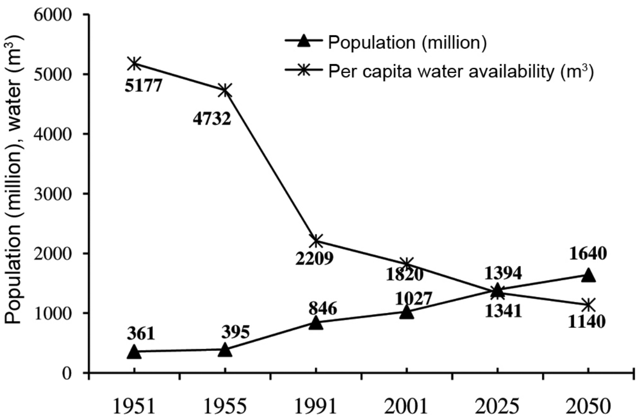

Figure 2. Trends and projection of population and per capita availability of water per year in India[6].

showed that groundwater has depleted at the rate of 54 ± 9 km^3/year between April 2002 and June 2008 (ref. 9); the depletion was equivalent to a net loss of 109 km^3 of water from August 2002 to October 2008 (ref. 10). Hence, reducing overexploitation of groundwater is a challenge. On the other hand, groundwater development in the eastern Indian states, viz. Assam, Bihar, Chhattisgarh, Odisha and West Bengal remains low (22–43%), which should be enhanced to the level of the country's average (61%)[8]. Hence, there is a potential for use of drip or sprinkler irrigation to minimize water in North India and increase its use in eastern India.

Rice cultivation and water usage

Traditionally, rice is mostly grown by puddling the main field and transplanting seedlings into wet and saturated soil. The rice agro-ecosystems occupy areas in the eastern plains and plateaus, sub-Himalayan West Bengal and Indo-Gangetic Plains (IGP), Tripura, Chhattisgarh, western and eastern coastal areas and Assam valley of India[11]. Water input to rice fields is practised for saturating land, facilitating puddling operation, maintenance of water layer, and to compensate for evaporation, transpiration, seepage and percolation losses. On average, 2500 litre of water is applied to produce 1 kg of rough rice[12], which is 2–3 times more than other cereals[13]. This cultivation technique is labour-, water-, and energy-intensive and is becoming less profitable as these resources are becoming increasingly scarce[3]. However, most of the water applied during crop growth is not used directly for transpiration, and is therefore considered lost from the fields. In the Philippines, water use has been reported at 1300–1500 mm during the dry season and 1400–1900 mm in the wet season[14]. It was estimated that seasonal water input for typical puddled transplanted rice was 660–5280 mm depending on the growing season, climatic conditions, soil type and hydrological conditions, with 1000–2000 mm as a typical value in most cases[15]. In India, this value ranged from 1566 mm in clay loam soil to 2262 mm in sandy loam soil. In the IGP, it varied from 1144 mm in Bihar to 1560 mm in Haryana[16]. However, in recent years a major problem is the increasing water scarcity. In fact, water scarcity is threatening Asia's irrigated rice systems. In Asia, 17 m ha of irrigated rice area may experience physical water scarcity and 22 m ha may have economic water scarcity by 2025 (ref. 17). It implies that water needs to be used minimally through water-saving methods or techniques in the future.

Water loss from rice fields and water-saving essentiality

The loss components of a puddle rice field are evaporation, transpiration (combined as evapotranspiration, ET), percolation and seepage. So far as measurements are concerned, ET values are mostly reported. Typically, ET from rice fields is 4–5 mm d^{-1} during wet months and 6–7 mm d^{-1} during dry months; this can be as high as 10–11 mm d^{-1} in subtropical regions. It was estimated that about ~30–40% of ET is due to evaporation[14,18]. Losses through seepage and percolation account for 1–5 mm d^{-1} in heavy clay soils and 25–30 mm d^{-1} in sandy and sandy loam soils[14]. The combined losses through seepage and percolation may be 25–50% of total water loss in heavy soils with shallow groundwater table (20–50 cm depth); and 50–85% of total water loss in coarse textured soils with groundwater table (1.5 m depth or more)[16,19,20]. Losses through seepage and deep percolation from one field are recaptured and used in other fields downstream.

