Climate Change-Resilient Rice Production Technology: A High Yielding, Water Efficient and Remunerative Option for South Asian Farmers

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ABSTRACT

Rice (*Oryza sativa* L.) production in South Asia is increasingly threatened by the erratic nature of onset of monsoon rain and climate change. Wide variation in rainfall pattern affects the timing of nursery raising and transplanting later in the main field. Existing rice cultivation practices such as direct seeded rice using drum seeder (DSR), system of rice intensification (SRI), and conventional transplanting (CT) are not able to address the production problems adequately. Therefore, we developed a package of practices - Climate Change-Resilient Rice Production Technology (CRRPT) - which allows keeping rice seedlings in the seedbed for an extended period to synchronize with the onset of monsoon rain. On-station trials during 2015-2016 comparing CRRPT with DSR, SRI, and CT demonstrated that in CRRPT the seedlings can be maintained successfully in the seedbed for up to 55 days while achieving the equivalent yield of CT (30 days seedling) because of improved plant vigor. The CRRPT seedlings of 25 d and 35 d gave 22% and 11% more yield compared to CT (30 d seedling). Total water requirement in CRRPT was reduced by 20%, 14% and 13% for 55d, 45d and 35d seedlings, respectively, compared to that for CT (30d). In an on-farm study with 120 farmers' fields in West Bengal during 2017-2018, average yield increased by 32% and net profit increased by 96% in CRRPT compared to CT. Thus, CRRPT is remunerative, water efficient, climate change-resilient and can be easily adopted in the farmers' fields. Results demonstrate that there is wide scope for its adoption for sustainable rice production in West Bengal and South Asia.

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1. Introduction

Food security in the world is challenged by increasing population and threatened by declining water availability under the changing climatic conditions (Bouman, Lampayan & Tuong, 2007; IPCC, 2018). Rice is the staple food of more than half of the global population (Gnanamanickam, 2009). Hence, exploring ways to increase rice production with less water is essential for increasing food security. Water-saving rice production practices like aerobic rice (Bouman et al., 2007; Humphreys et al., 2005), alternate wetting and drying - AWD (Cabangon et al., 2001; Humphreys et al., 2005), direct seeded rice - DSR (Humphreys et al., 2005), raised beds (Connor et al., 2003; Humphreys et al., 2005; Jehangir, Murray-Rust, Masih & Shimizu, 2002), a system of rice intensification - SRI (Uphoff & Randriamiharisoa, 2003), a ground-cover rice production system - GCRPS (Dittert et al., 2003), and rice-based conservation agriculture (Gathala et al., 2015; Hobbs, Sayre & Gupta, 2008), can reduce unproductive water

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outflows and increase crop water-use efficiency (WUE). However, these technologies can sometimes lead to a yield penalty with temperature rise and erratic precipitation patterns (Rahman, Kang, Nagabhatla & Macnee, 2017). In fact, there is a huge uncertainty in the onset of monsoon in South Asia. Monsoonal rain in South Asia can come early or be postponed by up to two weeks (Ashfaq et al., 2009). Such variations and uncertainties in monsoonal rain can severely affect yields of rice as well as that of succeeding winter crops, rendering farming a less profitable enterprise (Loo, Billa & Singha, 2015).

Eighteen years (1997-2015) of data by the Indian Meteorological Department (IMD) have shown delays in onset of monsoon by two to ten days each year in the Eastern Gangetic Plains of West Bengal, one of the main rice growing regions in South Asia, resulting in delays as well as difficulties in rice transplanting (Giri, Biswas & Banarjee, 2017). Oftentimes in rice fields where transplanting is a common rice establishment method, a delay in transplanting is a routine phenomenon because of postponement of monsoon by a week or two, especially in deficit irrigation and rainfed lowlands (Lampayan et al., 2015). This results in lowering the growing degree days and solar radiation (Kumar, Rao, Tripati & Venkateswarlu, 2014; Liu, Zhou, Li & Xin, 2017) and impacts rice growth and yield with poor tiller formation, a shortened vegetative period, and decreased dry matter accumulation. The adverse effect is not only in delayed rice harvest but also results in delayed sowing of winter crops which may later suffer due to terminal heat stress generally occurring from March onwards (Timsina & Connor, 2001). Further, under delayed monsoon conditions, rice seedlings may also become too old to transplant. Due to intense competition for nutrients, light and space among densely sown seedlings, they become weak and cannot be kept for a longer period in the nursery. In 2009-2010, about 23% of rainfed rice farmers in West Bengal were forced to keep their land fallow due to the late arrival of monsoon and unacceptably old rice seedlings (Khanna, 2012).

Several water-saving practices for rice production are being followed in South Asia. One among them is SRI in which 3-4-leaf single seedlings with one seedling per hill are transplanted at wider plant spacing (25cm x 25cm). In this system, intermittent irrigation and the addition of organic nutrients, intensive manual or mechanical weed control are adopted (Uphoff, 2002). Farmers usually start transplanting after the onset of monsoon under both irrigated and rainfed situations. Practical application of SRI at farmers' fields is however hardly possible on the years of delayed onset of monsoon; many times, seedlings are dislocated due to heavy showers just after transplanting. For example, in the Purulia district of West Bengal, Adhikari et al. (2019) reported that farmers who had planned to use the SRI method, reverted to the conventional method with older seedlings and higher plant density, due to the delayed monsoon. Another practice is DSR (drum seeder) in which rice is directly sown in the main field after puddling using a manually operated plastic drum seeder. This method offers some advantages over conventional transplanting, including faster and easier establishment, reduced labor and less drudgery, and often higher farmgate profit (Balasubramanian & Hill, 2002). One hectare of land can be seeded in a day by one person with a drum seeder (Hossain, Kumar & Ahmed, 2005). In this system, however, rice occupies longer duration in the main field, and hence requires a higher amount of water than the conventional method. Further, sudden heavy rainfall immediately after sowing of DSR, or after transplanting of young seedlings in SRI results in poor and uneven plant stands and lower yield.

