Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability

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Received: 19 June 2020 / Revised: 22 January 2021 / Accepted: 4 February 2021 / Published online: 22 February 2021
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Abstract

Puddled transplanted rice (*Oryza sativa* L.) followed by intensively tilled wheat (*Triticum aestivum* L.) (R–W) is the most predominant cropping system and the lifeline for billions of people in South Asia. The cultivation of R–W system requires high amounts of water, nutrients and energy, resulting in increased production costs and increased emissions of greenhouse gases. There are also increasing concerns of yield stagnation or decline in the R–W system, with increasing environmental footprints. Hence, the sustainability of the R–W system in South Asia, particularly in the northwest Indo-Gangetic Plains (IGPs), has been questioned and heavily debated. Based on the findings from peer-reviewed literature, this review aims to identify unsustainability issues and research gaps in the R–W system and propose possible solutions to mitigate those issues and technological interventions to close the research gaps. Among the unsustainability issues that the review has identified are declining crop, water and land productivity, deterioration of soil health, emissions of greenhouse gases due to intensive tillage and residue burning, deepening of groundwater levels and shift in weed flora and development of herbicidal resistance in crops. Potential solutions or technological interventions to mitigate the unsustainability issues include resource conservation technologies (RCTs) such as rice residue management, reduced tillage, laser land leveling, soil matric potential based irrigation scheduling, delayed rice transplanting, cultivation on permanent raised beds, direct-seeded rice (DSR), mechanical transplanting of rice and crop diversification with legumes. These interventions have the potential to reduce energy, water and carbon (C) footprints from the R–W system. Rice residue retention with Happy Seeder and adoption of zero tillage (ZT) for wheat establishment have significantly lowered the environmental footprints, with increased soil C sequestration due to additions of large amounts of plant-mediated C input. Residue mulching has helped increase root length of wheat by ~25% and root length density by ~40% below 15 cm depth, compared to no mulching. The Happy Seeder saved ~30% of irrigation water due to reduction of soil evaporation by ~42–48 mm through residue mulching. Crop cultivation on permanent raised beds is less energy-intensive and results in ~7.8–22.7% higher water use efficiency yet crop productivity in long run could be affected due to reduced root growth on beds. The puddled transplanted rice (PTR) established under wet tillage, however, can decrease the water percolation losses by 14–16% and crop water demand by ~10–25%, and it forms hard pan in soil plough (7–10 cm) layer due to increased soil bulk density. Water stagnation under continuously flooded PTR is the major source of methane emissions with serious environmental implications. Methane emissions from flooded rice can increase global warming potential by 18.1–27.6% compared to intermittently flooded rice with multiple aerations. The conventional tillage can favor the germination of grassy weeds in wheat, while the broad-leaved weeds increase under zero tillage. Zero tillage with mulch load conserved ~4.0% higher moisture due to ~2.3% lesser soil temperature and evaporated ~27.6% lesser than the conventional tillage. Delayed rice transplanting with short-duration variety has potential of saving of up to ~140 mm of irrigation water in the semiarid areas of NW IGPs. Although the DSR had lower yield potential than the PTR, it saved ~50% irrigation water. The laser land leveling technology saved ~30% irrigation water and ~25% electricity and had a yield advantage of ~4%, compared with PTR on un-leveled fields. The mechanical transplanted rice had higher grain yield and more water saving than the manual transplanting or DSR. The review demonstrates that a single technology may not be applicable everywhere and integrated approaches with the multiple criteria—productivity, economics, energy and environmental sustainability—would be required to address the unsustainability issues of the R–W system of the NW IGPs. There is a need to

elucidate and disseminate various site- and context-specific RCTs appropriate for the region to address the unsustainability issues and challenges of the system. Sustainable R–W production technologies with reduced water, energy and C footprints are required for increased water and energy productivity and C sequestration for the NW IGPs of South Asia.

Keywords Conservation agriculture · Cropping systems · Resource-conserving technologies · Tillage and residue management · Water-saving technologies

Introduction

South Asia comprises of low- to middle-income countries, where shrinkage of land and water resources, climate change and population increase are currently the most important issues and concerns for sustainable development. To sustainably feed the ever-increasing population of South Asia by using the limited resources has now been the greatest challenge faced by farmers, scientists and policy-makers (Bhatt et al. 2019; Srinivasrao et al. 2019). In the region, economic development is not happening at the pace of increasing population; the population pressure, changing dietary habits and use of non-renewable inputs (e.g., water, fertilizers, and pesticides) to obtain high yields require high use of natural resources. The present land-use practices in South Asia more particularly in the rice–wheat (R–W) cropping system are energy, capital, water and labor intensive; these are upsetting the ecological balance and exhausting the groundwater resources and soil organic carbon (SOC) along with adverse effects on soil physicochemical properties (Bhatt and Singh 2018; Srinivasrao et al. 2019). The perception and understanding of existing intensive land use, particularly in the R–W cropping system, therefore necessitate urgent discussions on its adverse effects on the soil, water and overall ecosystems. There is a need to change the tillage and crop establishment practices in the conventional R–W systems by replacing intensive tillage in wheat and puddling and flooding in rice for achieving the overall sustainability of this important cropping system in the region (Timsina and Connor 2001; Bhatt et al. 2020).

In South Asia, various rice-based cropping systems are practiced of which R–W is the most predominant system adopted by the farmers (Timsina and Connor 2001). The R–W system occupies ~13.5 million ha (Mha) of cultivable land in South Asia (Nawaz et al. 2019), mostly in India, Bangladesh, Pakistan and Nepal, but also large areas in China (Timsina and Connor 2001; Bhatt et al. 2020). The R–W systems provide food for a large majority of human population in these countries and have been the lifeline for the food security and livelihoods of burgeoning South Asian population (Nawaz et al. 2019). The R–W system is widespread in the northwest Indo-Gangetic Plains (NW IGPs) where it has spread rapidly during 1960–1990 due to large farm size, rapid use of 4-wheel tractors for tillage and land preparation, availability of high yielding cultivars of rice

and wheat, the widespread use of good quality groundwater for irrigation, and increased utilization of fertilizers and pesticides (Nawaz et al. 2019). This annual cropping system continued to expand in the NW IGPs due to the introduction of high yielding rice varieties for the existing wheat-growing areas and availability of groundwater for irrigation (Bhatt and Kukal 2018). During the recent decade, the yields and land productivities of R–W system in South Asia and particularly in the NW IGPs have either stagnated or decreased due to declining groundwater tables (Bhatt et al. 2020), deteriorated soil health, micro-nutrients deficiencies (Ladha et al. 2009), frequent and widespread insect pest infestations and climate change (Saini and Bhatt 2020). Notwithstanding these issues, the open field burning of crop residues particularly the rice residues results in emissions of greenhouse gases (GHGs), resulting in decline in carbon (C) sequestration in the R–W system of the region (Singh et al. 2020a).

Farmers in NW IGPs normally follow conventional agricultural practices, viz. intensively tilled and sown wheat followed by puddle transplanted rice, which are water, capital and energy intensive (Bhatt et al. 2020; Singh et al. 2019a, b). In the NW IGPs, irrigation in rice is applied 5–6 times to facilitate land preparation and puddling (wet tillage in standing water) before rice seedling transplanting. The intensive tillage and puddling for rice have, however, caused several problems, including the development of hard plough-pan, decreased input-use efficiency, declined yields, hiked insect pest outbreak and global warming. (Nawaz et al. 2019). Singh et al. (2019a) reported total energy expenditure for use through different inputs in rice production in the R–W system which are in the decreasing order as follows: irrigation water (40.0%); fertilizers (24.7%); electricity (17.7%); fuel (8.8%); plant protection biocides (7.2%); farm machinery (0.8%); human labor (0.5%); and rice seeds (0.3%).

