Solar pump irrigation system for green agriculture

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Abstract: Ever increasing fuel price and unreliable electricity supply hamper irrigated crop production in Bangladesh. Solar pump may be an alternative to the electric motor operated pumps for irrigated crop production in the country, especially for the off-grid rural areas. This paper presents the technical and economic suitability of solar pump irrigations of rice and non-rice (upland) crop productions in Bangladesh. Four solar pumps (submersible type, 1,050 W_p) were installed in different locations for irrigating rice, wheat and vegetables. The solar pumps were used for drip irrigation and furrow irrigation for cultivation of brinjal and tomato during the winter seasons of 2010-2011, 2011-2012 and 2012-2013. There were no significant differences of yields of brinjal between drip and furrow irrigations in the year 2010-2011 in Gazipur and during 2011-2012 in Jamalpur. But in 2012-2013, significantly higher yield of brinjal was obtained from drip irrigated plots (43.9 t/ha) compared to the furrow irrigated plots (38.6 t/ha). There was no significant difference between drip and furrow irrigation methods in Jamalpur in terms of tomato yield. Significantly higher yields of tomato were recorded in Gazipur from drip irrigated plots than those of furrow irrigated plots in both the year 2011-2012 and 2012-2013. Water savings by drip irrigation over furrow irrigation for brinjal and tomato were 53.3% and 56.2%, respectively. The yield of summer tomato was 33.7 t/ha in drip irrigated plot while 31.9 t/ha in furrow irrigated plot during 2011-2012. Water requirements of summer tomato in drip and furrow irrigation methods were 225 mm and 429 mm, respectively. For cultivation of wheat about 430 mm water was required and the yield was 3.0 t/ha. Boro rice was cultivated in Magura and Barisal during 2011-2012 and 2012-2013. During the cropping season total water requirement for boro rice cultivation was 1,024 mm in Magura and 1,481 mm in Barisal. Use of solar pumps was found economical for wheat (BCR 2.31), tomato (BCR 2.22) and brinjal (BCR 2.34) production, but not for boro rice (BCR 0.31). Being an environmentally sound and green technology solar pumps can be promoted for the cultivation of non-rice crops.

Keywords: PV panel, furrow irrigation, drip irrigation, tomato, brinjal, rice

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1 Introduction

Bangladesh has major problems of energy crisis, persisting poverty and environmental degradation. Ever increasing fuel price and unreliable availability of electricity hampers the irrigated crop production in Bangladesh. There are about 1.71 million irrigation pumps operating in Bangladesh among them 83% are diesel engine operated and 17% are electricity operated (BADC, 2012). The demand of electricity in irrigation is growing up since the cost of an electric powered pump is lower compared to a diesel engine driven pump. Solar pump may be an alternative for small scale irrigated crop production in the off-grid areas of Bangladesh. Being a tropical country, Bangladesh is endowed with

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abundant supply of solar energy. The ranges of solar radiation are between 4.0 and 6.5 kWh/m^2 day and the bright sunshine hours vary from 6 to 9 h/day (Biswas and Hossain, 2013; Islam and Ahiduzzaman, 2011). In Bangladesh, about 60% of the cropping land is under irrigation (AQUASTAT, 2011). There is a vast area to be irrigated where most of the areas (charlands, coastal areas, hilly areas, etc.) have no grid connection. Solar PV pumps can be used for irrigating these lands for better crop production and to increase cropping intensity.

Abu-Aligah (2011) reported that in locations where electricity is not available photovoltaic pumping system is a good option for irrigating crops and supplying drinking water. Namibia Renewable Energy Programme (NAMREP) conducted a study on feasibility of solar pumps in Namibia (Anon, 2006). The report concluded that for small to medium sized wells, a solar photovoltaic pump was much cheaper (on a life cycle cost basis) than a diesel-powered pump. When looking beyond the original purchase price, solar pumping systems costed from 22%-56% of diesel pumps cost and could achieve a payback over diesel engine operated pump in two years. Hahn (2000) reported that in regions with high insolation levels, photovoltaic pumping systems were technically suitable for use, beneficial for the environment and were cheaper over the diesel engine driven pumps.

Burney et al. (2010) conducted a study in the rural Sudano–Sahel region of West Africa. Using a matched-pair comparison of villages in northern Benin, and household survey and field level data they reported that solar-powered drip irrigation significantly augmentetd both household income and nutritional intake, particularly during the dry season, and was cost effective compared to alternative technologies. Zieroth (2005) conducted a feasibility study on water supply by solar pump in Mauke, Cook Island. Cost of solar pump use was US\$ 0.16/m^3 of water as compared to US\$ 0.22/m^3 for the diesel powered pump. A solar photovoltaic pump operated drip irrigation system was designed and developed for growing orchards in arid region considering different design parameters like pumps size, water requirements, the diurnal variation in the pressure of the pump due to change in irradiance and pressure compensation in the drippers. The system comprising with 900 W$_p$ PV array and 800 W dc motor-pump and drippers on each plant was tested in the field. The system could irrigate about one hectare area within two hours (Pande et al., 2003). In 1999 and 2000, cabbage and peppers, respectively, were grown comparing solar and conventionally powered drip irrigation systems at the Rutgers University Research and Extension Farm, Pittstown. The solar system in 1999 was operated by a 1.5 horse power motor powered by 18 solar modules. Solar powered pumping systems were capable of delivering water from rivers and wells in volumes up to 2000 gallons/minute (Tietjen et al., 2008).

Solar pumps were found technically suitable for low lift small scale irrigation in Bangladesh during eighties. But these pumps were not then found economically viable due to high PV cost (Mazed et al., 1987). Moreover, these photovoltaic solar panels could not function well during cloudy and rainy weathers. Presently, much improved and cheaper solar pump sets are available. The energy crisis is severe in Bangladesh during the irrigation season which is a threat to economical development of the country. Using solar pumps on a large scale energy demand in irrigation systems can be reduced substantially. Biswas and Hossain (2013) reported that though the initial cost of a solar pump is higher than a conventional diesel engine operated pump, solar pump has lower maintenance cost which makes it cost effective over the years. Moreover, a solar pump is a pollution free and environment friendly water pumping system. Therefore, this study was undertaken to evaluate the technical and economic performances of PV operated solar pumps at field conditions and to develop a suitable solar pump irrigation system for the farmers of the country in order to boost crop production as well as to uphold healthy environment.

