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Review Article

Cultivation of Rice: Evolving towards Climate-Smart Crops for Precision in Resource Use Efficiency

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Abstract

Rice cultivation is one of the important economic activities of farmers, and it has been the backbone of livelihood opportunities for several farmers in certain areas. However, due to the limited availability of freshwater and the progressive decline in the share of water for agriculture (because of water pollution, reducing water table, inefficient irrigation systems, and increasing demands of water for domestic, industrial and other usages) cultivation of rice by transplanting cannot be sustained. The water-guzzling nature of transplanted rice (TPR) is facing the challenges of water scarcity, posing threats to continued rice cultivation. Moreover, repeated puddling for TPR adversely affects soil physical properties, deteriorates the performance of succeeding crops, and contributes to methane gas emissions. A grim water scenario in agriculture together with the highly inefficient rice production technologies, currently adopted by a majority of farmers globally, warrants the exploration of alternative rice production practices. Therefore, the need of the day is to use less water for irrigation while maintaining the crop yield (as well as the quality of the produce) for better water-productivity towards the concept of '*Per Drop More Crop*'. Direct-sown rice (DSR) is an emerging resource-conserving, climate-smart alternative to TPR. DSR is gaining popularity because of its low input cost and resource-conserving nature. It offers the advantages like saving irrigation water, lower labor requirements, less drudgery, early crop maturity, higher economic returns, and reduced methane emission. The need of conserving natural resources, particularly water, for better ecological balance has become one of the priorities for saving life on the earth. Producing food/feed/fodder in an environment-friendly manner by adopting agricultural practices that do not over-exploit the natural resources and harm agroecological conditions is necessary for maximum ecological efficiency.

Introduction

Rice (*Oryza sativa* L.) is one of the most important food crops grown widely over 161 million hectares in more than 100 countries the world over [1]. Being a major source of food, it meets the calorie requirement of almost 70% of Asians [2, 3]. An additional 116 million tons of rice would be needed by 2035 to feed the burgeoning global population. The possibility of expanding the area under rice cultivation is limited. Therefore, the extra rice production has to come from the continuously diminishing cultivable lands with possible gain in productivity under the threats imposed by climate change [4]. Increasing food production with minimal adverse impacts on the natural resources/environment is the greatest challenge for global food security [5]. Moreover, ensuring healthy/nutritious diets for every individual would be another challenging task [6, 7]. Hence, for food and nutritional security in the rice-growing areas, it is essential to make consistent efforts to develop innovative rice production systems that are environmental friendly with better resource use efficiency and higher net income.

Rice is commonly grown by transplanting 20 to 25 day-old seedlings into the puddled soil with continuous irrigation, particularly by flooding. Late transplantation of rice is badly affected by erratic monsoon leading to yield losses of up to 30% [8]. Conventional rice cultivation through puddling aimed at higher yields with the help of increased inputs (like fertilizers, irrigation, and other agrochemicals) and maximizing the use of natural resources. However, it uses a major portion of irrigation water (much of which is lost due to surface evaporation and percolation) resulting in the limited availability of water for other crops and reduced groundwater table [9]. Moreover, continuous/extensive cultivation of TPR adversely affects the subsequent crops because of the negative impacts (breaking of capillary pores, destruction of soil aggregates, dispersed fine clay particles) on physical properties (poor structure, sub-optimal permeability, and compaction) of soil [10, 11]. Puddling, transplanting, and continuous flood-irrigation of rice in the traditional way of its cultivation requires higher water and labor inputs, both of which are becoming increasingly scarce and expensive, making rice cultivation less profitable. Furthermore, TPR is one of the major sources of greenhouse gas (GHG) emissions in agricultural production systems, and it has been estimated that rice/paddy contributes 11% of global total anthropogenic CH_4 emissions [12].