In the IGPs of South Asia, the average yield of the component crops of the R–W system varied substantially between 2.7 and 4.3 t ha⁻¹ for rice and 2.1 and 3.1 t ha⁻¹ for wheat (Timsina and Connor 2001) due to divergent soil texture, groundwater levels and water quality, crop production and soil management practices and climatic differences. The average annual yield potential of R–W system simulated using the crop models for the NW IGPs was, however, invariably higher at 16.7 t ha⁻¹ (Timsina and Connor 2001; Timsina et al. 2008). The wide differences in yield obtained at farmers' fields and the potential yields for rice

and wheat indicate large opportunities for closing the yield gaps (Nawaz et al. 2019) through advanced crop establishment techniques and plant breeding approaches. Besides technological advancements, the NW IGPs have advantage of having favorable climate and soil, which could contribute greatly for the food security in South Asia (Nawaz et al. 2019; Bhatt et al. 2020). Evidence suggests that the R–W system is facing several unsustainability issues in the NW IGPs, especially in the context of conserving natural resources and environmental sustainability (Bhatt et al. 2020; Nawaz et al. 2019).

Across the R–W systems in the IGPs, a range of resource-conserving technologies (RCTs) have been developed, evaluated and disseminated; particularly in the NW IGPs, these technologies have been evaluated and used by farmers for more than 30 years. Yet, there are wide knowledge gaps pertaining to the adoption of different RCTs by farmers due to variations in soil textural classes, groundwater levels, climatic conditions and availability of technologies and knowledge. Further, the soil moisture dynamics, particularly during the intervening period (after wheat or rice harvesting), has not been addressed adequately in the NW IGPs (Bhatt et al. 2020; Bhatt and Kukal 2015b, c, d). It is imperative to increase the land productivity under R–W system by improving the crop, water, energy, nutrient and pesticide use efficiency and reducing the C and water footprints. In response to these challenges and issues, the present review aimed to

identify the unsustainability issues and research gaps in the R–W system in the NW IGPs and propose different RCTs to mitigate the unsustainability issues and close the research gaps. More specifically, we aimed to identify the integrated package of RCTs for the R–W farmers of the region, which helps them increase land and water productivities under prevalent conditions of poor soil health, declining groundwater tables and adverse climatic conditions. The smart technological interventions and possible solutions for the site- and context-specific management strategies along with their pros and cons are discussed to address the multifaceted challenges the R–W system is facing in the era of climate change in the NW IGPs. To conduct this review, we searched published peer-reviewed papers from Science Direct, Scopus and Web of Science. In addition, we also used Google Scholar, Research Gate and Academia to identify relevant peer-reviewed papers, reports and working papers. Based on the rigorous review, the challenges and issues in R–W cropping system of NW IGPs and the proposed interventions and management strategies to address those challenges are summarized in Fig. 1. The remaining of this review is structured and discussed around those issues and challenges.

Fig. 1 Challenges and issues in rice–wheat (R–W) cropping systems of NW IGPs, and the proposed interventions and management strategies to address those challenges (the bigger fonts in each box represent challenges, and smaller fonts underneath the challenge represent possible interventions and management strategies)

Sustainability issues related to rice–wheat system

Formation of hard pan in soil plough layer

The R–W systems are characterized by a diverse edaphic environment. Wet tillage (puddling; tillage in standing water)—a pre-requisite under conventional tillage (CT), requires repeated tilling in standing water to i) crush soil clods, (ii) eliminate macro-pores, (iii) reduce puddled layer strength and iv) disperse fine clay particles (Bhatt et al. 2016). Wet tillage induces the formation of hardpan with higher soil bulk density that affects root proliferation in terms of root geometry and architecture of succeeding wheat crop (Singh et al. 2009a, b). Repeated wet tillage of heavy to medium textured soils which is aimed at reducing percolation losses can cause compaction of soil below 7–10 cm of the soil surface (Hossain et al. 2020). The water losses through percolation decreased by ~14–16% with increased wet tillage intensity, while percolation reduced water demand by ~10–25%. The high wet tillage intensity resulted in the formation of closed pores which are considered good for rice establishment. Under the moderate wet tilled condition, ~17% higher rice root mass has been reported than the intensively wet tilled soils. However, the intensively wet tilled soils apparently had unfavorable impacts on the succeeding wheat crop (Bhatt et al. 2020). In the surface layer of shallow wet tilled soils, the root mass density (RMD) was higher than in the sub-surface layers. However, in 15–20 cm soil layer, the RMD was higher in shallow wet tilled soils than in deeply tilled soils which because of the formation of compact soil layer resulted in hindrance for the root penetration (Aggarwal et al. 1995). With increased tillage intensity, the soil bulk density increased from 1.63 to 1.67 Mg m⁻³ in 16–18 cm depth, and from 1.61 to 1.66 Mg m⁻³ in 18–20 cm depth.

Greenhouse gases emissions

Wet tillage in rice cultivation blocks soil pores and holds water resulting in plough-pan formation and increased production of methane (CH₄) even in the light-textured soils. Methane production results from the reductions of carbon dioxide (CO₂) and nitrous oxide (N₂O), the latter due to the reduction of NO₃⁻, the intensity of which depends upon the soil redox potential and decomposition rate of soil organic matter (SOM). These chemical processes in wetland soils contribute to the emissions of the GHGs, viz. CH₄ and N₂O in rice ecosystems (Saini and Bhatt 2020; Singh and Benbi 2020a). The greenhouse gas intensity was significantly higher for R–W (by 0.2 kg CO_{2e}

kg⁻¹ grain) and maize–wheat (by 0.1 kg CO_{2e} kg⁻¹ grain), compared with cotton–wheat cropping system (Singh and Benbi 2020a). In contrast to rice, wheat requires an aerobic root zone and favors dry soil. Thus, the alternate aerobic and anaerobic regime affects the physicochemical and biological soil properties and alters the nutrient availability, root proliferation, moisture availability and finally the crop–root interactions (Bhatt et al. 2019; Benbi et al. 2016). A large volume of irrigation (~50 mm during nursery preparation and ~1500 mm during the growing season) is required for cultivating rice (Guerra et al. 1998) especially in the light-textured soils of the NW IGPs resulting in large global warming potential (GWP). A study in the NW IGPs found ~18.1 and 27.6% lower GWP measured as CH₄ emissions, respectively, for rice fields with intermittently flooded with single and multiple aerations compared to fields that were continuously flooded throughout the growing season (Singh and Benbi 2020a).

Shifts in weed flora and herbicidal resistance

In flooded rice ecosystems, the major weed floras are *Echinochloa colona* and *Echinochloa crus-galli*. The repeated wet tillage and water stagnation in puddled transplanted rice (PTR) help get rid of the hardy weeds and increase the efficiency of application of selective herbicides. In the NW IGPs, several herbicides are used to control *Echinochloa sp.*; the use of a single herbicide can lead to the emergence of new and hardy weed species, viz. grassy weeds (*Lepetochloa achinensis*, *Cynodon dactylon*, *Ischaemum rugosum*, and *Paspalum distichum*), broadleaves weeds (*Ludwigia hyssopifolia*, *Eclipta prostrata*) and sedges (*Cyperus rotundus*, *Cyperus iria*, *Cyperus difformis*, *Fimbristylis milacea*). The direct-seeded rice (DSR), which has been gaining ground in labor scarce South Asian countries, is constrained by the prevalence of many weeds including *Digitaria sanguinalis*, *Leptochloa chinensis*, *Dactyloctenium aegyptium*, *E. colona* and *Cyperus* spp. (Chauhan and Peña 2012; Chauhan et al. 2012; Mahajan and Chauhan 2013). The weed flora in the DSR is different than in the PTR. Their weed management practices are therefore different requiring different herbicides. The application of the same herbicide molecule for long time has resulted in the development of resistance against herbicides due to enzyme acetoacetate synthase (Kumar et al. 2014; Vrbničanin et al. 2017). It has been ascribed to strong selection pressure exerted by these herbicides (Tranel and Wright 2002). It has been experimentally proven that the use of same herbicides over the years exerted adverse impacts on the weed infestation and the weed pressure exerted on the productivity of the R–W system. The conservation tillage on the other hand has led to a positive effect on the suppression of weeds in wheat. The adoption

of recommended agronomic practices, understanding the nature of the weed incidences and use of CA practices have largely helped the farmers to increase the land productivity in the region. There are reports that the CT practices favor the germination of grassy weeds compared to ZT in wheat under R–W system, while the reverse was observed for the broad-leaved weeds (Brar and Walia 2007).