We hypothesize that robust and healthy rice seedlings can be used under the situations of late onset of monsoon, and together with use of such seedlings, when the rice crop is treated with balanced nutrients, it uses less water and produces higher yields than the existing rice production practices. Thus, to facilitate farmer adaptation to erratic monsoonal behaviour and overcome the problem of low rice yield due to use of unhealthy and old seedlings, suitable climate change-resilient rice cultivation techniques are required. While developing such techniques, we need to tailor the entire process of raising rice seedlings by modifying the package of practices from the existing knowledge pool. Farmers used to transplant seedlings at distinct ages, mostly from 25 to 50 days after emergence (De Datta, 1981). Transplanting of young seedlings generally has a positive impact on yield, but rice productivity tends to decrease if seedlings are older than 25 days (Mandal, Sainik & Ray, 1984; Rao & Raju, 1987; Singh & Singh, 1999; Thanunathan & Sivasubramanian, 2002; Wagh, Khanvilkar & Thorat, 1988). This could be due to longer vegetative growth and significantly greater 1000-grain weight with young seedlings (Chandra & Manna, 1988). Lower tiller production from aged and weak seedlings was attributed to the extended stay of seedlings in the nursery undergoing a high competition among adjacent seedlings (Mandal et al., 1984; Pasuquin, Lafarge & Tubana, 2008). A lower density of seedings in the nursery bed provides sufficient space for optimum growth (DRR, 2011; Om, 1996; Sarwal, Maqsood, Wajid & Anwarul-Haq, 2011). Panda et al. (1991) reported that nitrogen application in rice nurseries produced healthy and vigorous seedlings and reduced seedling mortality after transplanting under rainfed lowland situations with intermediate deep water and flash floods. A supply of additional phosphate at the initial growth stage (Ros, Bell & White, 1997) also helps to sustain rice seedlings in a nursery for a prolonged period. Unlike nitrogen (N) and phosphorus (P), potassium (K) does not have a pronounced effect on tillering but plays an important role during the reproductive phase. Potassium makes the plant hardy through lignification of sclerenchyma tissues (Dobermann & Fairhurst, 2000). Omission of K application (WMRS, 2013) but application of micronutrients, particularly zinc (Zn) and boron (B), in nursery beds resulted in healthy rice seedlings (Hossain et al., 2001; Shaheed, 2002).

Studies providing an integrated assessment of factors to produce transplanting-ready robust rice seedlings that will remain in the seedbed for a longer time are generally lacking. Such studies are needed for developing a protocol in establishing robust seedlings that can be transplanted under delayed onset of monsoon under changed climatic conditions. After a series of experiments in several farmers' fields in West Bengal, India (Biswas & Patra, 2016; Biswas, 2017; WMRS 2010, 2013), we formulated a package of technology to ensure robust seedlings and increased yield under the situations of delayed onset of monsoon, and termed such a package as the Climate Change-Resilient Rice Production Technology (CRRPT). The objective of the current study was to compare the performance of CRRPT with robust seedlings of different ages with the existing and common rice production practices in terms of grain yield, water use, production cost, and net profits with a long-term goal of climate change adaptation for rice production in South Asia.

2. Materials and Methods

2.1. Study Sites

An on-station study was conducted during 2015 and 2016 at the Central Research Farm of the Bidhan Chandra Krishi Viswavidyalaya, the State Agricultural University, Gayeshpur, India ($22^{0}58^{/}$N latitude; $88^{0}31^{/}$E longitude; 9.75 m above mean sea level) in the tropical sub-humid region of eastern India. Average annual rainfall of the area is 1600 mm, 85% of which is received from late June to late September. January is the coldest month with monthly mean temperature ranging from 15.5 to 21.3^0C. The atmospheric mean temperature begins to rise towards the end of February and reaches maximum (27.6–31.7^0C) during May. The mean relative humidity remains high (82–95%) during June to October and declines to 70% in January. The annual wind speed varies from 0.6 to 6.8 km hr^{-1}. In general, the pan evaporation loss ranges from 0.8 to 1.2 mm d^{-1} during January and reaches above 6.0 mm d^{-1} during May (Figure 1). Soil of the experimental site was sandy loam, Aeric Haplaquept. Basic chemical properties of the surface (0–15 cm) soil were: pH 6.75, organic carbon 5.4 g kg^{-1}, available N, P_2O_5 and K_2O as 85, 15.3 and 40 kg ha^{-1}, respectively. Important soil physical properties of different horizons are presented in Table 1. The experimental site has the history of practicing a rice–wheat system for the three years preceding this study. Rice-wheat is a predominant system contributing to food security for a large proportion of the population in South Asia (Timsina & Connor, 2001)

Table 1. Textural status, bulk density (BD), saturated hydraulic conductivity (k_{sat}), field capacity (FC, at 0.03 MPa suction), wilting point (at 1.5 MPa suction), and total available moisture (TAM) of different horizons of the soil profile (on-station experiment), 2015-2016.