Therefore, more efficient management of water is needed for rice production. Several strategies are being pursued to reduce rice water requirements, such as saturated soil culture[21], alternate wetting and drying[18,22], system of rice intensification (SRI)[23–26] and aerobic rice[27–29]. In addition, an emerging water-saving technique is the use of micro-irrigation (sprinkler and drip irrigation). This is prevalent in fruit and vegetable cultivation; now researchers have started experiments to understand the feasibility of using micro-irrigation in rice. Hence, it is the need of the hour to elucidate existing information on the use of sprinkler and drip irrigation to rice for future strategies.

System of rice intensification: a water-use efficient method

SRI, which was developed in Madagascar, is now spreading to most rice-growing countries. It has become the method of choice for increasing rice production with reduced water demand and increased water productivity[23,26]. Paddy fields are kept moist but not continuously flooded, either by saturated soil culture or by alternately wetting and drying. Under SRI, young seedlings are transplanted with wider spacing[26], with active soil aeration using mechanical weeders and the application of available organic manure to stimulate beneficial soil organisms[24,25]. Yield increase (25–50% or more) has been reported by researchers[24–26]. Such practices should be adapted to local conditions. Studies on the yield and water productivity performance of SRI should be systematically done using drip or sprinkler systems.

Current scenario of micro-irrigation in India

Micro-irrigation includes sprinkler and drip irrigation aiming at minimizing water use and enhancing water use efficiency (WUE) by crops. These may include joint application of fertilizers as in drip-fertigation. Pivot irrigation and/or irrigation using rain guns are also included under micro-irrigation. In India, area under micro-irrigation is only 7.7 m ha at present. Out of this, drip and sprinkler irrigation coverage is 3.37 and 4.36 m ha respectively, whereas its theoretical potential is estimated at around 69 m ha, and untapped potential is 61.8 m ha. There is large variation with respect to the adoption of drip or sprinkler irrigation in different regions of the country (Table 1). The top five states are Rajasthan, Maharashtra, Andhra Pradesh, Karnataka and Gujarat, that have adopted greater area compared with other states. In eastern India, Chhattisgarh is well ahead. Except Chhattisgarh, penetration (area under micro-irrigation divided by total net sown area in the state) of micro-irrigation is much lower in eastern India than the national value of 5.5%. There is a huge scope of micro-irrigation in eastern India.

A survey-based study showed that there were benefits of micro-irrigation in crops other than rice; for example, 50–90% increase in WUE, 30.5% savings in energy consumption, 28.5% savings in fertilizer consumption, 42.4% increase in fruit crops productivity, 52.7% in vegetables productivity, 31.9% savings in irrigation cost, 42% increase in farmers' income. An impact study report by the National Mission on Micro-irrigation, Government of India, clearly indicates that the overall efficiency of micro-irrigation (50–90%) is much higher than surface irrigation (30–35%). For rice crop, its application and adoption by farmers are not encouraging. Therefore, there is need to address problems in using micro-irrigation in rice and to make it adoptable for rice crop.

Table 1. Total micro-irrigation area coverage (except rice), and micro-irrigation penetration in India (as on 31 March 2015); penetration indicates area under micro-irrigation divided by net sown area[4]

State	Micro-irrigation area (ha)	Penetration (%)
Haryana	573,140	16.3
Punjab	42,966	1.0
Rajasthan	1,684,549	9.3
Madhya Pradesh	352,117	2.3
Sikkim	8,313	10.8
Mizoram	2,152	2.2
Nagaland	5,205	1.4
Chhattisgarh	256,193	5.5
Odisha	100,578	2.3
Bihar	102,050	1.9
Jharkhand	16,222	1.5
West Bengal	51,180	1.0
Andhra Pradesh	1,163,306	10.4
Karnataka	846,947	8.5
Gujarat	829,373	8.1
Maharashtra	1,271,126	7.3
Goa	1,864	1.4
Kerala	29,464	1.4
Tamil Nadu	320,445	6.4
All-India total	7,775,314	5.5

Evidence and scientific understanding on rice micro-irrigation

Researchers have examined the use of sprinkler or pivot irrigation for rice since late 70s and early 80s. It has also been the goal of farmers and researchers in Zimbabwe[30] and USA[31,32]. Earlier experiments on sprinkler irrigation were carried out at Arkansas, USA[33,34] with positive findings on the feasibility of sprinkler irrigated rice and 50% of irrigation water saving. At Louisiana, USA, sprinkler-irrigated rice produced fewer florets, fewer filled grains panicle^{-1} than flood irrigation, whereas panicles/m^2 and specific grain weight were not significantly affected resulting into reduced grain yield by 25% (ref. 35). Reduced plant height was also reported in Texas, USA. At Arkansas, irrigation water applied to rice ranged from 610 to 1220 mm (ref. 36). Vories *et al.*[37] reported 460–1435 mm for 33 Arkansas rice fields, and Smith *et al.*[38] reported 382–1034 mm in Mississippi, USA.