Declining groundwater tables

The R–W system has aggravated the problems associated with deterioration of soil structure and declining groundwater tables resulting in decreased crop, land and water productivity. The conventional crop establishment techniques for the R–W system are highly exhaustive in terms of labor, water and power, but especially water owing to the significantly higher water demand of rice (Bhatt et al. 2020; Bhatt and Kukal 2018; Singh et al. 2019a–b). The Punjab and Haryana in NW Indian IGPs are producing rice at the cost of their natural resources (Dhillon et al. 2010). In rice establishment following wet tillage in south-western Punjab in India, Singh et al. (2019a) reported that of the total energy input of $52.4 \pm 1.3 \text{ GJ ha}^{-1}$, ~40% energy was required for irrigation water and ~17.7% for electricity used for pumping of groundwater. The groundwater is being continuously pumped out from the below-ground aquifer since 1970s that has resulted in drawdown of groundwater in NW IGPs (Hira et al. 2004). In central Punjab, annual fall in the groundwater table has been reported to augment from 20 cm year^{-1} (1973–2001) to 100 cm year^{-1} (2000–06). Of the total 141 administrative blocks in Punjab, significant numbers are already facing water stress due to declining groundwater tables (Humphreys et al. 2010). In the NW IGPs, the groundwater levels are declining at $0.1\text{--}1.0 \text{ m year}^{-1}$ due to poor infrastructure and blind reliance on the groundwater (Bhatt et al. 2020; Hira et al. 2004). Mahajan et al. (2011) predicted that the annual per capita water availability in India is expected to decrease from 1600 m^3 to 1000 m^3 by 2025. It would also reduce the share proportion of agriculture sector by 8–10% up to 2025 (Mahajan et al. 2009) because of rising water demand by other allied sectors. The central Punjab has been reported with lowering of the groundwater table depth ($< 1000 \text{ cm}$), where it had increased from ~3% to ~76% during 1973–2002 (Hira et al. 2004). The declining groundwater tables and over-fertilization are responsible for increased energy consumption and deteriorated water quality (Singh et al. 2019a). Recently, NASA (National Aeronautics and Space Administration) gravity mapping satellite ‘GRACE’ reported a drawdown of groundwater by $\sim 30 \text{ cm year}^{-1}$ from $440,000 \text{ km}^2$ area

of NW India, indicating a decline of $0.04 \text{ m groundwater year}^{-1}$ (Soni 2012).

Water loss from conventional rice and rice–wheat production systems

There is a tremendous amount of loss of irrigation water from rice and R–W production systems in the NW IGPs, particularly in coarse-textured soils (Hira 2009). Hence, the soil water balance needs to be computed to quantify crop water demand and schedule irrigation, compute water and land productivities and determine seepage, drainage and evapotranspiration (ET) requirements of R–W systems (Bhatt and Kukal 2017; 2018). Bhatt and Kukal (2018) reported that soil tillage for wheat and rice establishment was not able to alter the total applied water either through rain or irrigation. Nearly ~40% of the total water input was turned to deep drainage in CT wheat (CTW) compared to DSR with CT (DSR-CT). In zero tilled wheat (ZTW), deep drainage was lowered to ~30.4%. The double tilled plots did not change the water movement out of rhizosphere; however, no-till wheat followed by no-till rice (double no-till treatment) promoted deep drainage in comparison with the tilled plots. No-till wheat plots experienced with greater seepage losses than the tilled ones by ~284–561 mm. In rice, no-till plots resulted in lower seepage losses as compared to tilled ones. Tillage did not affect the water losses through evaporation and transpiration of the annual R–W system, including the intervening period (Bhatt and Kukal 2018). The double no-till plots demanded a lower quantum of the irrigation water which might be due to the poor crop stand. The maximum variation in soil moisture ($\Delta\theta$) was observed in the no-till wheat plots compared with other established methods due to the capillaries’ continuity (Bhatt and Kukal 2018). Under DSR, the profile moisture was lower (by ~42–47 mm) in the ZT plots, compared with the CT plots (by ~54–55 mm), because of elevated evaporation losses in the untilled plots.

Bhatt and Kukal (2018) also demonstrated that the double no-till in R–W system decreased the ET losses in wheat and led to poor crop development which required the lesser amount of irrigation water used for transpiration. However, direct-seeded no-till plots (without any mulch loads) had higher soil temperature and higher change in soil moisture ($\Delta\theta$) between sowing and harvesting of rice. During the first year of investigation, there were lower seepage losses (by ~265–462 mm) than in the second year (by ~561–732 mm). Further, double no-till plots (ZTW-ZTDSR) resulted in higher seepage losses (by ~35.7% and 16.4%, respectively, for rice and wheat) than the double tilled plots (CTW-DSRCT) (Fig. 2). During the rice-growing season, there was significantly higher deep drainage compared to the wheat season. The drainage losses decreased in no-till wheat plots but increased in no-till

Fig. 2 Components of soil water balance under different rice and wheat establishment methods including intervening periods (total water inputs, viz. irrigation (I), rainfall (R), seepage (S), drainage (D) and evapotranspiration (ET) (Acronyms: *CTW-DSRCT* Conventionally tilled wheat followed by conventionally tilled direct-seeded

rice, *CTW-DSRZT* Conventionally tilled wheat followed by zero tilled direct-seeded rice, *ZTW-DSRCT* Zero tilled wheat followed by conventionally tilled direct-seeded rice and *ZRW-DSRZT* Zero tilled wheat followed by zero tilled direct-seeded rice. Adapted from Bhatt and Kukal (2018)

DSR plots. On the contrary, the DSR in a clay loam soil also in Punjab in the NW IGPs required lower amount of irrigation water than the PTR, which is ascribed to reduced seepage and drainage losses (Sudhir Yadav et al. 2011). They reported that up to ~50% of water saving was found in the plots with intermittent irrigation compared to continuous flooding. Tillage did not affect ET losses in plots established with direct seeding during both crop seasons. The lower land productivity in the no-till plots did not match with the higher ET losses which were due to significantly elevated weed pressure in the zero-till plots which shared a proportion of irrigation water to meet their ET requirements.