2 Methodology

2.1 Installation and testing of solar pump

Four China made submersible solar pumps (Lorentz, PS 1200, 2.2 hp, rpm) were installed in four locations covering different Agro-Ecological Zones (Bangladesh Agricultural Research Institute, Gazipur; Regional Agricultural Research Station, Barisal; Regional Spices Research Centre, Magura and Regional Agricultural Research Station, Jamalpur). Among the four pumps, one was used for surface water lifting and other three were used for ground water lifting. The surface water lifting pump was installed in Barisal and ground water lifting pumps were installed in Gazipur, Magura and Jamalpur. In Jamalpur, Magura and Barisal the solar pumps were powered by 1,050 W_p solar panels fitted on a fixed tracker. Whereas in Gazipur the pump was powered by 1,440 W_p solar panels mounted on a solar auto tracker. The delivery pipe was made of PVC and was 38 mm in diameter (all four locations). The delivery lifts of the pumps installed in Gazipur, Jamalpur and Magura were 33.5, 24.0, 24.0 m, respectively. In Barisal the solar pump was installed to lift water from a pond where the delivery lift ranged from 4.0 to 8.0 m. The performance of each of the pumps was tested in the project locations. Data on available solar radiation, generated voltage, current, lift, discharge and other relevant data were recorded for each of the pumps. Water discharges were measured volumetrically using 50 L graduated water tanks. A digital solar meter (Model: 776E, accuracy ±3%, Digital Engineering, USA) was used to measure the global solar radiation.

2.2 Irrigation of brinjal in Gazipur

The solar pump was used for drip irrigation and furrow irrigation for brinjal cultivation in the experimental field of FMPE (Farm Machinery and Postharvest Process Engineering) division, BARI (Bangladesh Agricultural Research Institute), Gazipur during rabi (October-April) season of 2010-2011 and 2012-2013. The soil type was loamy sand. The plot size was 40 m×13 m (520 m^2). The brinjal varieties were BARI Begun-8 planted in 2010 and BARI Begun-6 planted in 2012. Two rows of brinjal were planted in each bed on 11 October in 2010 and 26 October in 2012. Row to row and plant to plant distances were 70 cm× 70 cm. Fertilizers such as cow dung 9.5 t/ha, urea 375 kg/ha, TSP (Triple super phosphate) 155 kg/ha and MP (Murate of potash) 260 kg/ha were applied in brinjal field. Total dose of cow dung and TSP, one third of urea (125 kg/ha) and MP (86.7 kg/ha) were applied as basal dose during final land preparation. Rest of urea and MP were applied after 20 days and 45 days of planting. Fertilizers were applied as per national fertilizer recommendation guide of Bangladesh (FRG, 2012). Two beds of brinjal were irrigated by the drip method having three water tanks, each of 500 liter water holding capacity. The drip sets were made with plastic pipes, water tank, capillary tubes, pegs etc. Irrigation was applied when the soil moisture content reduced below the soil moisture content of 32% (IWM, 2012). The soil moisture content was monitored by a digital soil moisture meter (TDR 300, accuracy ±3%, Terf-Tec International, USA). Brinjal was harvested several times from January to April.

2.3 Irrigation of winter tomato in Gazipur

The solar pump was used for drip and furrow irrigations for tomato cultivation in the experimental field of FMPE division during *rabi* (October-March) 2011-2012. The soil type was clay loam. The plot size was 40 m×13 m (520 m^2). Six beds of tomato were irrigated by the drip method having three water tanks each of 500 l water holding capacity. The drip sets were made with plastic pipes, water tank, capillary tubes, pegs, etc. The tomato variety was BARI Tomato-14. Two rows of tomato were planted in each bed on December 4, 2011. The age of seedlings was thirty one days. Row to row and plant to plant distances were 60 cm × 40 cm.

Cowdung 10.0 t/ha, urea 600 kg/ha, TSP 500 kg/ha, MP 200 kg/ha, zinc 10 kg/ha and boron 8 kg/ha were applied in tomato field. Total dose of cow dung, TSP, MP, zinc, boron and one thirds of urea (200 kg/ha) were applied as basal dose before final land preparation. Rest of the urea was applied in two splits, 20 days after transplanting and 45 days after transplanting. Tomato was harvested during the period of February to April 2012. Irrigation was applied when the soil moisture content went below 35% (as per the recommendation of IWM, 2012).

2.4 Irrigation of brinjal in Jamalpur

The solar pump was used for drip irrigation and furrow irrigation for brinjal cultivation in the experimental field of Regional Agricultural Research Station, Jamalpur during *rabi* 2011-2012. The soil type was sandy loam. The plot size was 20 m×10 m (200 m^2). Four beds of brinjal were irrigated by the drip method having two water tanks each of 500 L water holding capacity. The drip sets were made with plastic pipes, water tank, capillary tubes, pegs etc. The brinjal variety was BARI Begun-7. Two rows of brinjal were planted in each bed on November 17. 2012. Row to row and plant to plant distances were 70 cm×70 cm. Cowdung 8.0 t/ha, urea 375 kg/ha, TSP 150 kg/ha and MP 250 kg/ha were applied in brinjal field. Total dose of cow dung (9.5 t/ha), TSP (155 kg/ha), MP (85 kg/ha) and one third of urea (125 kg/ha) were applied as basal dose before final ploughing. Rest of urea was applied in two splits, twenty five days after transplanting and fifty days after transplanting. Brinjal was harvested in several stages from January to April 2012. Irrigation was applied when the soil moisture content became below the soil moisture content of 30% (IWM, 2012).

2.5 Irrigation of winter tomato in Jamalpur

The solar pump was used in drip irrigation and furrow irrigation for tomato cultivation in the experimental field of Regional Agricultural Research Station, Jamalpur during *rabi* 2010-2011 and 2012-2013. The soil type was sandy loam. The plot size was 30 m×10 m (300 m^2). The soil type was clay loam. Four beds of tomato were irrigated by the drip method having two water tanks each of 500 L water holding capacity. The drip sets were made with plastic pipes, water tank, capillary tubes, pegs etc. The tomato variety was BARI Tomato-14. Two rows of tomato were planted in each bed on November 4 in 2010 and October 30 in 2012. The age of seedlings was thirty two days in 2010 and twenty eight days in 2012. Row to row and plant to plant distances were 60 cm and 40 cm, respectively. Cow dung 8.0 t/ha, urea 600 kg/ha, TSP 500 kg/ha, MP 200 kg/ha, zinc 10 kg/ha and boron 8 kg/ha were applied in tomato field. Total dose of cow dung, TSP, MP, zinc, boron and one third of urea (200 kg/ha) were applied as basal dose before final ploughing. Rest of urea was applied in two splits, twenty days after transplanting and forty five days after transplanting. Tomato was harvested during the period of February to April. Irrigation was applied when the soil moisture content went below 33% (as per the recommendation of IWM, 2012).