On a free-draining soil in New South Wales, Australia, line-source sprinkler system was examined with water amounting to 26–128% of Class-A pan evaporation. It was concluded that sprinkler irrigation was capable of much higher efficiency of water use than ponding to rice[32]. However, plant production was not encouraging because of much shorter, more upright and robust stature plants in sprinkler-irrigated plots than those being continuously ponded. In central Sardinia rice area of Italy, in contrast, sprinkler irrigation clearly led to agronomic and environmental benefits, and economic advantages due to decreases in water requirement by ~50% without decrease in rice yield[39].

In Asia, researchers have used aerobic method[14,16,29,40–44]; a mixed response, i.e. similar or reducing yield was observed with concomitant saving of water. Under drip irrigation in Shanghai, China, drought-resistant varieties showed better yield capacity than puddled rice varieties; drip irrigation attained more than 95% of the yield level that was obtained under puddle condition[45]. Adaptation of rain-gun sprinkler has begun in Potohar plateau, Pakistan, to provide supplemental irrigation to dryland farming. However, wide-scale adoption was not reported in canal-irrigated areas of the Indus Basin[46].

A detailed elucidation has been made on the performance of rice crop with micro-irrigation across rice-growing countries over the past several decades (Tables 2 and 3). Findings showed the potential for minimizing water usage in rice cultivation and improving WUE. However, reduced grain yield was also found due to water deficit in soil and sub-optimal physiological functioning of plants. Overall, depressing effect of lower water depth applied through sprinkler irrigation has been reported from USA and Australia[35,47]. More specifically, yield reduction due to water stress in sprinkler-irrigated rice had been reported in Texas, Arkansas and Louisiana in USA, as well as in Australia. Westcott and Vines[35] reported yield losses up to 25–35% due to sprinkler irrigation. On a free-draining soil, Blackwell *et al.*[32] found that yields obtained in sprinkler-irrigated rice were relatively lower, while grain yields from ponded plots were more than 7.0 tonne ha^{-1}. Private organizations have also conducted research on rice by drips in various countries like Australia, Brazil, China, India, Japan, Spain, Thailand and USA.

Water relation in plants and reasons for yield reduction

Water deficit in soil, either during vegetative or reproductive stage of rice, affects rooting pattern and soil moisture extraction by plants. The effects may be leaf rolling, leaf elongation rate, leaf death, greater drying, decrease in relative water content (RWC), etc. Plants send signals for cessation of root growth under severe water stress; the effects may vary with cultivars. The physiological functions are also related, viz. root water extraction[48], variation in canopy size[49] and stomatal control of transpiration[50]. Spikelet sterility increases and grain yield of rice drastically reduces due to water stress, especially if it occurs during flowering and grain-filling stages[48]. Due to moisture deficit in the soil, root length density, in general, is greater in the surface soil layers and declines with depth[51]. Physiological functioning in plants, the rate of apical development, biomass production, spikelet number, panicle development, grain size and grain yield may be reduced to even their half, depending upon the severity and cultivar tolerance[52]. Hence, rice varieties having deep root systems would perform better under micro-irrigated condition.

There are chances that water stress may occur due to irrigation through drip or sprinklers, with accumulation of proline and abscisic acid (ABA) in rice plants. Proline accumulation is negatively correlated with midday leaf water potential and positively with leaf turgor and osmotic adjustment[53]. Muirhead[54] found a decrease in yield of sprinkler rice by 50% or more compared to continuous flooding. Blast disease of rice (*Pyricularia grisea* (Cooke) Sacc.) generally spreads through airborne spores. This has been the most devastating disease in North America. The severity of blast in a region, varies greatly each year due to weather conditions. Crop rotation is an important control practice because the fungus can survive on straw residue from the previous year. When highly susceptible cultivars are grown with flood irrigation, plant pathologists recommend deep flooding. Since sprinkler irrigation is not flooded, blast disease was common in many rice fields of mid-south United States in 2009.