Crop residue burning and environmental pollution

In the NW IGPs, Punjab and Uttar Pradesh in India are the major residues producing states (Fig. 3). In Punjab, Sidhu and Beri (2005) reported a total rice straw production of ~19 million tons (Mt), of which ~78% was burnt in open fields. The open field burning of rice residues especially after combine harvesting has been practiced extensively for timely sowing of wheat under the R–W system in NW IGPs. Beri et al. (2003) reported that ~80–84% of the rice residues and ~14–20% of wheat residues are burnt in the Indian Punjab. Thus, the large quantities of rice and wheat residues produced under the R–W system have raised

Fig. 3 Rice and wheat crop residues produced and the quantity of total residue available for agricultural cycling in different rice producing states of northwestern Indo-Gangetic Plains (NW IGPs) (Adapted from Singh and Singh 2003)

serious environmental complications as most of them are burnt in open fields producing GHGs, viz. CO_2 , CO , CH_4 , N_2O , NO_2 and SO_2 (Saini and Bhatt 2020). Of all systems, R–W is the largest producer of crop residues. A total of $350 \times 10^6 \text{ kg year}^{-1}$ residue is generated in India, of which rice residue shares a significant portion (~51%) followed by wheat residues (~21%) (Singh and Sidhu 2014). Of the two crops, rice residue management has become a significant challenge because loose and scattered residues impede the tillage operations (Singh et al. 2020a). The management of wheat residues on the other hand has not been a major issue. Wheat residues in NW IGPs are being used as fodder, while rice residues are not preferred by animals because rice straw contains higher silica content than wheat straw (~9–14% vs. ~4–8%) (Singh and Sidhu 2014). Farmers with no alternative options and due to the shorter window period between rice harvest and wheat sowing prefer to burn most rice residues at the site/field itself to dispose of straw (Singh et al. 2020a). Therefore, crop residue burning in the R–W system has now been a severe problem causing soil degradation and GHG emissions (Singh et al. 2020a).

The Punjab Remote Sensing Centre in India indicates that rice residue of ~75% of the rice area in Punjab was burnt in 2010–2011 (Punjab Remote Sensing Centre 2015). Residue burning problem and the resulting human health and environmental consequences are increasing over time across the NW IGPs. During the early November 2017, NASA satellite images identified the burning hot spots and marked the intensity of residue burning as ‘very high,’ more particularly of rice residue burning in Haryana, Punjab, western Uttar Pradesh and Uttarakhand in NW IGPs (NASA 2017). The open field residue burning has resulted in air pollution in vast geographical areas causing several human and animal health environment-related issues.

Rice contains 400 g C, 6.5 g N, 2.1 g P, 17.5 g K and 0.75 g S (kg residue^{-1}), which is equivalent to 2.4 t C, 0.035

Fig. 4 Nutrient concentration in the surface (0–15 cm) layer of a loamy sand soil after 11 cycles of rice–wheat cropping under contrasting rice residue management scenarios, viz. residue incorporation, removal and burned (Adapted from Beri et al. 2003)

t N, 0.0032 t P, 0.021 t K and 0.0027 t S ha^{-1} (Singh et al. 2008). Prior to 2000s, around 114 Mt of rice and wheat residues were produced that contained 1.9 Mt nutrients (Sarkar et al. 1999). During burning, almost all C, 90% of N, 60% of S and 20–25% of P and K in rice straw are lost (Dobermann and Fairhurst 2002). In Punjab, rice residue burning is considered responsible for the loss of 0.7 Mt N year^{-1} apart from considerable quantities of annual GHGs emissions: CO_2 (~70%), CO (~7%), CH_4 (~0.66%) and N_2O (~2.1%) (Yadvinder-Singh et al. 2010). Because of loss of nutrients, declined soil health, increased CO_2 emissions, air pollution and deteriorating soil physicochemical properties, burning of rice residues has not been a viable option.

Rice residue incorporation into the soil has been reported to restore soil fertility due to increased concentration of N, P and K (Singh et al. 2005a). Beri et al. (2003) reported that crop residue incorporation positively impacts available P, K and S in a loamy sand soil after 11 cycles of R–W cropping (Fig. 4). On the other hand, because of higher C/N ratio of rice residues, its soil incorporation leads to decreased crop productivity of succeeding wheat crop, compared with removal or burning because of N immobilization (Beri et al. 1995). Arora et al. (2020) suggested several alternatives to residue burning including compost, electricity production and biochar preparation which has considerable potential to resolve the problem of rice residue burning along with mitigation of GHGs emissions and reduction of GWP.

Smart technologies to address challenges in the rice–wheat system

Over the last three decades, intensive efforts were made to identify viable, site-specific, sustainable and eco-friendly R–W management options (Singh et al. 2020a). Among the

best management practices, inclusion of leguminous crops in R–W system, crop residue and farm manure management and CA and water-saving technologies has been promoted that have a considerable potential to enhance the land and water productivity in R–W system.

Inclusion of legumes and crop diversification

The continuous R–W cropping with intensified tillage in NW IGPs has shown negative impacts on SOM, land degradation and rapidly declining groundwater resources. Therefore, crop diversification with oilseed and pulses instead of growing rice had shown potential for reduced tillage, soil health improvement, reduced water requirements and increased water economy (Arora et al. 2020). A 5-year study on soybean–wheat system in Punjab in the NW IGPs under a raised bed system revealed that the soybean residue mulching reduced the soil temperature and improved inherent soil moisture conditions (Ram et al. 2013). Straw mulching increased SOM in the topsoil layer while reducing the irrigation water use due to its shading effect, reduced water vapor pressure gradient and wind speed and increased water use efficiency (WUE) due to its vapor lifting capacity, compared with un-mulched treatment. The results showed that ~17% and 23% higher WUE was observed in flat-sown soybean and wheat, respectively, compared with un-mulched plots. The restoration of soil fertility and improvement in SOM and soil physicochemical and biological properties helped in achieving a higher yield of the next crop. Therefore, practicing the crop rotation with legumes between the two crops helps in enhancing soil N economy and contributes toward cropping systems' sustainability (Timsina and Connor 2001; Arora et al. 2020).

Crop diversification can play a vital role in reducing the crop irrigation water requirement (Jalota and Arora 2002; Arora et al. 2008). Therefore, shifting the area from rice to less water demanding crops such as cotton, maize or legumes in summer, monsoon season, could help enhance the water productivity of the R–W system. In many studies, ET losses decreased to an extent when the R–W system was changed to cotton–wheat (C–W) or maize–wheat (M–W) as cotton and maize have reduced water requirements compared to rice (Table 1; Jalota and Arora 2002; Arora et al.

2008). Replacing the monsoon rice by maize in the R–W system results in a substantial decrease in irrigation water requirement, although the system productivity of M–W system was decreased in some years due to lower rice equivalent yield of maize (Gathala et al. 2011). The WP of maize (5.0–5.6 kg m⁻³ based on rice equivalent yield) was ~8–22 times higher compared to rice and 3.5–5.0 times higher than that of wheat (Gathala et al. 2013). The M–W system had ~126–160% higher irrigation water productivity (IWP), compared with the R–W system. Likewise, soybean–wheat can also be a potential crop rotation for effective management of natural resources (Ram et al. 2013).

Crops lose water through ET during their growth from the field. Kukal et al. (2014) reported that water productivity based on crop ET was highest in R–W followed by C–W. In M–W, there was lower water loss from the bare soil (*E_b*) due to larger maize canopy. It is therefore suggested that approaches for improving water productivity must be followed in the cropping system perspective with the aim of lessening the *E_b* losses by shortening the non-crop period and/or reducing the soil evaporation loss (Jalota and Arora, 2002; Kukal et al. 2014).