These limitations of TPR necessitate searching for alternative management approaches to enhance water productivity in the rice production system. The major challenges are to achieve this with lesser water, labor, and agrochemical inputs. Dry/direct-sown rice (DSR) is such an alternative, which require low inputs and provide comparable yield. It offers an exciting opportunity to improve water productivity and environmental sustainability. However, controlling weeds in DSR would be a major challenge if we shift toward large-scale adoption of DSR [13]. Micronutrient (particularly Zn and Fe) deficiency due to imbalanced N fertilization and higher infiltration rate is another constraint in DSR [14]. Nonetheless, DSR can be adopted as an alternative to TPR by selecting short-duration cultivars, water/irrigation management, integrated micronutrient management, effective weed management, using conservation agriculture practices. Thus, DSR holds the potential and it is a feasible alternative to conventional TPR in the current context of shortage of water and GHG emission [15].

Food, Feed and Fodder for Burgeoning Global Populations

The global human population is expected to exceed 7 billion by 2050, which would certainly pose the challenges of sustainably feeding the burgeoning global population. To feed the ever-growing human population, we need to produce more food and livelihood opportunities from the diminishing availability of arable land and water [16]. The diverse nature of food requirements needs to produce more feed and fodder also for animal husbandry, fishery, piggery, poultry, etc. to feed the growing global populations. These are only the preliminary challenges; the more important challenges of the day would be to produce them safely and sustainably. The changing global climate affects the productivity and quality of the produce due to the environmental variations, which create issues for the availability and quality of food/feed/fodder [17].

One of the challenges in producing more food, feed and fodder is the limited availability of freshwater for domestic, agricultural, animal husbandry, and other uses. The major factors that limit water availability include the unpredictable, reduced rainfall, increased temperature/evaporation, and water runoff without recharging the groundwater level. Scarcity as well as excessive water, both causes damage not only to crops but also to other species; hence, the need of the day is to plan and manage even distribution of water throughout the year. Currently, 70% of freshwater is used for agricultural purposes, but it is declining continuously. However, certain crops like rice use more water for irrigation compared to the other crops. Therefore, it would be necessary to minimize the loss of irrigation water and save it not only for the cultivation of food crops but also for growing feeds and fodders to produce *More Crop Per Drop* of water. Growing rice by dry/direct sowing, instead of transplanting, would be an essential alternative.

Direct-sown rice

DSR is one of the viable options for saving natural resources for future generations by reducing the unproductive losses of water, minimizing labor input and emission of GHG [15]. Constraints of labor at the peak of cultural practices and higher cost of cultivation of rice can be redressed by adopting DSR. The available weed management technologies, modern herbicides, and escalating labor costs are encouraging/compelling farmers to adopt DSR [18]. Some of the rice cultivars are being identified as better performers under varying agroclimatic conditions prevailing in different parts of the world, particularly under DSR environments. Though a wealth of information is available about rice, we need more information about the genes/pathways responsible for the genetic plasticity of rice for adaptation to the varying agroclimatic conditions observed under DSR. Hence, intensive studies would be required towards the development of better cultivars for DSR to cope up with the emerging challenges of rice cultivation. Larger areas in the states of Assam, Bihar, Eastern M.P., Orissa, Eastern U.P. and West Bengal in India are dry, unbunded, and rain-fed; hence, DSR is a common practice in these areas. Reduced water inputs (11–18%) and increased water productivity of rice under DSR were reported earlier [19]. Malik et al. [20] proposed that DSR can produce a similar yield to that of TPR provided with effective weed management.

Drivers for Adoption of DSR

Water Scarcity

Water is becoming an increasingly scarce natural resource. Availability of water for irrigation is increasingly facing competition with its usage in other non-agriculture sectors. Although the conventional rice cultivation system is a major freshwater user, its water productivity is very less compared to that of other crops. TPR accounts for 50% of total irrigation water used in Asia [21], which is 24–30% of total freshwater used at the world level [22]. In a conventional way of rice production, it is estimated that about 5000 litres of water is required to produce one kilogram of rice which is considerably higher than the water required for other cereals [23]. The limited availability of water for agriculture and increasing competition for its usage for domestic and industrial purposes affect the sustainability of irrigated rice cultivation. Hence, improving the water use efficiency of crops, enhancing agricultural water productivity, and ensuring the availability of water for other crops are necessary for ecological integrity. DSR is one of the potential alternatives to improve water use efficiency and water productivity.