Soil layers (mm)	Textural groups (%)			BD (g cm^{-3})	k_{sat} (mm h^{-1})	FC (mm h^{-1})	WP (mm)	TAM (mm)
	Sand	Silt	Clay					
0-150	50.14a	16.23b	33.63b	1.43c	4.3a	38.29c	12.36bc	25.91a
150-300	36.32c	27.64a	36.04b	1.47c	1.9c	12.53b	12.55ab	22.34b
300-450	32.26c	24.37a	43.37a	1.52a	1.5c	13.07b	13.06a	24.33a
450-600	42.13b	24.18a	33.69b	1.49bc	2.6b	11.42b	11.40c	19.91c

Means followed by different letters within a column differed significantly at 5% level of significance.

Following the on-station study, an on-farm study was conducted for two years (2017 and 2018) in 120 farmers' fields in five districts (Bankura, Purulia, West Midnapore, East Midnapore, and Birbhum) of the Red and Lateritic region of West Bengal (Figure 2). The region (17,928 km^2) is composed of lateritic soil (formed through desilication and accumulation of sesqui oxides), red soil (red or reddish-brown color having variable thickness with or without occasional lime and iron manganese concretions in the profile) and gravelly soil. Around 20-30% of the zone is hilly slope and the ridge of Chota-Nagpur plateau. The climate is dry, tropical, humid to sub humid, with temperature index of 3.5 to 17.0, moisture index 10 to 20 (*ustic*) and growing season of 150-180 days. Rice is grown in the wet season from June to October, with long-term average annual rainfall and evaporation of 1,247 mm and 435 mm, average maximum and minimum temperatures of 32.3 ^{0}C and 25.0 ^{0}C, and average maximum and minimum relative humidity of 91% and 72%, respectively, during the crop season (SenGupta, 2001; Table 3).

2.2. On-station Study

2.2.1. Experimental Design, Treatments, and Crop Management

The on-station experiment was conducted in a randomized complete block design replicated four times with seven treatments: DSR sown with drum seeder, SRI, four CRRPT levels (25, 35, 45, and 55 days old seedlings, hereinafter referred to as CRRPT-25d, CRRPT-35d, CRRPT-45d, and CRRPT–55d), and the conventional method (30 days old seedlings). The plot size was 8m x 10m. To avoid any confounding effect, the nursery sowing date (11 June 2015 and 13 June 2016) for CRRPT, SRI and CT as well as sowing DSR in the main field was the same. Average rice growth durations in the main field were 113, 113, 105, 98, and 93 days for CT, CRRPT-25 d, CRRPT-35 d, CRRPT– 45 d, and CRRPT-55 d, respectively. In CRRPT, a basal dose of 2.5:10 g m^{-2} ($N:P_2O_5$) along with 2.5 kg m^{-2} organic matter, 0.5 g m^{-2} Zn and 0.11 g m^{-2} B was applied during the preparation of the wet nursery to produce climate change-resilient robust seedlings. Then, sprouted healthy seeds of variety MTU 7029 (135-140 days duration) were spread over beds, and N was top dressed @ 2.5 g m^{-2} at 15-day intervals. The rice nursery was maintained weed-free throughout the growth period by hand-weeding along with a thin film of water. Treatment details for different rice cultures used in the experiment are given in Table 2. Land (the main experimental field) was prepared with a rotavator followed by laddering, and puddling was done prior to transplanting. $N:P_2O_5:K_2O:Zn$ @80:40:40:2.5 kg ha^{-1} was applied in all CRRPT plots. One-fourth of N, full P, and one-half of K and full Zn were applied as basal in the main field. Of the remaining, one-half of N was applied at maximum tillering and one-fourth N and the remaining K were applied at panicle initiation. In addition, two additional sprayings @ 7g N, 4.5 g Zn and 0.1 g B per liter water at 21 DAS and at PI were also applied (Biswas, Guha Sarkar, De, Patra & Patra, 2018). Seedlings raised in a conventional nursery were transplanted @ 4 seedlings $hill^{-1}$, resembling farmers' practice, whereas only one seedling per hill was used in SRI and CRRPT. Insect and disease pressures were generally low in both years, except in conventional plots where chemical protection measures were taken against yellow stem borer (*Tryporyza incertulas* Walker) in both years and against rice bug (*Leptocoryza varicornis* Thunberg) in 2015.