Effect of crop residue and organic manure management on soil and hydrology

The analysis of 25-years of soil laboratory data in Punjab in NW IGPs showed a positive impact of rice residue incorporation and/or retention on SOM in an intensive R–W system. An increased concentration of SOC was observed due to the accumulation of above- and below-ground biomass in large quantities in soils under R–W system (Singh et al. 2005b; Benbi et al. 2016). Under reduced conditions, soil microbes responsible for oxidation of organic matter become ineffective, and SOM becomes more lignified (Benbi et al. 2012) and accumulates in the recalcitrant form in soils (Singh and Benbi 2018a). The build-up of SOC affects soil physicochemical and hydrothermal properties (Singh and Benbi 2016). The plant-mediated C input promotes soil aggregation due to the cementation of sand, silt and clay into secondary aggregates (Benbi et al. 2016; Singh and Benbi 2018a, b). The adhesive substances such as mucilage, Fe-oxides,

Table 1 Comparison of rice–wheat, cotton–wheat and maize–wheat cropping systems for their effect on evapotranspiration (ET), crop yield, the wheat equivalent yield of non-rice crops and irrigation water productivity (IWP) Arora et al. (2008)

Cropping systems	ET (mm)	Component crop yield (t ha ⁻¹)		Wheat equivalent yield (t ha ⁻¹)	IWP (kg m ⁻³) based on	
		First crop	Second crop		ET	Net water loss
Rice–wheat	1030	6.0	4.5	9.7	0.94	0.78
Cotton–wheat	980	2.0	3.5	8.6	0.88	0.80
Maize–wheat	860	3.5	4.5	7.2	0.84	0.67

Fe-hydroxides, root exudates, decomposition products of organic matter, microbial cells and excretory products of micro-organisms act as binding agents and promote soil aggregation (Baumert et al. 2018). Carbon input increases the SOC concentration and favors the formation of water-stable aggregates in soil (Benbi et al. 2016). The formation of macro-aggregates was increased under the balanced use of fertilizers applied conjointly with farmyard manure (FYM). The SOC concentration was highest in macro-aggregates (CMacA, > 2.0 mm) followed by meso-aggregates (MesoA, 0.25–2.0 mm) and lowest in coarse micro-aggregates (CMicA, 0.11–0.25 mm) (Benbi et al. 2016). Their results revealed that CMacA had the lowest, while the meso-aggregates (MesoA, 0.25–2.0 mm) had the highest C preservation capacity.

Crop residues and organic manure management effect on (i) soil health, (ii) GHGs emissions, (iii) crop productivity, (iv) soil hydraulic conductivity and v) water infiltration rate are due to improved soil physical structure and increased number of macro-pores (Bhatt et al. 2020; Singh and Benbi 2016). The improvement in soil properties is generally pronounced particularly when crop residues are incorporated in the soil. Direct drilling in fields with surface retained residues increases soil hydraulic conductivity by ~4.1 times, compared with residue burning. In the R–W system, soil physical properties were improved after 5 years of rice straw incorporation at 5 t ha⁻¹ year⁻¹ (Bhagat and Verma 1991). The FYM and rice straw + FYM application increased the proportion of macro-aggregates (> 0.25 mm) due to improvement in mean weight diameter of aggregates. There occurs an increase in soil porosity, water retention capability, water movement through the saturated soils under the influence of gravity. The improved soil physical properties, enrichment of soil with essential plant nutrients due to FYM application and rice residue incorporation collectively contribute to increased crop yield (Bhagat and Verma 1991). However, these technologies required a certain set period (usually 3–5 years) for apparent significant effects on crop and water productivity (Bhatt and Kukal 2015d). After 5 years of R–W cropping, Singh and Benbi (2016) reported that the moisture content was significantly higher in soil with FYM application either alone or in combination with NPK, compared with CK, the unfertilized control (Fig. 5). In this study, the damaged soil structure due to wet tillage was restored with greater water retention, improved soil hydraulic properties, soil porosity and decreased bulk density with integrated nutrient management (NPK + FYM). On contrary, several reports showed the non-significant effect of residue incorporation on improvement in soil aggregation under the R–W system (Benbi et al. 2012).

Fig. 5 The volumetric water content (θ) in the plough layer (0–15 cm) at different matric potentials under the influence of different nutrient management strategies in a rice–wheat soil Adapted from Singh and Benbi (2016)

Carbon sequestration

The R–W system is highly intensive in terms of C inputs and outputs through the addition of above- and below-ground biomass and burning of rice residues (Benbi et al. 2016; Singh and Benbi 2020a–b). The burning of rice residues although seems an easy way out for the farmers because of large rice straw load and shorter window period between paddy harvesting and wheat sowing, yet residue burning has not been a viable option, as it leaves significant C footprints which negatively impact the C sustainability of R–W system (Singh et al. 2020a). Among different rice residue management strategies, the development of Happy Seeder (HS)—a modified ZT machine, capable of drilling wheat seed into the standing rice stubble without any preparatory tillage appeared highly cost-effective, eco-friendly and sustainable technology (Sidhu et al. 2008; Kumar et al. 2019). In a 5-year study on the R–W system in sandy loam soils, Benbi et al. (2016) reported that annual C input as above- and below-ground biomass varied between 0.9 and 4.3 t C ha⁻¹ year⁻¹ under different nutrient management practices. The annual C input through root biomass produced under the R–W system varied from 0.62 to 1.44 t C ha⁻¹ year⁻¹, and through leaf + stubble biomass from 0.28 to 0.60 t C ha⁻¹ year⁻¹. In the 0–15 cm depth soil plough layer, rice root biomass incorporated varied from 0.82 to 1.90 t ha⁻¹ year⁻¹, and wheat root biomass from 0.71 to 1.67 t ha⁻¹ year⁻¹ (Benbi et al. 2016). ZT had 864.0 ± 7.1 kg C ha⁻¹ higher C added through rice residue + roots to SOC pool compared with CT (Singh et al. 2020a). The rice residue retention on

soil surface or incorporation into soil had 4.6 to 4.8 times higher C added through rice residue + roots to SOC pool, compared with CT. The amount of C sequestered varied between 111.4 and 119.9 kg ha⁻¹ among different rice residue management methods (Singh et al. 2020a). Therefore, SOC could be enhanced by sequestration of C back into the soil. It would have a special significance for the R–W system practiced in tropical and subtropical conditions where the soils are inherently low in SOC.

Conservation agriculture

In South Asia, CA was introduced for achieving the long-term sustainability of agricultural production systems in the context of changing climate (Bhan and Behera 2014). Broadly, CA has been advocated with three basic principles, viz. (i) diverse crop rotation, (ii) no or reduced tillage and (iii) mulching or residue retention (Farooq and Siddique 2014). CA promotes reduced or no-tillage with at least ~30% of residue retention on the surface of soils; it can sequester C and improve soil physicochemical, hydrothermal and microbiological properties (Jat et al. 2019). A recent study in Punjab in the NW IGPs has shown soil health improvement under CA after 3–5 years of the R–W system implementation (Bhatt et al. 2015d). Other studies have shown residue retention on the soil surface under R–W system could help in conserving soil moisture (Bhatt and Kukal 2017), regulating soil thermal regimes (Balwinder-) and improving WUE (Kukal et al. 2014). The resiliency of CA to climate change by reducing labor and diesel costs and reducing soil moisture loss is the main factors for the adoption of CA (Thomas and Twyman 2005). The sustainable cultivation of R–W system involves restricted tillage with crop residue retention and inclusion of legumes in the system (Timsina and Connor 2001; Bhatt and Kukal 2017). The synergistic interaction of CA with improved R–W management practices such as timely sowing and efficient weed control measures certainly improves grain yield, but their response to a specific CA practice (e.g., less soil disturbance in no-till systems) can have a moderate impact (Kirkegaard and Hunt 2010). In addition, C sequestration and mitigation of GHGs emissions under CA have been questioned by some researchers (Chan et al. 2011; Epule et al. 2011), suggesting for the need of continuing research on the environmental sustainability of R–W system in South Asia.

Resource conservation technologies

Among recent RCTs, laser land leveling (LLL), short-duration cultivars, irrigation scheduling based on soil matric potential (SMP), crop diversification and raised bed planting are of paramount significance (Bhatt et al. 2020). These technologies have served the purpose of improving the

livelihoods of the farmers without putting much stress on natural resources (Bhatt et al. 2019). These RCTs require a period of 3–5 years for significant effects on crop and water productivity (Bhatt et al. 2019). Nonetheless, these RCTs are highly site- and situation-specific and their performance varies widely in different regions with diverse soil texture and agroecological conditions (Bhatt et al. 2019). These RCTs provide a wide range of advantages including improved yield, reduced production costs, increased irrigation WUE, improved nutrient use efficiency, efficient control of insect pests and reduced GHGs emissions (Bhatt et al. 2019; Rehman et al. 2015; Bhatt et al. 2020).