Shortage of Labor

Conventional rice cultivation (TPR) is highly labor-intensive. Starting from land preparation (puddling), transplanting, and other related activities require a large number of labors, about 25–50 man-days per hectare. In addition, the drudgery leading to many occupational hazards and involvement of women as labor are some serious concerns [24]. Moreover, the rapid economic transformation has triggered the shifting of labor or agricultural workforce from agriculture to the growing industrial sector, resulting in reduced labor availability for agriculture [25]. According to National Sample Survey (NSS) and Periodic Labor Force Survey report (2018-19), the contribution of the agricultural sector to employment in India has declined to 58% per cent in 2018. Furthermore, the increasing labor scarcity and higher wages for labor have significantly increased the cost of cultivation of TPR and thus decreased profitability. However, shifting to a resource-conserving and smarter technique for rice cultivation known as DSR results in 10-25% more savings compared to TPR [25, 26].

Adverse Effects of Puddling/TPR on the Physical Properties of Soil

Puddling, an essential component of TPR, results in the breakdown of soil aggregates, destruction of macropores, and formation of a hardpan at a shallow depth of the field. Puddling has several advantages for TPR like weed control, reduced percolation loss of water/nutrients, the quick establishment of seedlings, and improved nutrient availability. However, besides these advantages, puddling leads to disturbed physical properties of soil and detrimental effects on the subsequent crop [10, 27, 28]. These are some of the reasons for increased interest in shifting from TPR to DSR especially in those regions where water is becoming scarce and another crop is taken immediately after rice [8, 29].

Emission of Greenhouse Gases

Greenhouse gases are one of the major culprits for global warming and the global climate changes being experienced, which seriously affect the ecological balance and might disturb the ecological integrity in future. TPR with flooded irrigation has a significant impact on global-warming potential primarily through the emission of methane (CH_4) which accounts for 10-20% (50-100 Tg every year) of the total global annual CH_4 emission [30]. Hence, the cultivation practices of rice are one of the important targets for mitigating GHG emissions [31]. As per the estimation of the Intergovernmental Panel on Climate Change, TPR is one of the leading global agricultural sources of the emissions of anthropogenic methane because of prolonged flooding, and the resulting anaerobic conditions. The anaerobic conditions are a prerequisite for the activities of methanogenic bacteria and methane production. Methane emission starts at the redox potential of soil below -150 mV and is stimulated at less than -200 mV. The aerobic conditions observed in the DSR field are responsible for lower CH_4 emissions, especially during the early stage of crop growth. Other GHGs reported to be emitted from rice fields include carbon dioxide and nitrous oxide [32]. Therefore, to minimize the emission of GHGs it becomes necessary either to stop the cultivation of rice or to reduce the areas under rice. However, in view of global food security, rice cultivation cannot be abandoned. Hence, it would be prudent to shift to DSR cultivation and minimize the area under TPR.

Benefits of DSR

The benefits of adopting DSR include saving irrigation water for other crops, minimizing input costs (cost of irrigation and labor), and maximizing water-productivity. An additional benefit of DSR comes from better carbon credits over TPR by mitigating GHG emissions [33]. Wassmann et al. [31] reported less methane emission from DSR filed compared to that from TPR. Because of the threats of global warming, switching to DSR would be a viable option for ecological integrity [34]. Better seedling vigor of Nagina-22 (an abiotic stress tolerant cultivar) with more number of surviving seedlings compared to that of the IR-64 (a high yielding rice cultivar) was reported when grown by dry/direct-sowing [34]. We observed visible differences in the root system architecture of direct-sown and transplanted rice plants. A more efficient root system with 32% increased root length of Nagina-22 compared to that of IR-64 plants was observed when they were grown by direct-sowing (Figure 1). Further, under DSR conditions the root surface area was higher in Nagina-22. The vigorous growth of roots of Nagina-22 grown by direct-sowing with more number of root tips and larger root volume can be linked with the better performance of high-yielding lowland-adapted cultivars. Therefore, in addition to deeper roots, a larger surface area would be beneficial to improve nutrients and water uptake efficiencies, especially during reproductive growth. Roots also play an important role in cytokinin synthesis. Cytokinin synthesis is enhanced in plants with a well-developed root system or when the physiological activity of roots is high. Root architectural plasticity would be one of the important characteristics required for rice cultivars suitable for variable environmental conditions under DSR.