2.2.2. Water Use Efficiency (WUE)

Need-based flood irrigation was given with ground water. On an average 5, 5, 3, 3, and 2 irrigations of 50 mm each were given for CT, CRRPT-25d, CRRPT-35d, CRRPT-45d and CRRPT–55d, respectively during 2015 and 2016. Two mandatory irrigations at panicle initiation and grain filling stages were applied for all treatments and the remaining irrigation was applied at the tillering stage. Water use efficiency (liters of water used kg^{-1} of grain; Bouman, 2009; Molden, Sakthivadivel, Perry, de Fracture & Kloezen, 1998) was computed as:

$$WUE = ET \text{ or crop water use (liters } ha^{-1}) / \text{yield (kg grain } ha^{-1})$$

Seasonal evapotranspiration (ET) or crop water use was estimated by considering effective rainfall, irrigation, capillary rise, deep percolation, surface runoff, change in soil water storage, pan coefficient, and crop coefficient (Allen, Pereira, Raes & Smith, 1998) as follows:

$$ET \text{ (crop water use)} = P + I + C - D - R - \Delta S$$

Where P is the effective precipitation measured during the cropping season and was measured using an automatic rain gauge installed at the experimental site. The volume of irrigation water (I) applied to each plot was measured with a Woltman® helical turbine meter fitted to a long straight section of pipe at the tube-well outlet. The capillary rise (C) from ground water table was assumed to be zero considering the existence of deep-water table (> 2.5 m). Deep percolation (D) was calculated daily from the difference in the daily decline of water level in the plots and open lysimeters (PVC pipe with 20 cm dia. and 50 cm height) embedded into the hardpan to a depth of 30 cm. Runoff (R) occurred on the heavy rainfall days and was calculated from the amount of rainfall and the difference between the height (h) of the bunds and the water depth (d) prior to the rainfall as following:

$$R\ (runoff) = Rainfall - (h - d)$$

Soil samples were collected with a soil core from soil surface to 60 cm depth at 15 cm intervals to measure soil moisture content gravimetrically. The change in soil water content (ΔS) over the season was calculated as the difference between soil water content to the depth of 60 cm before the pre-puddling irrigation (m_1) and soil water content shortly after harvest (m_2) as following:

$$\Delta S\ (\text{soil water content}) = m_2 - m_1$$

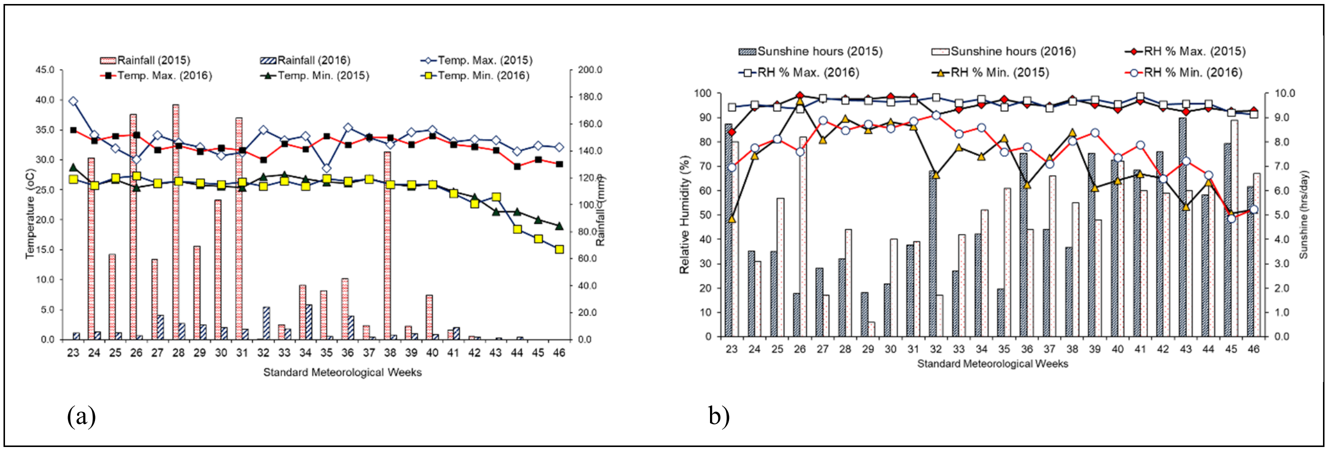
2.2.3. Grain Yield

Grain yield was estimated by hand-harvesting from 20 m^2 area in each plot at physiological maturity of the crop. Crop was cut at about 15 cm from above the soil surface. Rice grains were separated from straw manually and samples were oven-dried to constant weight at 70^0 C and grain yield was expressed at 14% moisture content. Rice residues were removed for use as fuel, resembling the predominant farmers' practice in the region.

Table 2. Standard management practices employed in on-station (2015-2016) and on-farm (2017-2018) experiments (main rice field).