2.6 Irrigation of summer tomato in Gazipur

Solar pump was used for drip irrigation for summer tomato cultivation in the experimental field of FMPE division during the *kharif* (May-August) season of 2011-2012 and 2012-2013. The variety was BARI Tomato-4. The plot size was 27 m×12 m (324 m^2). The soil type was clay loam with field capacity of 26% (IWM, 2012). Two beds of plants were irrigated by the drip method having two water tanks each of 500 L water holding capacity. The drip sets consisted of plastic pipes, water tank, capillary tubes, pegs etc. The tomato shed was covered with greenhouse shaped polythene shed. The shed size was 12 m×2.52 m and bed size was 12 m× 1.2 m. Row to row distance was 55 cm and plant to plant distance was 50 cm. Cow dung 9.0 t/ha, urea 375 kg/ha, TSP 155 kg/ha and MP 260 kg/ha were applied in tomato field. Total dose of cow dung and TSP, one third of urea (125 kg/ha) and MP (86.7 kg/ha) were applied as basal dose before land preparation. The rest of urea and MP were applied after twenty days and forty five days after the date of planting. Irrigation was applied when soil moisture reduced to about 35% (w/v). The date of planting of tomato seedlings was June 26, 2012. Finally the harvesting of summer tomato was done from August to September.

2.7 Irrigation of wheat in Gazipur

Wheat was cultivated in 496 m^2 land area in the experimental field of FMPE, Division, BARI, Gazipur during the *rabi* season of 2012-2013. The wheat variety was BARI Gom-26. The date of sowing was 23 November 2013. Wheat was sown by bed planter. There were two rows on the bed and row spacing was 20 cm. Seed rate was 100 kg/ha. The field was fertilized with urea, TSP, MP and gypsum at 220, 180, 50, 120 kg/ha, respectively. Half of urea, the whole amount of TSP, MP and gypsum were applied at the time of final land preparation. The rest of urea was top dressed at crown root initiation (CRI) stage. Irrigation was applied in the bed. Three irrigations were applied at CRI stage, maximum tillering stage and grain filling stage. Irrigation was applied by flood method in the bed. The date of harvesting was April 16, 2013.

2.8 Irrigation of boro rice in Magura and Barisal

The solar pump was used for flood irrigation of *boro* (January-April) rice field in the experimental field of Regional Agricultural Research Station, Rahmatpur, Barisal and Regional Spices Research Centre, Magura during *boro* season of 2011-2012 and 2012-2-13. Each plot size was 17.5 m×12.5 m in Barisal and 14.0 m×6.5 m in Magura. In Barisal the soil type was sandy loam and in Magura it was clay loam. The rice variety planted in Barisal was BRRI dhan28 and in Magura it was *Kazol Lota* (Aromatic rice). The ages of seedlings in Barisal and Magura were thirty six to forty days. The date of planting of seedlings in Magura was 4 February and in Barisal, 29 January in 2012. Seedlings were planted on 29 January in Magura and 24 January in Barisal in 2013. Row to row and hill to hill distance was 20 cm. Uera 200 kg/ha, TSP 380 kg/ha, MP 140 kg/ha, zinc 15 kg/ha and boron 7 kg/ha were applied as basal dose before final land preparation. One thirds of urea was applied as basal dose and second one thirds urea was applied 27 DAT (days after transplanting). Rest one third urea was applied at 60 DAT. Weeding was done manually at 36 DAT. Flood irrigation was applied when the soil moisture content reached below the saturation condition. The insecticides were applied as and when necessary.

2.9 Financial analysis

Total cost of solar pump for crop production is the sum of fixed cost and variable cost. Fixed cost is the sum of depreciation, interest on capital cost, repair, maintenance and shelter cost and cost of land use. Depreciation is often defined as the annual loss in value due to use, wear, tear, age, and technical obsolescence. Several methods or equations can be used to compute annual depreciation. Straight line method was used in this study to calculate depreciation because straight line method of calculating depreciation is widely used. The useful life of solar pump was assumed to be twenty years. Annual interest rate was considered 14% of the capital cost of the pump. The land use costs for brinjal, tomato, wheat and boro rice were taken from (AED, 2012). The variable cost is the sum of input cost and operating cost (fuel, oil, operator, etc.).

2.10 Calculation of carbon dioxide emission

Carbon dioxide (CO_2) emission from irrigation pump in Bangladesh was calculated from the total diesel consumed by the irrigations pumps in a year. Total numbers of irrigation pumps (DTW, STW and LLP) used in Bangladesh from 2000 to 2011 were obtained from the reports of Bangladesh Agricultural Development Corporation (BADC). Total quantity of diesel and electricity used by the irrigation pumps were also obtained from the secondary source of BADC (BADC, 2012). Then electric power was converted to diesel power using the conversion factor that one MWh electricity equivalent to 200 L diesel (DESA, 2012). Carbon dioxide emission was calculated by multiplying 2.8 kg for 1 (one) liter of diesel fuel (Anon, 2013). Then total quantities of carbon dioxide emissions from total numbers of irrigation pumps in different years were calculated.

3 Results and Discussion

3.1 Performance of solar pumps

Variation of discharge of solar pump with solar radiation at different times of a day was tested in Gazipur and presented in Figure 1. The test was conducted on June 11, 2012 from dawn to dusk. It is observed from the figure that solar pump could not lift any water at low solar radiation (<60 W/m^2). Discharge increased with the increase of solar radiation and it reached peak in the noon (12:00 m.) and then decreased gradually as solar radiation decreased. During the testing period the maximum discharge was found 111 L/min at 12.30 pm and average discharge was 61.24 L/min.

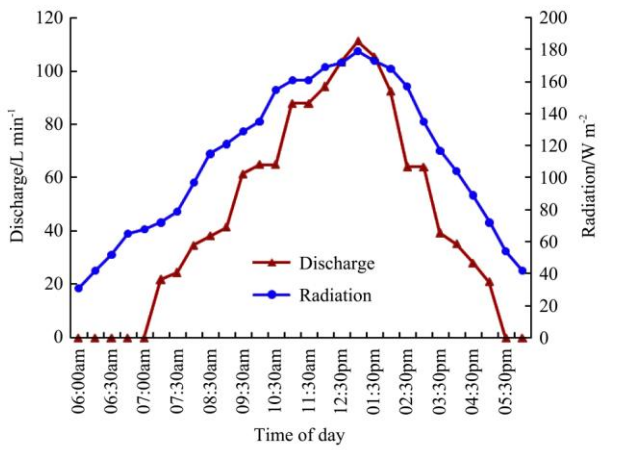

Figure 1 Variation of discharge of solar pump with solar radiation at different times of a day in Gazipur

Discharge of submersible solar pump with solar radiation at different times of a day in Jamalpur is given in Figure 2. The pump was tested on 18 March 2012. It is observed from the figure that discharge increased with the increase of solar radiation. The highest discharge (112 L/min) was found in 12.10 pm at the highest solar radiation of 310 W/m^2. The average discharge during the day was 74 L/min.