In addition to the depressing factors, installation of sprinkler or drip system in larger areas would involve initial high costs, maintenance and preventive measures

Table 2. Performance of rice to sprinkler irrigation, water usage and water use efficiency (WUE) and critical observation based on experimental studies by other researchers across rice-growing countries

Location	Year of study, soil and methods	Yield performance, water usage and WUE; critical observations	Reference
IRRI, Philippines	1976–82; silty clay-loam; dry season experiment with var. 'IR 36' using line-source sprinkler; irrigation at 110% of actual evapotranspiration (ET) (ETa) as the wettest, while 55% less than maximum ET (ETm) as the driest.	Grain yield 5.0 tonne ha^{-1} at 110% ETa, decreased to 4.61 tonne ha^{-1} at the moisture regime which was 30% less than ETm; further reduced to 0.94 tonne ha^{-1} at 55% less than ETm; strong linear relationship between grain yield and ETa during flowering period due to vapour pressure deficit (VPD), canopy temperature; soil moisture at 95% and 28.6% of total crop extractable water showed midday leaf water potential –0.9 and –2.5 MPa, spikelet sterility 20% and 73% respectively;leaf rolling in stressed level; exsertion of rice panicle was sensitive to changes in leaf water potential; up to 30% of spikelet sterility was associated with poor panicle exsertion.	55–57
New South Wales, Australia	Early 80s in Murrumbidgee irrigation area, free-draining soil, line-source sprinkler operated at 26–28% of pan evaporation.	Grain yield 3.40 kg/mm of water in sprinkler, 1.85 kg/mm in ponded treatment; excellent weed control by herbicides applied through sprinklers.	32
Southeastern Queensland, Australia	Mid-80s; clay soil; dry and wet conditions; short duration under upland with var 'Shinhakaburi', long duration upland with var. 'IR 43' and short duration lowland var. 'Labelle'; weekly sprinkler irrigation.	Grain yield 6.8 tonne ha^{-1} in 'IR43', grain yield under dry conditions was <10% of the corresponding yields in wet trial; low grain yield in other varieties due to inefficient conversion of solar radiation to dry matter; dry conditions signalled leaf rolling, delayed heading and affected grain setting.	47, 58
Southeast Texas, USA	1982–84; clay soil; sprinkler irrigation; 100%, 50% and 25% of estimated ET.	Reduced yield by 20–28% in sprinkler due to weeds and disease infestation; water usage 931–1171 mm through sprinkler, and 1262–1742 mm through flood irrigation; sprinkler irrigation was not a viable alternative to conventional flood irrigation.	59
Louisiana, USA	1983–84; clay soil; sprinkler irrigation thrice a week with 0.038 m water to maintain soil moisture tension above –30 kPa.	Grain yield 4.45–5.90 and 7.14–7.85 tonne ha^{-1} in sprinkler and flood irrigation respectively; decreased water use in sprinkler irrigation but reduced dry matter and florets $panicle^{-1}$ due to increased sheath blight (*Rhizoctonia solani*)	35
Portageville, Missouri Marsh Farm, USDA-ARS, USA	2009–10; sandy loam and silty loam; centre pivot irrigation 150 m long with 190-mm drill spacing for hybrid rice varieties. 'Templeton', 'Francis', 'Cocodrie', 'Taggart', 'Catahoula' under drill-seeded with 151 kg N ha^{-1}.	Grain yield 8.20–8.31 tonne ha^{-1} in 'Templeton' and 'Francis', less in other varieties; water usage 414 mm in 34 days, 503 m in 45 days; soil moisture tension 10–70 kPa for 15 cm soil deptn and 30–50 kPa for 30 cm soil depth; WUE 1.7 and 2.1 kg m^{-3} for flood and pivot irrigation respectively; more chances of *Pyricularia grisea* and *Bipolaris oryzae*, but less of *Rhizoctonia solani* in sprinkler-irrigated rice; disease outbreaks in centre pivot irrigation with inadequate weed control.	60, 61
Montanana, Zaragoza, NE Spain	2001–03; sandy loam and clay loam; solid-set sprinkler system, every 2–3 days with 14–16 mm per irrigation, lysimetric measurement of ET.	Crop height 1.55 m in 79–129 days and 1.70 m in 113–147 days; ET 750–800 mm in sprinkler-irrigated rice; crop coefficient (K_c) 0.83–1.20 with average of 0.92 in the initial stage, 1.06 and 1.03 during mid and late season respectively.	62
Kooshkak, Islamic Republic of Iran	2000–01; silty loam; rice var. 'Champa-Kamphiroozi', sprinkler irrigation at 1.0 pan evaporation (ETp) and 1.5 ETp compared to flooding and intermittent irrigation, N rate 32–152 kg ha^{-1}.	Grain yield 3.75–4.29 tonne ha^{-1} in sprinkler irrigation at 1.0–1.5 ETp with N 52 kg ha^{-1}; 5.96 and 6.06 tonne ha^{-1} in continuous and in intermittent flooding respectively; water usage 836–1373, 1778 and 2262 mm in sprinkler, intermittent and continuous flooding respectively; increased WUE by 20–60% in the former two methods than continuous flooding.	63
Monoo Farm, Lahore, Pakistan	2002–04; clay loam; sprinkler irrigation using rain-gun twice a week at 100–150% of ETc; 192–261% of ETc in the basin, with var. 'Super Basmati', puddle transplanted rice (June to October)	Grain yield 3.1–3.2 tonne ha^{-1} in sprinkler, and 3.1 tonne ha^{-1} in basin irrigation, ~18% more yield in sprinkler; water 5612–8417 m^3 ha^{-1} in sprinkler operating 39 times, and 10,795 m^3 ha^{-1} in basin irrigation operating 19 times; irrigation requirement could be as low as 26% with crop WUE 0.55 kg m^{-3} compared with 0.25 kg m^{-3} for basin.	46