	Direct seeded rice using drum seeder	**System of rice intensification**	**Climate change-resilient rice production technology (4 seedling ages)***	**Conventional***
Nursery management (for one ha main field)	Not required	10 kg seed in 100 m^2 raised bed with thoroughly mixed 300 kg FYM surrounded with bamboo slits and sprinkled water at evening and morning	10 kg seed in 1000 m^2 raised bed with thoroughly mixed 2500 kg FYM, 2.5 kg N, 10 kg P, 2.5 kg Zn and 0.I kg B surrounded with bamboo slits and sprinkled water at evening and morning along with 2.5 kg N top dressing at 15 days interval	50 kg seed in 1000 m^2 flat bed with thoroughly mixed 200 kg FYM in wet nursery
Land preparation	Three ploughings followed by planking	Three ploughings followed by planking	Three ploughings followed by planking	Three ploughings followed by planking
Sowing / transplanting	Sowing of 40 kg ha^{-1} seed with drum seeder	Placing of 8-10 days old (3-4 leaves) one seedling $hill^{-1}$ along with rhizosphere soil at 25 cm X 25 cm spacing	Seedling age as per treatment at one seedling $hill^{-1}$ at 20 cm X 15 cm spacing	Transplanting of 30 days old 3-4 seedlings $hill^{-1}$ at 20 cm X 15 cm spacing
Water management	Maintenance of 2 cm water after crop establishment	Moist soil and intermittent drying	Maintenance of 2 cm water after crop establishment	Maintenance of 2 cm water after crop establishment
Nutrient management	$N:P_2O_5:K_2O:Zn$ @ 80:40:40:2.5 kg ha^{-1} ; ¼ N+P+K+Zn as basal , ½ N at 21DAS and ¼ N at PI	10 t FYM as basal	$N:P_2O_5:K_2O:Zn$ @80:40:40:2.5 kg ha^{-1} ; ¼ N+P+K+Zn as basal , ½ N at 21DAS and ¼ N at PI, spraying of (7g N + 4.5g Zn + 0.1 g B) per liter at 21 DAS and at PI	$N:P_2O_5:K_2O:Zn$ @80:40:40:2.5 kg ha^{-1} ; ¼ N+P+K+Zn as basal , ½ N at 21 DAT and ¼ N at PI
Weed management	Butachlor 50 EC (SS) @ 1 kg ai ha^{-1} + hand weeding at 21 DAS	2 weedings with rotary weeder at 10-day intervals from 20 DAT, entire weed biomass is incorporated in the field itself	2 weedings with rotary weeder at 10-day intervals from 20 DAT, entire weed biomass is incorporated in the field itself	Butachlor @ 2 kg ai ha^{-1} + hand weeding at 21 DAT

*Treatments for on-farm experiment (see Table 5 for management indicators for on-farm experiments).



(a) b)

Figure 1. Meteorological data on (a) temperature and rainfall and (b) relative humidity and sunshine hours during the two years of on-station experimentation, 2015-2016.

Table 3. Average weather across the study region during rice growing season at on-farm experimental sites in West Bengal, India, 2017-2018.

Month	Maximum Temperature (ºC)		Minimum Temperature (ºC)		Maximum Relative Humidity (%)		Minimum Relative Humidity (%)		Sunshine hour		Rainfall (mm)		Evaporation (mm)	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
June	36	36	26	26	76	91	75	52	10.6	9.5	123	70	195	92
July	32	33	25	26	80	94	72	56	7.5	6.1	719	639	115	98
August	32	32	26	26	81	92	72	58	8.9	6.3	437	618	137	95
September	34	33	26	25	81	93	72	64	8.1	6.3	257	168	117	96
October	32	33	23	21	74	86	73	53	8.7	8.2	151	28	97	94
November	29	31	16	17	68	75	56	44	8.2	9.0	3	9	51	93

2.3. On-farm Study

An on-farm study was conducted to validate the results of CRRPT in farmers' fields of five districts of West Bengal for two years. Input support for both CRRPT and conventional practices was provided to 15,000 farmers in the above districts through district government extension agencies. Not all farmers compared both methods; some farmers used only CRRPT and some only the conventional method. For the on-farm study, of all farmers, only 120 farmers (24 from each district) were randomly selected representing various farmers' types and only those who conducted trials using both CRRPT and the conventional method. Date of seed sowing in farmers' fields ranged from 29 May to 26 June in 2017 and from 13 to 30 June in 2018. Average seedling age for CRRPT was 39 days (ranging from 21 to 49 days) and 31 days (ranging from 21 to 38 days) during 2017 and 2018, respectively. Insect and disease pressures were generally low in both years in CRRPT plots in most of the on-farm trial locations. However, infestation of yellow stem borer (*Tryporyza incertulas* Walker) and rice bug (*Leptocoryza varicornis* Thunberg), and incidence of sheath blight (ShB) (*Rhizoctonia solani* Kühn AG 1A) and rice blast (*Pyricularia oryzae* Cav.) reached the economic threshold level in conventional plots during both years and hence chemical protection was needed. Need-based irrigation was applied similar to that for the on-station experiment. Selected management indicators for conventional and CRRPT seedling treatments are shown in Table 5.

2.3.1. Yield, Yield Components, and Economics

Density of panicles m^{-2}, abortive tillers m^{-2}, filled grains panicle^{-1}, grain filling percentage, and grain yield from each experimental unit were recorded at physiological maturity. Procedure for sampling and sample processing followed similarly to that for the on-station experiment. Prevailing prices of different crop management inputs and yield output during the period of the on-farm study were used for calculation of production costs and values of the produce or returns. These prices were assumed to be stable during the experimental period. The market prices were assumed to be a reliable reflection of opportunity costs, irrespective of ownership (e.g., in case of land and tractors) and facilitated the cropping system comparison. The Directorate of Agriculture, Government of West Bengal (Anonymous, 2014) has surveyed costs for, and returns from, different crops at different locations within the state and set crop-specific and location-specific input use and expected yields. Hence, we calculated the cost of production based on these standards. Production cost under different rice cultures was calculated separately before harvesting. The cost for harvesting and processing depended on the grain yield. Therefore, harvesting and processing cost per unit yield was calculated using mean yields for different treatments in combination with the published standard costs for harvesting and processing of rice (Biswas, Ghosh, Dasgupta, Trivedi, Timsina & Dobermann, 2006). Net returns or profit was calculated by subtracting production cost from the gross value of the produce, including by-product value or gross return. The benefit-to-cost ratio (BCR) was calculated by dividing the net returns by the production cost for different treatments. Missing values were substituted with the corresponding average for the locality.