Desirable Traits for a DSR Cultivar

Rice being a water-loving plant, its cultivation under DSR conditions faces several abiotic and biotic stresses. Water deficiency, particularly at germination, affects early seedling vigor as well as stand establishment; hence, the genotype/landrace/cultivar selected for DSR must have good seedling vigor for optimum stand establishment. DSR is mostly grown in rain-fed areas where intermittent drought is a common situation; therefore, drought tolerance in a DSR cultivar would be the most desirable trait. Moreover, deficiency of micronutrients, observed in DSR, also requires a better root architecture for efficient nutrient and water uptake from soil. Lodging of the crop is generally observed in the case of DSR, mainly because of shallow seeding and loose/less compact soil [35]. A cultivar suitable for DSR must be lodging resistant, dwarf, having a thicker stem, higher lignin content, thicker sclerenchyma, and more vascular bundles in the stem. In addition, a genotype possessing resistance to multiple biotic stress and tolerance to various abiotic stresses would be more suitable for DSR. Considering the advantages of DSR and the requirements of a suitable cultivar, the need of the day is to breed for the varieties harboring genes for several qualitative/quantitative traits. Hence, identification of QTLs, candidate genes, and molecular markers for DSR-associated traits might help develop rice varieties for dry/direct-sowing [36]. Modern tools and techniques of molecular biology such as RNAi [37] and epigenome editing [38], in addition to the conventional physiological and genetic approaches, might help further improve/develop a better performing cultivar for DSR.

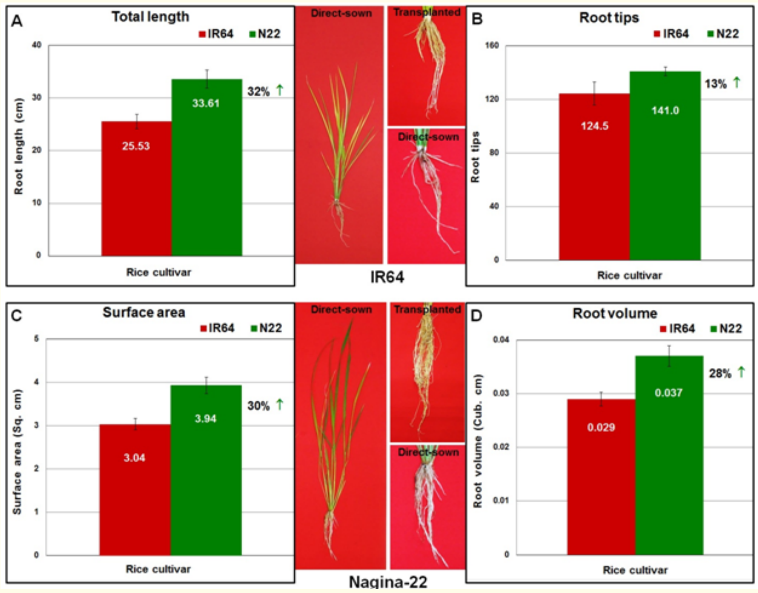

Figure 1: The characteristic feature of roots of contrasting rice (Nagina-22 and IR-64) cultivars grown by direct-sowing (and transplanting), and their effects on plant growth and development.

Problems Associated with DSR

DSR has several potential benefits not only for the farmers but also for the environment. However, it is also important to understand and predict possible risks associated with the direct sowing of rice. The relative abundance of weeds is one of the major constraints of DSR [13, 39, 40] which considerably affects the crop yield. Weed management in DSR is comparatively more challenging than in TPR mainly because of the competitive nature of weeds (which gets suppressed due to puddling in TPR) [13, 41, 42]. Therefore, it is important to adopt integrated weed management (IWM) strategies in DSR to obtain comparable yields. Adoption of DSR requires herbicide-based weed control [43] to minimize the cost of production, especially for labor. Hence, it would be desirable to develop newer herbicides effective against a wide range of weeds. The development of herbicide resistance in the weeds due to improper use/application of herbicides is another important concern. The adoption of DSR in many South-East Asian countries has resulted in serious problems of controlling specific weeds like weedy-rice, a dominant weed species representing a major threat to rice production [13, 44-47].