Table 3. Performance of rice to drip and/or drip-fertigation, water usage and WUE, and critical observations based on experimental studies by other researchers across rice-growing countries

Location	Year of study, soil and methods	Yield performance, water usage and WUE; critical observations	Reference
IRRI, Philippines	1998–99; silty clay-loam, drip 2–3 times a week, dry-seeded aerobic variety double haploid lines crossed from 'Azucena' and 'IR64'; weed control by chemical and manual methods.	Grain yield 0.8–3.2 tonne ha^{-1} in drip, and 2.3 tonne ha^{-1} in wet under upland condition, water regime at 1.6 times ET with soil water potential above –0.04 MPa; spikelet sterility 30–78% in drip, relative water content (RWC) in leaves 81–98%.	64
Texas, USA	2001–06; drip irrigation with var. 'Cocodrie'.	Similar grain yield and biomass production in drip and flood irrigation; 58% saving of irrigation water compared to flood irrigation.	65
Virgin Island, USA	2006–09; silty clay-loam; dry-season in aerobic condition, drip scheduled at 0.04 MPa	No difference in crop growth; grain yield 2.88, 3.93 and 3.61 tonne ha^{-1} in 'Cybonnet', 'Bengal' and 'Neptune' respectively; higher yield in 'Cybonnet' and 'Neptune' under drip by 10–27%, whereas higher yield in 'Bengal' and 'Taipei' by 6% in surface flooding.	66
Xinjiang, China	2011–12; sandy loam; drip irrigation with plastic mulch in furrow, compared with no mulch furrow and conventional flooding; japonica var. 'Ninggeng28' and 'Xindao17'.	Grain yield 5.78–5.90 tonne ha^{-1} with 1103–1121 mm water through drip, 8.32–8.58 tonne ha^{-1} with 3420–3552 mm water in flooding; WUE 0.52 and 0.25 kg m^{-3} in drip and flooding respectively; supplemental irrigation (30–60 mm) up to three-leaf stage at soil water potential –30 kPa in 0–20 cm depth, irrigation with same amount during three-leaf stage to two-weeks before harvest at –10 kPa to avoid spikelet sterility.	67
Xinjiang, China	2012 – up to seven seasons; sandy loam; drip with plastic mulch, compared with flood irrigation.	Grain yield 10–12% higher in drip and plastic mulch and 60% water saving; drip-plus-mulch-favoured conversion of soil NH_4^+ to NO_3^- increased availability of K and Zn, whereas decreased availability of Mn, and negligible effect on P availability.	68
Ludhiana, Punjab, India	2013–14; sandy loam, direct-seeded rice; rainy season; medium duration var. 'PR-115', drip at 1.5, 2.25 and 3.0 times pan evaporation (PE); N 120, 150 and 180 kg ha^{-1}.	Grain yield 7.34–8.01 and 6.63–7.60 tonne ha^{-1} with 860 and 1455 mm water in drip and flood irrigation respectively; water saving by 40–42%; WUE 0.81–0.88 and 0.42–0.52 kg m^{-3} in drip and flood irrigation respectively.	69
Madurai, Tamil Nadu, India	2009–13; sandy loam; rainy and winter season; drip-fertigation at 100 and 150% PE; hybrid rice.	Grain yield 5.51–5.68 and 4.95–5.08 tonne ha^{-1} with 822–1027 and 591–757 mm water in drip at 150% and 100% PE respectively; WUE 6.93–8.25 kg ha^{-1} mm^{-1} in drip fertigation; drip fertigation of 100% PE with 100% fertilizer along with azophosmet and humic acid increased yield.	70, 71
Coimbatore, Tamil Nadu, India	2011–12; red loamy/calcareous black, summer season, subsurface and surface drip-fertigation; conveyance through PVC pipe; NPK at 150 : 50 : 50 kg ha^{-1}.	Grain yield 3.74–4.25 tonne ha^{-1} in drip with 647.5–692.9 mm water, i.e. 8–17% higher yield and 7–27% increased water productivity compared to flood; suggested for large root system of rice to be suited for aerobic drip.	72–74
Bhubaneswar, Odisha, India	2013; sandy loam; rainy season; short duration rice var. 'Khandagiri', puddled transplanted, supplemental irrigation through drip.	Grain yield 4.27, 4.39 and 3.92 tonne ha^{-1} in 100%, 125% and 75% of ETc in drip respectively, whereas it was 4.48 tonne ha^{-1} with surface irrigation; drip (108–179 mm) and surface irrigation (5 cm) after three days of drainage of standing water; surface irrigation (250 mm) by hose pipe; WUE 0.604 kg m^{-3} in drip at 100% ETc and 0.432 kg m^{-3} in surface irrigation.	75
Morena, Madhya Pradesh, India	2014–15; sandy clay; rainy season; sub-surface drip irrigation (SSDI) at 1.0 IW/CPE, with N : P:K : Zn at 120 : 60 : 40 : 5 kg ha^{-1}.	Grain yield 5.5 tonne ha^{-1} with 6316 m^3 water (irrigation plus rainfall) in SSDI compared to 5.5 tonne ha^{-1} with 8420 m^3 water with traditional flood irrigation; water productivity 0.88 and 0.59 kg m^{-3} respectively.	76
Bhopal, Madhya Pradesh, India	2013–14; heavy clay; rainy season; drip to SRI rice with 30 × 30 m spacing; compared with conventional rice-continuous flooding, fertilizer N, P_2O_5 and K_2O at 150, 100 and 120 kg ha^{-1}.	Grain yield 7.07 tonne ha^{-1} in system of rice intensification with 20 cm dripper spacing, highest water productivity of 0.90 kg m^{-3} and water-energy productivity of 7.85 kg kWh^{-1}; the corresponding values were 3.14 tonne ha^{-1}, 0.16 kg m^{-3} and 1.02 kg kWh^{-1} respectively, in conventional rice with flood irrigation.	77