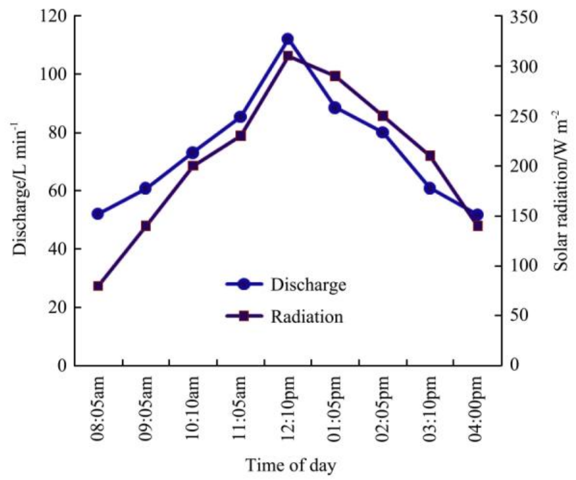

Figure 2 Discharge of submersible solar pump with solar radiation at different times of a day in Jamalpur

In Magura similar type of solar pump was tested on 24 April 2012. The pump was tested during the period of 7.00 am to 5.00 pm. The highest discharge (169 L/min) was found at 1.00 pm when the maximum solar radiation was recorded as 470 W/m^2 (Figure 3). The average discharge during the day was 110 L/min. The average discharge of solar pump tested in Magura was higher than that of Jamalpur. The reason was that during the testing period, the solar radiation in Magura (470 W/m^2) was higher than Jamalpur (310 W/m^2). Solar pump in Jamalpur was tested in the month of March and in Magura it was tested in April of 2012. April is the hotter month than March, therefore more solar radiation was received in the month of April. On the other hand, Magura is more temperate zone than Jamalpur due geographical location in Bangladesh. This is why more solar radiation as well as more discharge from same size of solar pump were obtained in Magura than those of Jamalpur.

Variation of discharge of solar pump with solar radiation at different times of a day tested in Barisal is shown in Figure 4. The test was conducted on 22 November 2012 from dawn to dusk. The pump was installed in a pond for surface water lifting. It is observed from the figure that solar pump could not lift any water at low solar radiation (<50 W/m^2). Discharge increased with the increase of solar radiation and it reached peak in the noon (11:30 am) and then decreased gradually as solar radiation decreased.

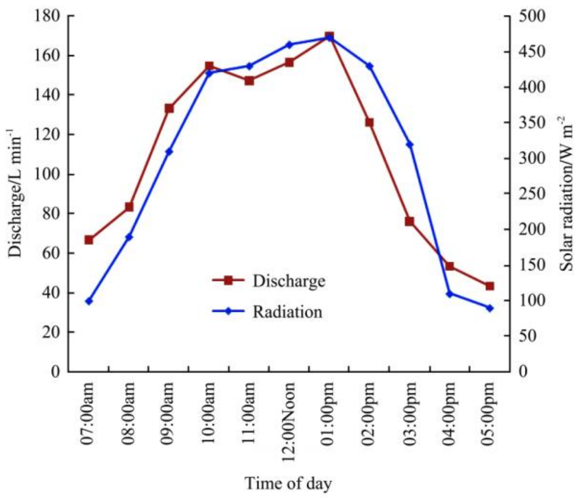

Figure 3 Discharge of submersible solar pump with solar radiation at times of a day in Magura

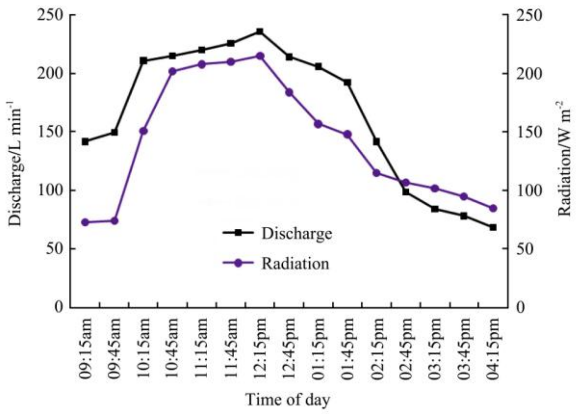

Figure 4 Discharge of submersible solar pump with solar radiation at different times of a day in Barisal

From the above results it is observed that solar pumps installed in different locations run well during operation. All the solar pumps were operated by submersible and variable speed dc motors. So, it can be operated only day time when solar radiation is available. Due to variable speed motor, the pump can be operated even at cloudy day with lower discharge. But it cannot be operated at the solar radiation less than 60 W/m^2. Discharge varied in different times of a day due to variation of solar radiation. Solar radiation is instantaneous and it varies every moment. Discharges also varied among the pumps in different locations because all the pumps were not tested at the same times. Even in the same times solar radiations in different locations were different. Availability of water in all the wells was not same and depths of pumps in the well were different. For example, in Jamalpur water level was 15 m but at the same time water level in Gazipur was 24 m. These were the reasons for variations of discharges of same model of solar pumps installed in different locations.

3.2 Irrigation of brinjal using solar pump

The solar pump was used for drip irrigation and furrow irrigation for brinjal cultivation in the experimental field of FMPE Division, BARI, Gazipur and during rabi 2010-2011 and 2012-2013 and also Regional Agricultural Research Station (RARS), Jamalpur during 2011-2012. Table 1 shows yield of brinjal in different years and locations by drip and furrow irrigations. Brinjal variety of BARI Begun-8 and BARI Begun-6 were cultivated in Gazipur in 2010-2011 and 2012-2013, respectively and irrigated by drip and furrow methods. In Jamalpur, brinjal variety of BARI Begun-7 was cultivated in 2011-2012 and also irrigated by drip and furrow methods. There were no significant differences of average fruit weights and yields of BARI Begun-8 and BARI Begun-7 between drip and furrow irrigations in both the years 2010-2011 and 2011-2012 in Gazipur and Jamalpur, respectively. But in 2012-2013, significantly higher yield (at 5% level) of brinjal (BARI Begun-6) was obtained from drip irrigated plots (43.86 t/ha) than furrow irrigated plots (38.60) in Gazipur. Higher fruit weight attributed higher yield of brinjal for drip irrigation. Therefore, significant effect of drip irrigation was found for brinjal variety of BARI Begun-6 but not for BARI Begun-7 and BARI Begun-8. Besides this, BARI Begun-7 in Jamalpur and BARI Begun-8 in Gazipur were partially infected by leaf curl virus disease. Patel et al. (2009) reported that for an application of 600 mm of water, drip yielded 33.5 t/ha (+26.3%) compared to 26.5 t/ha with surface irrigation.