Water-saving technologies

The real water-saving technologies are those which minimize the unproductive evaporation losses and partition the share of unproductive evaporation to transpiration to favor inflow of soil nutrients to the plants through roots. Among different RCTs, short-duration cultivars and optimum date of rice transplanting are the real water-saving technologies advocated for the farmers in NW IGPs (Humphreys et al., 2008). These technologies aim at reducing the water losses that cannot be economically recaptured; however, their efficiency varies spatially and temporally (Loeve et al. 2002). The objective of redeeming water is to decrease the water wastage in crop production and to supply that to other areas where it is required, e.g., in urbanization, industries, etc. Many farmers apply irrigation water with uncertainties of losses that could be saved and reused in water-stressed conditions. Timsina et al. (2008) used the DSSAT-CSM-CERES-Wheat V4.0 model for irrigation scheduling for wheat under R–W system based on drainage, runoff and ET in Punjab in the NW IGPs. They reported that the crop and water system model could efficiently be used as a decision support system to guide farmers to schedule irrigation to wheat in the coarse-textured soils of NW IGPs. Among different water and energy-saving technologies, tensiometer-based irrigation scheduling, LLL, DSR, bed planting and alternate wetting and drying (AWD) for rice are some of the cutting-edge technologies. These technologies could be used to reduce the undesirable drainage losses especially in regions where the water could be recaptured. For effective saving of irrigation water, irrigation water management for the entire sequence including the fallow period, instead of just for rice or wheat individually, should be considered. Bhatt and Kukal (2015a, b) reported that for accurate quantification of soil moisture dynamics, complete R–W cycle including intervening period must be considered. They demonstrated that the removal of straw mulches loads from the soil surface under CT resulted in higher soil temperature that easily diffused the water vapors to the atmosphere and lowered volumetric water content by reduced transpiration share

and nutrient intake through roots which reduce both land and water productivity of R–W systems in the region. During the intervening period, evaporation increased by ~7.6% and ~12.8%, which resulted in lower volumetric moisture content (0–7.5 cm soil depth) by 10.3% and 9.4% in CT without residue compared to ZT with residue (Bhatt and Kukal 2015a, b). After rice harvesting, ZT with mulch loads conserved ~4.0% higher moisture due to ~2.3% lesser soil temperature which evaporated ~27.6% less than CT (Bhatt and Kukal 2015c). On average, double CT plots had ~14, 29 and 45% lower soil water tension than double ZT plots.

Short-duration rice cultivars

Reducing crop duration in field helps in reducing the irrigation water requirement and soil evaporation, which leads to higher water productivity. In the Indian Punjab, Pusa-44 (a long-duration rice variety) that takes ~160 days to mature requires a significantly higher amount of irrigation water than short-duration varieties (e.g., PR-126 and PR-127) which take only around 123 and 137 days; these short-duration varieties have potential to save water by ~15–20% (Singh et al. 2015a, b, c). The disadvantage of short-duration rice cultivars is the lower yield potential than long- and medium-duration cultivars (Chen et al. 2019), which hampers its adoption by farmers. However, though the yield potential is low, its production efficiency is still higher ($54.5 \text{ kg ha}^{-1} \text{ day}^{-1}$ for PR-126) compared with PR-124 ($50.0 \text{ kg ha}^{-1} \text{ day}^{-1}$) and PR-122 ($50.6 \text{ kg ha}^{-1} \text{ day}^{-1}$) (Singh et al. 2020b). The WUE was also highest for PR-126 and lowest for PR-124; the higher WUE of PR-126 was due to its short duration and hence the need for fewer numbers of irrigations (Singh et al. 2020b).

Delayed rice transplanting

Since the early transplanted rice in pre-monsoon season has the higher ET requirement than late transplanted rice, timely rice transplanting is important for increasing the crop and water productivity in R–W system in the semiarid areas of NW IGPs. The early planted rice for which transplanting occurs in May when the air is dried has higher evaporative losses and hence requires frequent irrigations to cater its water demand. On the other hand, if rice seedlings are transplanted after June 20, due to monsoon commencing in July–August, there will be an increase in air humidity and thereby decrease in water vapor loss. The late transplanting could therefore help prolong the interval between two irrigations and lower the total irrigation water requirement and increase the IWP (Bhatt and Kukal 2017; Bhatt et al. 2020). Jalota et al. (2009) in NW IGPs reported ~17% higher crop water productivity (CWP) for rice seedlings transplanted on June 25 compared to that transplanted on

May 25. Further, CWP increased to ~23% when a short-duration variety was selected instead of a long-duration variety. Jalota et al. (2009) reported a saving of ~140 mm of irrigation water with appropriate selection of rice transplanting date and variety using the CropSyst Model. They reported saving of irrigation water by almost double when the selection of the transplanting date and cultivar was done appropriately (Jalota et al. 2009). The selection of the photoperiod sensitive short-duration cultivars and transplanting by July 5 helps substantial saving of the irrigation water as the evaporative demands are curtailed because of the higher relative humidity which reduces the air capacity for uplifting the water vapors. Therefore, fewer numbers of irrigations would need to be applied for achieving higher yields (Sharma et al. 2011).

Rice transplanting by June 15 experienced mean temperatures between 31 and 33 °C during maximum tillering stage with more number of days to promote tillering compared with transplanting on June 25 (Jalota and Arora 2002). The later transplanting resulted in lower yields which ascribed to restricted solar radiation and photosynthetic efficiency (Bhatt et al. 2020; Yamane et al. 2003). Delayed transplanting of long-duration rice cultivars would result in delayed harvest and consequently delay in wheat sowing which would experience terminal heat stress and lower wheat yields. Thus, delayed transplanting of short-duration rice cultivars would be recommended to increase CWP and IWP and sow subsequent wheat on time. For rice transplanted after June 20, decreases in air temperatures at the pollen development stage are responsible for spikelet's fertility of photo-insensitive cultivars (Sharma et al. 2011). Long days with high solar radiation and short nights at the reproductive stage of rice in subtropical climate conditions are highly favorable for higher yield (Bhatt et al. 2020). In NW IGPs, solar radiation during the rice-growing period was $> 2500 \text{ MJ m}^{-2}$, when rice transplanting was done by June 10 but decreased to ~2400 MJ m^{-2} when transplanted by July 1 (Chahal et al. 2007). The ET demand for rice in the region decreased from 800 to 500 mm with delayed transplanting from May 1 to June 30 (Hira and Khera 2000). Therefore, mid-June rice transplanting though would result in slightly lower grain yield; it could save irrigation water significantly in the NW IGPs.