2.4. Statistical Analysis

Statistical analyses of data were performed using an analysis of variance (ANOVA) for randomized complete block design for the on-station study and t test for the on-farm study with IRRISTAT statistical software (Gomez & Gomez, 1984).

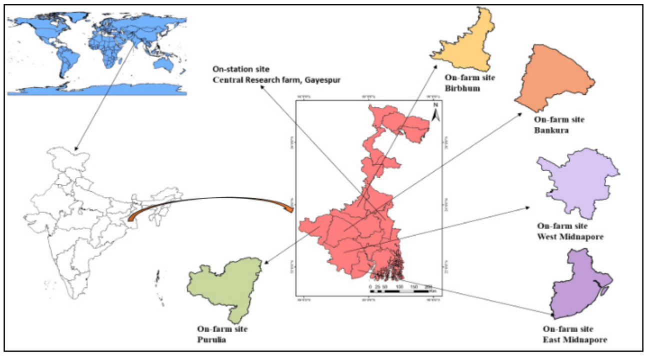


Figure 2: Experimental sites for the on-farm study in West Bengal, India, 2017-2018.

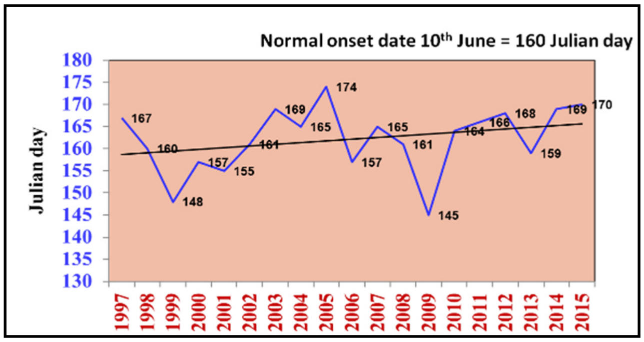


Figure 3: Onset of monsoon in the Eastern Indo-Gangetic Plains of West Bengal, India (Giri et el., 2017).

3. Results and Discussion

3.1. On-station Study

3.1.1. Grain Yield

Grain yields varied with different management practices. Grain yields in CRRPT-25d (6.17 t ha^{-1}) and SRI (5.85 t ha^{-1}) were greater than in conventional (5.14 t ha^{-1}) and CRRPT-45d (5.32 t ha^{-1}). However, yield performance of DSR drum seeder (5.46 t ha^{-1}) was similar to SRI. Rice yield did not suffer with seedlings of 45 or 55 days old grown with CRRPT while its yield increased by 22% and 11%, respectively, with CRRPT-25d and CRRPT-35d compared to that in the conventional method (Table 4). The main aim of using CRRPT seedlings was to exploit early vigor of the plant through balanced nutrition, which would be beneficial for rice growth and productivity in both normal and aberrant monsoon years. Transplanting younger seedlings during normal years promotes early tiller emergence, enhances linear dry matter accumulation, and produces effective tillers with higher grain filling efficiency (Vishwakarma, et al., 2016). Aged seedlings under CT, on the other hand, faces severe competition for light, space, and nutrients, especially N. Application of N at 15-day intervals accompanied by lower seed rate, high organic matter application, and balanced fertilizer application in the seedbed allowed the CRRPT seedlings to stay usable for transplanting for longer duration (Patra, Ray, Das, Halder, Hembram & Majumder, 2014). Our results demonstrated that CRRPT with varying seedling ages with their robust characteristics are climate change-resilient and provide the elasticity of the transplanting period without reducing rice yield.

3.1.2. Water Use

Water use was highest in DSR drum seeder (2,383 l water kg^{-1} of grain) followed by SRI (2,087 l water kg^{-1} of grain) and conventional (2,011 l water kg^{-1} of grain). The CRRPT-35d to CRRPT-55 seedlings proved to be the most water efficient rice cultivation techniques utilizing 1,601-1,729 l of water to produce one kg rice. The lower water requirement kg^{-1} grain yield in CRRPT-35d to CRRPT-55d compared to CRRPT-15d to CRRPT-25d is attributed to the longer duration of seedlings in the nursery and shorter duration in the main field. In case of CRRPT-55d, seedlings remain in nursery up to 55 days and its main field duration can be reduced by around 25 days as compared to conventional transplanting with 30 days old seedling. The reduced water requirement for CRRPT compared to existing production or water management practices is attributed to the reduced nursery area (only 10% of the main field) coupled with the reduced duration of the crop in the main field.

More than 80% of annual precipitation in South Asia occurs during monsoon season; most precipitation events are too erratic and unpredictable. The number of rainy days in the West Bengal state during the rainy season has been decreased gradually from 60 days in 2003 to 36 days in 2010 (Barman, Saha, Kundu & Mahapatra, 2012) with an average monsoon span of 121 days (June 13-October 12). Recent data also shows a slight shift in the onset of monsoon and reduction of monsoon period (Giri et al., 2017; Mishra, 2006) (Figure 3). The yield and water use data provide a greater window for transplanting from 25 to 55 days old seedlings raised with CRRPT without reducing yield, or even getting a yield advantage over the conventional method. This is mainly due to robust seedlings grown with wider spacing (Lampayan et al., 2015), appropriate nutrient management (Sarangi et al., 2016; Vandamme, Wissuwa, Rose, Ahouanton & Saito, 2016; WMRS, 2010), and transplanting of single seedling hill^{-1} (Uphoff & Randriamiharisoa, 2003) for proper growth and development of rice.