Table 1 Yield of brinjal in different years and locations by drip and furrow irrigations

Irrigation method	2010-11: Gazipur (BARI Begun-8)		2011-12: Jamalpur (BARI Begun-7)		2012-13: Gazipur (BARI Begun-6)	
	Average fruit weight (g)	Yield (t/ha)	Average fruit weight (g)	Yield (t/ha)	Average fruit weight (g)	Yield (t/ha)
Drip	85.31	26.49	80.42	27.29	523.16	43.86
Furrow	87.23	26.71	78.81	25.82	510.71	38.60

Significance	ns	ns	ns	ns	*	*

Note: * denotes significant at 5% level, ** denotes significant at 1% level and ns denotes not significant.

Irrigation applied in drip and furrow irrigation methods in the years 2010-11, 2011-12 and 2012-13 for brinjal cultivation in Gazipur and Jamalpur are given in Table 2. Application of total irrigation in brinjal field in Gazipur during 2010-11 in drip and furrow methods were 54 mm and 131 mm, respectively. During the brinjal growing season, the rainfall was recorded to be 330 mm. This is why irrigation required in both drip and furrow methods were less than the optimum irrigation (300-400 mm by furrow method) for winter brinjal (Bhogi et al., 2010). Hence the water saving by drip irrigation over furrow irrigation for brinjal was about 58.78%. In Jamalpur irrigation applied for cultivation of brinjal (BARI Begun-7) during 2011-2012 by drip and furrow methods were 228 mm and 453 mm, respectively. Water saving by drip method of irrigation was 49.66%. During the growing season of brinjal, 126 mm rainfall was received in Jamalpur. For cultivation of brinjal (BARI Begun-6) in Gazipur during 2012-2013, irrigations were applied 238 mm and 460 mm by drip and furrow methods, respectively. Water was saved by 53.25% by drip method over furrow method of water applications. During the growing season, small rainfall (88 mm) was received. Among the three years (2010-2011, 2011-2012 and 2012-2013), the highest irrigation amount was required in the year 2012-2013 due to the lowest rainfall. In drip method, average water saving was 53.25%. In drip method of irrigation, low water was applied at less irrigation interval and hence total water application was low. Bhogi et al. (2010) found 35% to 51% water saving from drip irrigation over furrow irrigation for brinjal cultivation. There was substantial amount of water saving by drip irrigation system as compared to furrow irrigation system. This may be due to the fact that maximum amount of water was stored in the root zone and deep percolation losses were minimum at lower irrigation levels. These results are in agreement with the findings of Sivanappan (1979) in brinjal, tomato, chilli, okra and sweet potato. The pictorial views of drip and furrow irrigation by solar pump are shown in Figure 5.

Table 2 Irrigation applied in drip and furrow irrigations methods in different years for brinjal cultivation in Gazipur and Jamalpur

Methods of irrigation	2010-11: Gazipur (BARI Begun-8)		2011-12: Jamalpur (BARI Begun-7)		2012-13: Gazipur (BARI Begun-6)		Average water saving (%)
	Irrigation applied (mm)	Water saving (%)	Irrigation applied (mm)	Water saving (%)	Irrigation applied (mm)	Water saving (%)	
Drip	54	58.78	228	49.66	238	48.26	53.25
Furrow	131		453		460		

Brinjal field

Irrigation by solar pump in Brinjal field

Figure 5 The pictorial views of drip and furrow irrigations by solar pump

3.3 Irrigation of winter tomato using solar pump

The solar pump was used for drip irrigation and furrow irrigation for tomato cultivation in the experimental field of RARS, Jamalpur during *rabi* season of 2010-2011 and in FMPE Division, BARI, Gazipur during *rabi* seasons of 2011-2012 and 2012-2013. Yield of tomato in different years and locations by drip and furrow irrigations are shown in Table 3. Tomato variety of BARI Tomato-14 was cultivated in RARS, Jamalpur during 2010-2011 and BARI Tomato-14 and BARI Tomato-15 were cultivated in Gazipur during 2010-2012 and 2012-2013, respectively and irrigated by drip and furrow methods. There was no significant difference of fruit weights and yields of BARI Tomato-14 between drip and furrow irrigation methods in Jamalpur. Yield of BARI Tomato-14 was comparatively low in Jamalpur than that of Gazipur because tomato was infected by bacterial wilt. Tomato in farmers' field in Jamalpur was also infected by bacterial wilt during the year 2010-2011. Significantly higher fruit weights and yields of tomato were found in Gazipur from drip irrigated plots than those of furrow irrigated plots in both the year 2011-2012 and 2012-2013. In Gazipur, higher yield of tomato was obtained for BARI Tomato-14 in 2011-2012 than BARI Tomato-15 in 2012-2013. This might be due to the varietal effect as well as favourable climatic effect in the year 2011-2012. Hartz and Hanson (2009) reported that drip irrigation enhanced better nutrient uptake in tomato resulted higher yield and better quality.