Direct-seeded rice and alternate wetting and drying of rice

Keeping the rice fields continuously flooded has been a traditional practice of rice cultivation in the IGPs of South Asia. The DSR by maintaining the soil moisture at field capacity has been recommended for increasing water productivity for the medium- to fine-textured soils in the NW IGPs. Water balance for DSR has, however, been less extensively studied in coarse- and medium-textured soils as the DSR has not

been particularly successful in the light-textured soils due to iron (Fe) deficiency and weed infestation (Bhatt et al. 2020; Bhatt 2015)). Likewise, a substantial saving of irrigation water in rice cultivation has been reported with AWD due to restricted seepage losses of irrigation water which are higher in puddle transplanted rice (PTR). Sudhir-Yadav et al. (2011) reported significantly higher IWP in DSR compared with PTR, but rainfall and real water productivity were at par with irrigation scheduling based on 20 kPa SMP in rice. The DSR and AWD could therefore be used as alternative approaches but only in the medium- to heavy-textured soils. Nonetheless, increased IWP in DSR could impact the IWP of the following wheat crop and therefore necessitates the need to study soil water dynamics in R–W system instead of just for the individual crops across all soil types. Considering the R–W system including the intervening period, Bhatt (2015) reported significantly higher IWP in CT DSR than the ZT DSR. Lowland PTR cultivation has many advantages, such as higher nutrient availability, lower weed pressure, low or no Fe deficiency and higher land productivity as compared to aerobic cultivation (Bouman et al. 2005). Research findings suggest that the performance of DSR technology is the site-, soil- and cultivar-specific. In the light-textured soils, DSR plots had severe Fe deficiency and significantly higher weed population and competition, leading to lower water and land productivity (Bhatt et al. 2020). The reported water savings and yield increments in DSR than PTR are not universal; rather they vary with site, soil and climatic conditions (Table 2; Bhatt and Kukal 2015a), suggesting that DSR should not be recommended universally.

Laser land leveling (LLL)

Among various RCTs advocated to increase water and other input use efficiency, LLL has been the most widely accepted technology by large-scale farmers in the NW IGPs. A LLL

levels dikes and dikes in the field and ensures even distribution of irrigation water covering more area in less time. It is estimated that a significant amount of irrigation water can be saved by the LLL without any adverse impact on crop yield (Bhatt and Sharma 2010). Jat et al. (2009) reported a yield gain with improved IWP after the use of LLL in the field. The LLL can increase the water conveyance, and hence its use efficiency and finally the land productivity (Jat et al. 2006). The LLL has potential to save irrigation water and electricity by ~25% and increase in rice grain yield by ~4% than the traditional flood irrigation on un-leveled fields (Jat et al. 2006). The IWP for laser leveled rice fields was increased by ~39%, compared with the conventionally flooded field. Besides, there was also a saving in operational time of farm machinery and increase in the net sown area due to the removal of bunds and channels after using the LLL. Uniform water distribution reduced weed infestation in rice fields, and thereby reducing ~13% herbicide cost than the farmers' practice of weed management. The LLL technology has enormous potential for optimizing WUE in rice without any yield loss (Bhatt et al. 2020). Although LLL has several benefits, its lack of widespread adoption by small- and medium-scale farmers is due to the high cost of the equipment. Moreover, the machinery needs a skilled operator to set and adjust laser settings and operate the tractor. The equipment is restricted only to the regularly shaped fields and less efficient in irregular and small-sized fields (Bhatt et al. 2020).

Mechanical rice transplanting

Transplanting of rice under puddled conditions requires a huge labor input. But in recent decades, labor availability has been significantly reduced particularly during the narrow window period for transplanting due to outmigration and thereby increasing the cost of cultivation. The labor problem

Table 2 Water saving and yield increase in direct-seeded rice (DSR) over puddle transplanted rice (PTR) in different rice producing regions in Asia (Adapted from Bhatt and Kukal 2015a)

References	Soil texture	Country	Amount of saving water in DSR over TPR (cm) ^a	Increased yield of DSR over PTR (t ha ⁻¹ or %)
Farooq et al. (2006)	—	Pakistan	—	1 t ha ⁻¹ increment in grain yield
Ko and King (2000)	—	South Korea	—	0.6 t ha ⁻¹ increment in grain yield
Jahangir et al. (2005)	—	Pakistan	WP decreased by 12% due to lesser yields	
Pathak et al. (2013)	—	India	3–4 irrigations	Similar yields
Bouman et al. (2005)	—		450 mm	Similar yields
Mahajan et al. (2011)	Sandy loam	India	WUE increased by 7.6%	—
Chaudhary et al. (2007)	Sandy loam	India	WP increased by 17.6%	—
Brar et al. (2011)	—	India	WP increased to 5.0%	
Bhushan et al. (2007)	—	India	—	9.0% increase in yield

^aWUE Water use efficiency, WP Water productivity

has aggravated with the commencement of NREGA Act (National Rural Employment Guarantee Act 2007), which provides guaranteed hundred-day salaried work to laborers in their own village in India. Due to this Act, laborers do not prefer to move to other areas away from their place. Nonetheless, in view of COVID-19 pandemic, manual transplanting in labor shortage conditions necessitates the use of agri-machinery for mechanical transplanting rice (MTR) (Bhatt et al. 2020). The MTR has been the preferred technique over manual transplanting due to the advantage of labor-saving, although rice yield is almost similar irrespective of whether it is manually or machine transplanted (Pandirajan et al. 2006). However, the success of MTR depends upon a number of factors, viz. growing of mat-type nurseries and easiness in operation (Bhatt et al. 2015; Bhatt et al. 2020; Bhatt and Kukal 2018).

Singh et al. (2001) observed that ZT-MTR consumed less amount of irrigation water by ~125 mm than the transplanted rice under untilled and un-puddled conditions. In comparison with DSR, MTR helps in improving IWP of rice due to need to sow DSR about one month in advance as compared to MTR (Bhatt 2015). Early sowing requires frequent irrigations due to unsealed soil pores in the absence of puddling. Self-driven transplanters produced similar rice grain yield to manual transplanting while producing significantly higher grain yield than DSR under both aerobic (dry) and anaerobic (wet) conditions. It was due to the higher number of seedlings hill^{-1} under MTR which yielded a considerably higher number of effective tillers m^{-1} row length, higher 1000-grain weight and higher rice yield (Bhatt 2015). In some studies, MTR resulted in higher grain yield and higher water saving than the manual transplanting or direct seeding (Singh et al. 2005a). The uniform growth of rice seedlings was attributed to more uniform placement of rice seedlings and that too at desirable depth which maintained the plant-to-plant spacing. The significantly higher grain yield under MTR was also attributed to its positive impact on yield contributing agronomic traits (Kukal et al. 2014). They also observed that the IWP in MTR was also significantly higher (0.63 g kg^{-1}) than under DSR (0.21 g kg^{-1}) but was similar to that under PTR (0.67 g kg^{-1}).

Despite the numerous benefits of MTR including higher grain yield and fewer number of labor requirements, the acceptance of MTR in NW IGPs has not gained momentum. It was ascribed to the fact that the MTR requires high skill and technical know-how for raising mat-type nursery for use on well-leveled land which is highly laborious and time-consuming. Besides, the mat-type nursery requires extra caution for water management as it requires the regular sprinkling of water to combat Fe deficiency and then keeping the nursery size that optimally fits in the feeder trays. On top of that, raising nursery for a large area is considered as an expensive proposition. Besides, machinery requires

regular repair due to wearing and tearing of parts and requires specialized operator skills and extra expenditure. These issues must be kept in mind for making this technology more efficient and attractive to be accepted by farmers (Bhatt et al. 2020; Bhatt 2015). The foliar application of ferrous sulfate (FeSO_4) needs to ensure immediately after the appearance of Fe deficiency symptoms to combat likely set-back on plant growth during the initial period. The light and frequent irrigation to nursery also helps in arresting Fe deficiency in rice seedlings.

Permanent raised beds

To increase WUE and to alleviate constraints related to conventional flat sowing, permanent raised beds (PRBs) system has been developed (Humphreys et al. 2008; Bhatt et al. 2020). The PRBs have been recommended as an important RCT for enhancing system productivity, profitability and sustainability of cropping systems in the IGPs of South Asia, primarily through improving soil structure and reducing water use (Humphreys et al. 2008). Shifting a system from sowing on flats to that on PRBs presents efficient regulation of irrigation and drainage and consequently reducing aeration stresses. In the early 2000s, it was established that PRBs might result in increased productivity, economic feasibility and sustainability of R–W system in South Asia (Timsina and Connor 2001). Water savings in rice and wheat on PRBs ranged from 0–54% and 9–58%, respectively, which appear to be very high on farmers' fields (Kahlown et al. 2007) as compared with that on research station plots (Jat et al. 2005, 2008). In fine-textured soils in Punjab, Humphreys et al. (2008) observed that a post-sowing irrigation in wheat establishment on PRBs resulted in increased grain yield than under CT. Jat et al. (2008) at Modipuram found a significantly increased yield of 8th wheat crop grown on PRBs than under CT wheat established on flats surfaces.