Rice transplanting with CRRPT in the main field can be delayed even until 10 August, which is about three weeks later than the conventional method generally followed in the area. An additional key management indicator of CRRPT is the use of higher amounts of organic matter, phosphorus, zinc, and boron. Organic matter supplies various nutrients to seedlings; keeps the seed bed soft which facilitates easy uprooting of seedlings for transplanting; and maintains soil microclimate favorable for both microbe and seedling growth (Lal, 2004a,b; Pan, 2013). Phosphorus promotes profuse rooting of rice through storing, transferring, and bonding of energy molecules in plant cells (Newman & Andrews, 1973, Morgan & Connolly, 2013). Zinc is essential for chlorophyll production and helps to maintain the turgidity of the cell (Ishimaru, Bashir & Nishizawa, 2011; Nable & Webb, 1993) and its deficiency is prevalent in South Asia (Akhtar, 2013). High energy seedling growth with a high rate of boron helps with efficient cell division in the plant, resulting in improved plant growth (Rehman et al., 2018). Thus, integrated and balanced use of nutrients in CRRPT improves seedling vigor and overall seedling health. This is the key component of climate resilience where robust seedlings grown under wider spacing in the seed bed can wait for prolonged periods for transplanting.

Table 4. Rice yield and water use efficiency across various rice management practices in the on-station field study in West Bengal, India, 2015-2016.

Treatments	Yield (t ha^{-1})			Water use efficiency (l of water kg^{-1} of grain)		
	2015	2016	Mean	2015	2016	Mean
Direct seeded rice using drum seeder	5.13cd	5.80ab	5.46bcd	2238a	2528a	2383a
System of rice intensification	5.66b	6.04a	5.85ab	2019ab	2155b	2087b
CRRPT-25d	6.19a	6.14a	6.17a	1936b	1920cd	1928bc
CRRPT-35d	5.36bc	5.89ab	5.63bc	1665c	1829de	1747cd
CRRPT-45d	5.15cd	5.49c	5.32cd	1674c	1784ef	1729cd
CRRPT-55d	4.78d	4.85d	4.82e	1598c	1622f	1610d
Conventional	5.00cd	5.14cd	5.07de	1983b	2039bc	2011b

Means followed by different letters within a column differed significantly at 5% level of significance.

3.2. On-farm Study

3.2.1. Yield and Yield Components

Yield response to CRRPT in the on-farm study was similar to that in the on-station study as stated above. Averaged across locations, grain yield in CRRPT increased ~24% compared to that in the conventional method (Table 4). Grain yield increased from 4.22 t ha^{-1} with 55 days old seedlings to 6.07 t ha^{-1} with 25 days old seedlings under CRRPT (Table 6). Also, the grain yield with 30-day old seedlings under the conventional method was similar to that using 55 days old seedlings raised under CRRPT (Table 6), suggesting that the oldest seedlings under CRRPT performed similar to the conventional method and there was no yield penalty. Significant yield increase in CRRPT-25d compared to the conventional method may be attributed to higher panicles m^{-2}, lower abortive tillers m^{-2} (12 in CRRPT versus 34 in conventional) and higher grain-filling duration. This may be due to the "crowding" effect (Laulanie, 1993) in the conventional method. Better synchronization of phyllochron (periodicity in plant growth expressed as a number of days) and phytomer (a unit of plant growth that consists of a node associated with a leaf and a subtending internode which has a tiller bud at its base) in CRRPT may be the main cause of higher grain yield (Nemoto, Morita & Baba, 1995). Seedling vigor is an important contributor to subsequent tillering quality and resulting grain yield (TeKrony & Egli, 1991). In our study, we demonstrated that the robust seedling health and absence of intra-plant competition resulted in a larger number of filled grains and higher grain filling percentage in CRRPT over the conventional method (Table 6). These findings indicate that seedlings can be kept successfully for up to 55 days in the nursery under CRRPT without reducing yield in comparison to the standard conventional method. This highlights the applicability of robust seedlings with CRRPT for climate resilience in rainfed rice cultivation, especially in the case of delayed onset of monsoon in South Asia.

Table 5. Selected rice management indicators with respect to climate change-resilient rice production technology (CRRPT) and conventional plots in the on-farm study in West Bengal, India, 2017-2018.

	Conventional	CRRPT*
Seed rate (g m^{-2}) in seedbed	50	10
Nutrient management in seedbed (g m^{-2})		
Farm yard manure	500	2500
Nitrogen	2.5	2.5
Phosphate	0	10
Zinc	0	0.9
Boron	0	0.1
N top dressing at 15 days interval in seedbed	0	2.5
Spraying of (7g N + 4.5g Zn + 0.1 g B) per liter	0	Twice at 21 DAS and at PI
Transplanting window (main field)	Up to 15h July	Up to 10 August
Labor for seed uprooting and transplanting (8 h day ha^{-1}) in main field	37	30
Plant protection chemical (l ha^{-1}) in main field	3.65	1.0
Labor for harvesting and post-harvest operations (8 h day ha^{-1})	75	91

*For all age group seedlings.