Table 3 Yield of tomato in different years and locations by drip and furrow irrigations

Irrigation method	2010-2011: Jamalpur (BARI Tomato-14)		2011-2012: Gazipur (BARI Tomato-14)		2012-2013: Gazipur (BARI Tomato-15)	
	Average fruit weight (g)	Yield (t/ha)	Average fruit weight (g)	Yield (t/ha)	Average fruit weight (g)	Yield (t/ha)
Drip	55.36	35.64	60.98	62.95	69.75	39.92
Furrow	54.84	33.83	55.07	53.52	52.68	30.53
Significance	ns	ns	**	**	**	**

Irrigation applied in drip and furrow irrigations method in the years 2010-2011, 2011-2012 and 2012-2013 for tomato cultivation in Gazipur and Jamalpur are given in Table 4. Total irrigation applied in tomato (BARI Tomato-14) field in Jamalpur during 2010-2011 in drip and furrow methods were 249 mm and 568 mm, respectively. During the tomato growing season, 260 mm of rainfall was received in Jamalpur. Hence the water saving by drip irrigation over furrow irrigation for tomato was about 56.16%. In Gazipur irrigation applied for cultivation of tomato during 2011-2012 (BARI Tomato-14) and 2012-2013 (BARI Tomato-15) by drip and furrow methods. Irrigation waters applied by drip and furrow methods in the year 2011-2012 were 254 mm and 590 mm and in the year 2012-2013 were 335 mm and 610 mm, respectively. Water savings by drip method over furrow method in 2011-2012 and 2012-2013 were 56.95% and 45.08%, respectively. During the growing seasons of 2011-2012 total rainfall of 143 mm and in 2012-2013, 88 mm rainfall were received in Gazipur. Among the three years (2010-2011, 2011-2012 and 2012-2013) the highest irrigation water required in the year 2012-2013 due to the lowest rainfall in the year. In drip method of irrigation, average water saving was 52.72%. Sivanappan (1979) found similar results for drip and surface irrigation in tomato. It is reported by IFDC (2013) that drip of the water dissolves the nutrients slowly, without washing them away. Use of drip irrigation and fertilizer deep placement could double the yield of tomato than the traditional surface irrigation and broadcasting of fertilizer. The pictorial views of solar irrigated tomato are shown in Figure 6.

Table 4 Irrigation applied in drip and furrow irrigations methods in different years for tomato cultivation in Gazipur and Jamalpur

Methods of irrigation	2010-2011: Jamalpur (BARI Tomato-14)		2011-2012: Gazipur (BARI Tomato-14)		2012-2013: Gazipur (BARI Tomato-15)		Average water saving (%)
	Irrigation applied (mm)	Water saving (%)	Irrigation applied (mm)	Water saving (%)	Irrigation applied (mm)	Water saving (%)	
Drip	249	56.16	254	56.95	335	45.08	52.72
Furrow	568		590		610		

Solar irrigated tomato field in Gazipur

Tomato harvesting in Gazipur

Figure 6 Photographs of solar irrigated tomato in the experimental fields

3.4 Irrigation of summer tomato using solar pump

Solar pump was used for drip and furrow irrigation for summer tomato cultivation in the experimental field of FMPE division during the *kharif* season of 2011-2012. In the year 2012-2013 summer tomato was cultivated by drip irrigation. The summer tomato variety was BARI Tomato-4 and cultivated under polyethylene shed. The yield of summer tomato was found 33.73 t/ha in drip irrigated plot and 31.86 t/ha in furrow irrigated plot during the period of 2011-2012. Figure 7 shows the application of irrigation in summer tomato by drip and furrow method during 2011-2012 in Gazipur. Drip and furrow irrigation methods consumed 225 mm and 429 mm water, respectively. During the year 2012-2013, yield of drip irrigated summer tomato was 35.28 t/ha and amount of water requirement was 212 mm. Water requirement of summer tomato was lower than that of winter tomato because in summer season soil remains wet due to frequent rains.

3.5 Irrigation of wheat using solar pump

Wheat (BARI Gom-26) was cultivated in bed during 2012-2013 in Gazipur and was irrigated with furrow irrigation method. Yield and yield parameters of wheat during 2012-2013 in Gazipur is given in Table 5. For cultivation of wheat about 430 mm water was used and the yield was 3.0 t/ha.

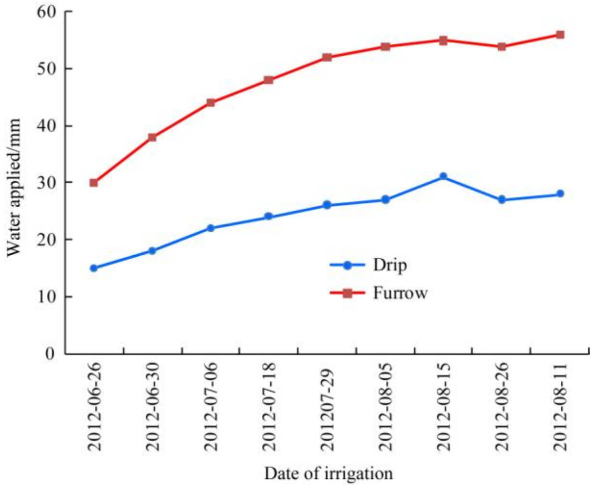

Figure 7 Irrigation applied in summer tomato field by drip and furrow methods at different days of the season in Gazipur during 2012-2013

3.6 Irrigation of boro rice using solar pump

Yield and yield contributing factors of solar irrigated boro rice cultivated in Magura and Barisal during 2011-2012 are given in Table 6. It is observed from the table that significantly higher plant height was found for *Kazol Lota* rice in Magura than BRRIdhan28 cultivated in Barisal. This variation was due to the varietal effect and may be the variations of weather conditions as well as fertility variation of soils. Larger panicles were observed for *Kazol Lota* rice than BRRI dhan28 but numbers of grains per panicle were significantly higher in BRRI dhan28 than those of *Kazol Lota* rice. Weight of 1000 grains was higher in BRRI dhan28 than *Kazol Lota* rice but their differences were insignificant. Yield of BRRI dhan28 was also found significantly higher than that of *Kazol Lota* rice. This was due to that BRRI dhan28 is a high yielding variety and *Kazol Lota* rice is local aromatic rice. These experiments were replicated in the year 2012-2013 and similar results were found (Table 7).

Table 5 Yield and yield parameters of wheat during 2012-13 in Gazipur

Variety	Plant population per m^2	Plant height (cm)	Length of panicle (cm)	Number of grain per panicle	1000 grain weight (g)	Grain yield (t/ha)
BARI Gom- 26	190.25	86.8	12.13	98.67	53.46	3.00

Table 6 Yield and yield contributing factors of solar irrigated boro rice in Magura and Barisal during 2011-12

Location	Variety	Plant height (cm)	Length of panicle (cm)	Number of grain per panicle	1000 grain weight (g)	Grain yield (t/ha)
Magura	*Kazol Lota*	96.45	26.33	98.67	20.33	2.56
Barisal	BRRI dhan28	88.00	24.21	108.33	23.43	3.24
Significance		*	ns	*	ns	*

Table 7 Yield and yield contributing factors of solar irrigated boro rice in Magura and Barisal during 2012-13

Location	Variety	Plant height (cm)	Length of panicle (cm)	Number of grain per panicle	1000 grain weight (g)	Grain yield (t/ha)
Magura	*Kazol Lota*	102.00	25.00	93.36	21.50	2.50
Barisal	BRRI dhan28	81.09	24.52	112.34	24.82	3.40
Significance		*	ns	*	ns	*

Irrigations applied at different days in rice field during *boro* season in Magura and Barisal during the period of 2011-2012 are given in Figure 8 and Figure 9, respectively. It is observed from the figures that water applied in the *boro* rice field varied with different dates. These variations were due to the variation of weather conditions as well as soil conditions. During land preparation, the water requirement was high for better puddling of soil. During the cropping season total water requirement for *boro* rice cultivation in Magura was 1,024 mm and in Barisal it was 1,481 mm. This variation was due to the type of soil and variations of weather and variety of rice. In Magura soil type was clay loam and in Barial soil type was sandy loam. On the other hand in Magura rice variety was *Kazol Lota* and in Barisal the rice variety was BRRI dhan28. During the crop season no effective rainfall was obtained in Barisal and Magura.