against theft, etc. Moreover, it requires shifting to other fragmented plots for succeeding crops. All these factors possibly are not conducive to small and marginal rice farmers in India.

Summary

Rice is intimately associated with daily food consumption and livelihood of Asians. Rice farming needs more attention for increasing production as well as reducing water usage. Drip or sprinkler irrigation is a way to tackle water scarcity. The slogan should be 'more rice with less water'. In this study existing information has been reviewed and compiled on micro-irrigation technology for rice cultivation, and the emerging key points are summarized as follows:

- Sprinkler or drip irrigation needs to be scheduled for rice crop in the initial growth stages when soil water potential reaches about –30 kPa in 0–20 cm soil layer, i.e. around field capacity; supplemental irrigation (40–50 mm) is required from three-leaf stage to three-weeks before harvesting. At the flowering stage, threshold soil water potential of –10 kPa may be considered appropriate to avoid spikelet sterility.
- Irrigation amount through drip or sprinkler should exceed crop evapotranspiration; about 750–1000 mm should be applied and frequency may be 1–3 times in a week depending upon the weather condition during crop-growing stage, rainfall, soil type, soil moisture depletion and varietal susceptibility to water stress.
- The variety should have a deeper root system, efficient in the conversion of solar radiation to dry matter, water stress-tolerant, suitable for growing under direct dry-seeding and aerobic method, and resistant to blast disease infestation. There are chances of occurrence of brown spot disease (*Bipolaris oryzae*), but less of sheath blight (*Rhizoctonia solani*).
- Application of effective fungicide is a must because rice blast may cause devastation and total crop failure. Similarly, effective weed management through manual, mechanical and/or application of herbicides, is required to curb weed menace.
- Efficacy of drip and/or drip-fertigation will be more if it is practised in combination with mulching. Plastic-film mulching will effectively reduce evaporation loss of water and weed menace.
- There is a need for further research to eliminate negative and discouraging factors of micro-irrigation, and make this emerging technique suitable for rice and to minimize water use.

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