Micronutrient deficiency is another important concern of adopting DSR cultivation [34]. Nutrient uptake and their use-efficiency by plants are reduced because of the limited availability of water in the soil. Therefore, integrated nutrient management (INM) becomes essential while adopting DSR. Increased pH, higher carbonate and bicarbonate in a calcareous soil under aerobic conditions affect the Zn availability to DSR. Similarly, Fe availability also becomes limited in DSR, especially when soil pH goes high. Infestation of insect pests (particularly root-knot nematode, planthoppers) and diseases (rice blast and sheath blight) are some other problems observed in DSR fields. Poor stand establishment, particularly because of limited water availability during initial days, is another problem generally observed with DSR cultivation which can be easily managed by seed priming [48]. Crop lodging is another difficulty faced by the farmers when they adopt DSR, which not only cause reduced yield and quality of the produce but also makes harvesting of the crop a difficult task. Therefore, the rice cultivars used for DSR should have lodging resistance, dwarf/intermediate plant height, thicker stem with high lignin content, and thicker sclerenchyma/more vascular bundles at the periphery of the stem. Unfortunately, no specific variety has been bred for DSR conditions but the naturally adapted cultivars have been selected as DSR. Although *indica* rice has been reported to be more suitable for DSR with better yield potential than *japonica rice*, most of the high-yielding *indica* rice cultivars do not perform well under DSR conditions [36].

Though one of the major problems associated with TPR is the emission of GHGs, particularly the anthropogenic methane gases, DSR is associated with emissions of nitrous oxide (N_2O). Agriculture's share in the emissions of N_2O is comparatively high, and the global warming potential of CH_4 and N_2O is 25 and 298 times higher than that of CO_2, respectively [30]. Although DSR cultivation can help reduce CH_4 emissions, the aerobic soil conditions under DSR increases N_2O emissions.

Conclusions and Recommendations

When rice is grown by transplanting it requires 2000-5000 liters of water, depending on the environmental conditions and soil type, to produce one kilogram of rice (grain). This indicates very low water-productivity of TPR compared to that of DSR and other crops. The advantages of DSR, particularly saving of water [49], promote the adoption of DSR as a promising alternative to TPR. This would not only help save water for other crops but also improve water-productivity in the rain-fed areas. Some of the easier, economical, and farmer-friendly strategies like seed-priming might be a promising approach to overcome a few problems associated with DSR. Different innate features of crop plants like early plant vigor, short stature, and shorter crop duration need to be combined with increased water use efficiency to improve DSR traits for better water-productivity. However, there is a need of better understanding the basis of genetic plasticity of rice (occur in some of the landraces performing better under DSR conditions also) at transcriptome [36], epitranscriptome [50], and epigenome [51, 52] levels, which might help to decipher the molecular bases of the plasticity observed in the local rice genotypes/landraces/cultivars. Because of the global climate change being experienced nowadays, which even threatens the future existence of human beings on the earth, and the increasing demands of food/feed/fodder for the burgeoning global populations we need to search/opt for alternative strategies to grow more foods in environment-friendly and ecologically-sustainable manners [53]. Therefore, the need of the hour is to breed rice varieties suitable for dry/direct-sowing to sustain rice production with ecological integrity. The development of such varieties would enable farmers to take advantage of DSR and encourage them to grow food/feed/fodder in an ecologically-sustainable manner for increased ecological efficiency [54-56]. Thus, the goals of *Per Drop More Crop* could be realized if appropriate strategies for saving water and its efficient uses in agriculture are adopted.

The views expressed herein are those of the authors only, and these may not necessarily be the views of the institution/organization the authors are associated with.

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