In *boro* rice cultivation 1,324 mm water was used in Magura and 1,252 mm of water was required in Barisal. Average irrigation was applied in *boro* rice cultivation during the *boro* season of 2012-203 was 1288 mm of water. The pictorial views of irrigated rice fields solar pump are shown in Figure 10.

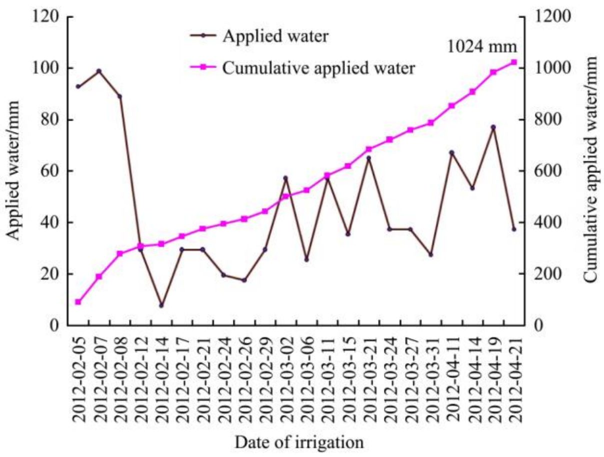

Figure 8 Irrigation applied at different days in *boro* rice field in Magura during 2011-2012

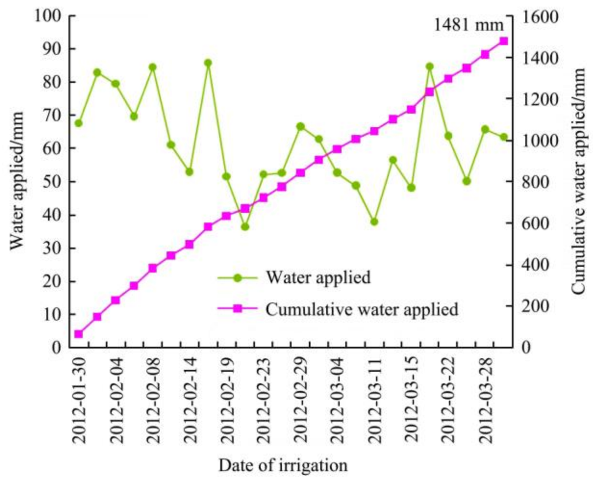

Figure 9 Irrigation applied at different days in boro rice field in Barisal during 2011-2012

Solar irrigated rice field in Barisal

Solar irrigated rice field in Magura

Figure 10 Photographs of solar irrigated rice fields in Barisal and Magura

3.7 Financial analysis of solar irrigation

Financial analyses of submersible solar pump irrigation for vegetable and cereal crops are given in Table 7. Initial cost of the submersible solar pump (Lorentz, PS1200) including installation cost was high (Tk. 450,000) but the service life is high (20 years). Fixed costs of solar pump for cultivation of all crops were same (Tk. 27900/year) but total fixed costs of different crops were different due to different of command areas. Estimated command areas of solar pump for tomato, brinjal, wheat and boro rice were 1.06, 1.40, 3.75 and 0.58 ha, respectively. Command areas for different crops were different due to different of water requirement of each crop (Figure 11).

Table 7 Financial analysis of submersible solar pump for surface irrigation of vegetable and cereal crops

Cost items	Tomato	Brinjal	Wheat	Boro rice
Initial investment/cost for pump (Taka)	450000	450000	450000	450000
Life of pump and solar panel (Year)	20	20	20	20
Depreciation (Tk/year)	20250	20250	20250	20250
Interest on investment (14%) (Tk/year)	34650	34650	34650	34650
Repair, maintenance and shelter (Tk/year)	4500	4500	4500	4500
Fixed cost for solar pump (Tk/year)	59400	59400	59400	59400
Average discharge (L/min)	100	100	100	100
Water requirement per season (mm)	610	460	430	1288
Command area (ha) at 60% irrigation efficiency (using hose pipe)	1.06	1.40	3.75	0.58
Land use cost (Tk/year)	23080	34132	43744	6944
Total fixed cost (Tk/year)	82480	93532	103144	94244
Total variable cost (input cost+ interest on operating capital) (Taka/year)	99153	86117	38664	66099
Total cost (Fixed cost + variable cost) (Tk/year)	181633	179649	141808	160343
Yield (t/ha)	38.00	30.00	3.50	4.25
Total production of crop (t)	40.28	42.00	13.13	2.47
Price at harvesting season (Tk/t)	10000	10000	25000	20000
Gross return (Tk)	402800	420000	328250	49400
Net return over variable cost (Tk)	303647	333883	289586	-16699
Net return over total cost (Tk)	22116	240351	186442	-110943
Benefit cost ratio over variable cost	4.06	4.88	8.49	0.75
Benefit cost ratio over total cost	2.22	2.34	2.31	0.31

Variables costs of all crops were calculated including input cost, operating cost and interest on operating capital. The highest gross and net returns were found for brinjal followed by tomato and wheat and the lowest gross and net returns were found for solar irrigated boro rice. Net return for solar irrigated boro rice was negative due to high invest for irrigation. The reason for high invest