3.2.2. Profitability of CRRPT System

Rice grown with CRRPT required lower costs and resulted in higher gross and net revenue than the conventional method (Table 7). Compared to the conventional plots, CRRPT rice resulted in a net profit of US $227 ha^{-1}, which is comprised of a ''yield effect'' of $223 ha^{-1} and a ''cost-saving effect'' of $3 (Table 7). Among the components of cost effect (pooled over the locations and years), saving on plant protection chemicals was the highest ($28 ha^{-1}) followed by labor for seedling uprooting and transplanting ($20 ha^{-1}) and seed cost ($20 ha^{-1}). However, CRRPT incurred $65 ha^{-1} more expenditure for labor used for harvesting and processing because of higher yield and hence more labor and time required for those operations in CRRPT. Because chemical protection against insect pests and pathogens was needed in the study area, the cost of spraying four times in the main field increased the cost of cultivation under the conventional method. The additional cost of farm-yard manure and chemical fertilizer, which is highly subsidized in South Asia and particularly in India, for the small nursery area in CRRPT was about the same as the additional cost of spraying plant protection chemicals in the conventional method. Weeding for CRRPT rice fields, except for the CRRPT-25d treatment, was less costly than weeding in the main field under the conventional method. Compared to the conventional method plots, the CRRPT plots achieved a higher return to production cost, lower production cost kg^{-1} grain, and higher benefit-to-cost ratio (Table 7).

Table 6. Yield components and yield of rice in the on-farm CRRPT and conventional plots in West Bengal, India (n=120), 2017-2018.

Treatments	Panicles m^{-2*}	Abortive tillers m^{-2*}	Filled grains panicle^{-1*}	Grain filling %*	Yield (t ha^{-1})		
					2017	2018	Average
CRRPT-25d	339a	10c	87a	91a	6.01a	6.13a	6.07a
CRRPT-35d	327a	11c	85a	89a	5.70b	5.79b	5.75b
CRRPT-45d	320a	13b	82b	85b	5.42c	5.26c	5.34c
CRRPT-55d	290b	14b	74c	83b	4.36d	4.29d	4.33d
Conventional	257c	34a	60d	76c	4.26d	4.18d	4.22d

Means followed by different letters within a column differ significantly at 5% level of significance.

Table 7: Economic returns from on-farm CRRPT and conventional plots in West Bengal, India (n=120), 2017-2018.

	2017		2018		Mean	
	Conventional	CRRPT	Conventional	CRRPT	Conventional	CRRPT
A. Gross revenue (grain and straw, US$ ha-1)	714a	908b	698c	950d	706e	929f
B. Total cost (US$ ha-1)a	472a	461b	470c	474d	471e	467f
Seed cost (US$ ha-1)	26a	6b	26c	6d	26e	6f
Labour for seedling uprooting and transplanting (US$ ha-1)	107a	87b	107c	87d	107e	87f
Labour for harvesting and processing (US$ ha-1)	208a	265b	204c	277d	206e	271f
Plant protection chemical (US$ ha-1)	36a	9b	39c	9d	38e	9f
C. Net revenue (A-B, US$ ha-1)	242a	447b	229c	477d	235e	462f
Benefit: cost ratio (A/B)	0.51a	0.97b	0.49c	1.01d	0.50e	0.99f

Means followed by different letters within a column differ significantly at 5% level of significance.

[a] Production cost includes nursery management, land preparation and crop establishment; fertilizer; plant protection; irrigation; harvesting; land rent and interest.

* 1 US $ = IRs 69.00.

4. Conclusion

The results of this study demonstrated that the CRRPT method required lower seed rate, labor, plant protection chemicals, and irrigation water, and resulted in higher yield and increased net income in comparison to the existing rice production practices. Significant yield increases and water savings were markedly demonstrated through the on-station study. The beneficial results from CRRPT from the on-station study were further validated with results from the on-farm study in 120 farmers' fields. The increased grain yield and water savings resulted in higher water productivity with CRRPT compared to the conventional rice production system. The combination of a significant positive yield effect and marginal cost-saving effect rendered the CRRPT technology adoption worthwhile while the technology showed stable productivity in the changing climate via greater elasticity in the rice transplantation window during the erratic monsoon events. The primary driver for farmer adoption of CRRPT, however, will not just be water savings or natural resource conservation but more importantly the consistent monetary gains, as observed across all study sites in our study. Water savings are only a potential added benefit as an offshoot of CRRPT. Appreciable advantages of CRRPT are the flexibility in the transplanting window due to climate resiliency and the increased farm profitability.

The study also revealed that the farmers need no additional machinery to implement CRRPT and the risk of crop failure is lower than in the conventional system of production. Farmers are encouraged to grow green manuring crops such as *dhaincha* (*Sesbania aculeata* L.), black gram (*Vigna mungo* L.), etc. with pre-monsoon showers after the harvest of the winter crop or before rice transplanting for soil fertility improvement. This, however, requires evaluation of various green-manuring crops across various locations in South Asia for their regional suitability.

Finally, this study demonstrated that CRRPT can be a remunerative option for large number of farmers across West Bengal, India. However, considering the low input cost, no requirement for additional machinery to implement, and an easier technology to practice, CRRPT can be recommended for its wider adoption across other rice-producing states in India and other rice-producing countries in South Asia. Our results demonstrate that CRRPT can be one of the promising technologies for rice production in the face of global climate change in South Asia.

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