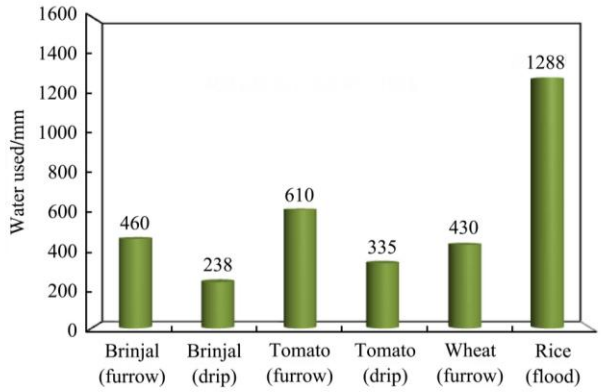

Figure 11 Water required (mm) in wheat, rice, tomato and brinjal irrigated by solar pump

was less command area and high water requirement of boro rice. The yield of tomato was higher than that of brinjal but total production of solar irrigated brinjal was higher than tomato due to higher command area. Benefit cost ratio for cultivation of solar irrigated wheat was the highest followed by brinjal and tomato. Benefit cost ratio of solar irrigated wheat over variable cost basis (8.49) was about two times higher than those of brinjal and tomato although the yield of wheat was about one tenth of brinjal or tomato. The reason was that the water requirement of wheat was lower than vegetables (tomato and brinjal) but command area and irrigation intervals of wheat were higher than vegetables. On the other hand, input cost of wheat was lower than vegetables but price of wheat was higher than vegetable at harvesting season. Beside these, wheat grains can be stored longer period for better price but vegetables must be sold just after harvesting. The benefit cost ratio of brinjal, tomato and wheat over total cost basis were 2.34, 2.22 and 2.31, respectively. So, cultivations of solar irrigated brinjal, tomato and wheat were economically profitable. For cultivation of solar irrigated *boro* rice, net margin was negative and benefit cost ratio was found less than unity (0.31). Therefore irrigation of *boro* rice by solar pump was not economically profitable. But solar pump was found technically suitable for cultivation of *boro* rice.

Financial analysis of submersible solar pump for furrow and drip irrigation of tomato and brinjal cultivation is given in Table 8. Water requirements by drip irrigation method were about 45% and 48% less furrow methods for tomato and brinjal, respectively. Therefore, command areas for drip irrigation method were higher than furrow methods. Also yield of tomato and brinjal in drip method of irrigation was slightly higher than that of furrow method. So, tomato and brinjal productions from drip irrigated plot were higher than furrow irrigated plot. Gross return and net return obtained from drip irrigated tomato and brinjal were higher than those of furrow irrigated tomato and brinjal although input costs of drip irrigation was higher than furrow irrigation. Again gross return and net return for brinjal were higher than those of tomato. The reasons were that command areas of both the drip and furrow irrigated brinjal plots were larger than tomato. And input costs of tomato were higher than brinjal cultivation. Benefit cost ratio over variable cost and total cost of drip irrigation were higher than furrow irrigation method for both tomato and brinjal. Benefit cost ratio over variable cost and total cost of drip irrigation and furrow irrigation methods for both tomato and brinjal were almost similar. Therefore, cultivation of tomato and brinjal by solar pump was economically profitable and drip irrigation was found more profitable than furrow method of irrigation.

Table 8 Financial analysis of submersible solar pump for furrow and drip irrigation of tomato and brinjal cultivation

Cost item	Tomato		Brinjal	
Initial investment/cost for pump (Tk.)	450000		450000	
Life of pump and solar panel (Year)	20		20	
Depreciation (Tk/year)	20250		20250	
Interest on investment (14%) (Tk/year)	34650		34650	
Repair, maintenance and shelter (Tk/year)	4500		4500	
Fixed cost for solar pump (Tk/year)	59400		59400	
Average discharge (L/min)	100		100	
Irrigation method	Drip	Furrow	Drip	Furrow
Water requirement per season (mm)	335	610	238	460
Command area (ha) at 60% irrigation efficiency (using hose pipe)	1.29	1.06	1.82	1.40
Land use cost (Tk/year)	28088	23080	44372	34132
Total fixed cost (Tk/year)	87488	82488	103772	93532
Total variable cost (input cost+ interest on capital) (Tk/year)	120667	99153	111952	86117
Total cost (Tk/year)	208155	181641	215724	179649
Yield (t/ha)	46.00	38.00	32.50	30.00
Total production of crop (t)	59.34	40.28	59.15	42.00
Price at harvesting season (Tk/t)	10000	10000	10000	10000
Gross return (Tk)	593400	402800	591500	420000
Net return over variable cost (Tk)	472733	303647	479548	333883
Net return over total cost (Tk)	385245	221159	375776	240351
Benefit cost ratio over variable cost	4.91	4.06	5.28	4.88
Benefit cost ratio over total cost	2.85	2.22	2.74	2.37

3.5 Carbon dioxide emissions

Carbon dioxide emission from irrigation pumps in different years in Bangladesh is shown in Figure 12. It is observed from the figure that carbon dioxide emission from irrigation pumps was increasing with the numbers of irrigation pumps. In 2000, CO_2 emission from irrigation pumps was 3.9 million tons and it was increased sharply to 8.4 million tons in 2011. Solar pump is pollution free and green irrigation pump to mitigate CO_2 emission. If these diesel or electricity powered irrigation pumps may be changed with solar pumps, Bangladesh can mitigated huge quantity of CO_2 emission each year. Therefore, solar pump may be use for irrigation of crops for sustainable green agriculture.

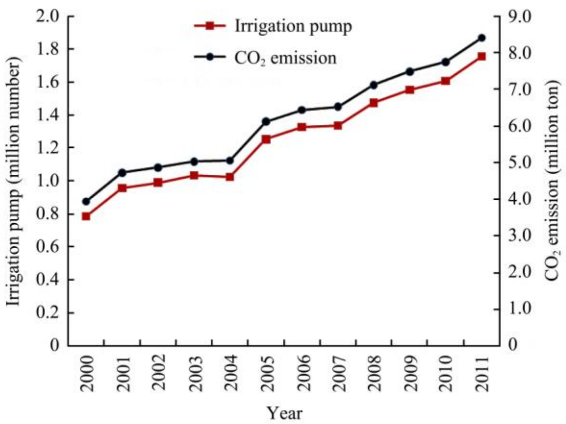

Figure 12 Carbon dioxide emissions from irrigation pumps in different years in Bangladesh

4 Conclusions

The field performance of solar pumps tested in different locations of Bangladesh for surface and groundwater lifting was found satisfactory. Solar pump was found technically suitable for irrigation in rice and non-rice crops. Drip irrigation in vegetables saved about 50% water than furrow irrigation method. Vegetables and wheat cultivation by solar pump irrigation was economically profitable. Rice cultivation by solar pump irrigation was not found economically viable under the tested situation. Diesel engine operated irrigation pump emits carbon dioxide and pollutes environment but solar pump is an environment friendly irrigation technology.

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