Increase in yield on the PRBs following crop residue incorporation into the soil is crucial for preserving soil fertility and productivity (Jat et al. 2008). A 4-year study on the R–W system established on PRBs in a sandy-loam soil in the Indian Punjab with surface retention of rice residue (6.0 t ha^{-1}) as mulch in wheat revealed a non-significant change in grain yield of both rice and wheat compared to that with residue removal (Yadvinder-Singh et al. 2008). Rice yields on PRBs established either as TPR or DSR decreased significantly compared to rice established on flats (Humphreys et al. 2008). A study conducted at Modipuram, NW India, also reported a decrease in the relative yield of PTR by ~90% in the first year and by ~77% in the third year on the PRBs (Singh et al. 2005b). Similarly, Jat et al. (2008) reported that grain yield of DSR on the PRBs yielded ~76% lower than the PTR in the 4th year, which might be due to the compaction

of side slopes of the beds during reshaping operations, and thus hindering free root proliferation in aged beds.

The well-drained coarse-textured soils as commonly found in the NW IGPs dry more rapidly on PRBs compared with flats due to exposed larger surface area for evaporation. When PRBs are aged, reshaping of beds is required for desired results. But reshaping the PRBs with tractors causes compaction of side slopes with tier pressure. Pressing of side slopes where rice seedlings are transplanted leads to reduced root growth. Besides, full-furrow irrigation has been recommended for rice establishment on fresh or PRBs every 2 days interval because of greater soil permeability in the un-puddled furrows and better soil macro-pores in the fresh beds or PRBs (Humphreys et al. 2008).

The amount of applied irrigation water was often less on the PRBs than on the flats due to the volumetric restriction of the water in the furrow (Kukul et al. 2005a, b). These authors also found that PRBs had ~ 1.3 °C higher soil temperature than the flat seedbeds during the germination stage of wheat. Wheat planted on PRBs recorded ~ 7.8 – 22.7% higher WUE as compared to the flat layout. Jat et al. (2005) reported higher crop yield and WUE in old PRBs in fine-textured soils. Jat et al. (2005) reported that the IWP of rice under PRBs was $\sim 42\%$ higher compared with CT and $\sim 35\%$ higher compared with ZT. On the other hand, Kukul et al. (2009) observed no water savings in PRBs in a sandy loam soil due to the development of cracks. It is well established that crop performance in terms of yield and IWP under PRBs are higher during the initial years, but with time reshaping of PRBs year after year can result in soil compaction due to increased soil bulk density (Kukul et al. 2008) (Fig. 6). From the initial grain yield of 4.64 t ha^{-1} in 2003, rice yields on PRBs declined linearly by ~ 19 – 59% between 2004 and

2006. Increased age of PRBs exerted restriction on root proliferation due to increased bulk density. The root density in 0–15 cm depth in the middle of fresh beds was $\sim 59\%$ higher than on the PRBs. The surface area of beds was increased by $\sim 25\%$ which resulted in increased absorption of radiant energy. The higher soil temperature in the bed surface resulting from increased radiant energy further accelerates the unproductive evaporation losses from the soil surface. The old beds result in lower yields due to restricted root growth as compared to the fresh beds (Kukul et al. 2008).

Irrigation scheduling based on soil matric potential

Irrigation scheduling in rice based on soil matric potential (SMP) using a tensiometer has been reported as an effective technique (Kukul et al. 2005a; Bhatt 2020a; Bhatt et al. 2020). Tensiometer-guided irrigation scheduling leads to a considerable reduction of irrigation water with almost comparable or even increased yields than traditional flood irrigation (Bhatt 2020b; Bhatt et al. 2020). Irrigation scheduling of rice as guided by tensiometer helped decrease water consumption by $538,179 \text{ L acre}^{-1}$ and electricity consumption by $101 \text{ kWh acre}^{-1}$ in the Indian Punjab (Vitta et al. 2014; Table 3). The major obstacle for the adoption of SMP-based irrigation scheduling in rice in Punjab is due to the free electricity supply to the agriculture sector. The farmers use irrigation water lavishly in view of power supply which is free of cost and feel it cumbersome to schedule irrigation as per SMP-guided tensiometers. The policies, therefore, need to be framed and implemented in the NW IGPs to ensure large-scale adoption of situation-specific water-saving technologies to arrest the rapidly declining groundwater table.

Fig. 6 The growth pattern of rice roots on permanent raised beds (PRBs, **a**), fresh raised beds (**b**) and the compaction of side slope (**c**) by tractor–tier pressure exerted on soil slopes of PRBs (Adapted from Kukul et al. (2008))

Table 3 Irrigation water and electricity (power) savings with soil matric potential-based irrigation scheduling using tensiometers compared to flood irrigation in different rice-growing regions in Punjab, northwestern IGPs (Adapted from Vatta et al. (2014))

Locations in Punjab (India)	Water saving (m ³ ha ⁻¹)		Water saving (%)		Power saving(kwh ha ⁻¹)	
	2012	2013	2012	2013	2012	2013
Jalandhar	984.4	1041.7	12	19	172.5	182.5
Amritsar	952.2	867.1	14	14	185.0	167.5
Ludhiana	1504.0	823.9	14	12	282.5	152.5
Moga	1530.3	1216.1	13	19	317.5	250.0
Kapurthala	1132.2	667.5	11	11	220.0	130.0
Tarn Taran	1372.1	752.0	16	12	260.0	142.5
Overall	1345.4	930.1	14	15	252.5	175.0

Table 4 Irrigation water saving in wheat under zero tillage over conventional tillage (Adapted from Singh et al. (2008))

Irrigation scheduling	Irrigation water applied (cm irrigation ⁻¹)		Water saving (%)
	Conventional tilled	Zero tilled	
Irrigation at pre-sowing	10	0	100
1st irrigation	7.5	6.38	15
2nd irrigation	7.5	6.75	10
3rd irrigation	7.5	7.5	Nil
4th irrigation	7.5	7.5	Nil
Total	40.0	28.1	30

Zero tilled wheat and Happy Seeder

The ZT wheat has gained considerable area under R–W system in the NW IGPs with progressive improvements in yield, economics and WUE (Ladha et al. 2009). In the untilled soils, direct wheat drilling can result in improved soil health and decreased water use (Sidhu et al. 2008; Singh et al. 2020a). In addition, ZT wheat can increase both crop and water productivity (Bhatt et al. 2017; Bhatt and Kukal 2017; Bhatt et al. 2020). The Happy Seeder, a modified ZT machine, has been the most promising technology for eco-friendly rice residue management (Sidhu et al. 2008; Singh et al. 2020a). Wheat under the HS technology sown on left-over moisture in soil directly saves at least one pre-sowing irrigation equivalent to irrigation water saving by ~30% (Singh et al. 2008; Table 4). Rice residue retained as surface mulch intercepts solar radiation and reduces soil evaporation losses by ~42–48 mm during the season. There is a decrease of ~30% irrigation water requirement, a large proportion of which comprises the decrease in evaporation loss than the transpiration, such decrease in irrigation water requirement ultimately improves the crop and water productivity. Sidhu et al. (2014) reported ~3.2% increase in wheat yield under the HS-seeded plots compared to the CT plots (Table 5).

. It has now been well established that the performance of ZT improves over the years (Jat et al. 2014). These authors

Table 5 Wheat yields under the Happy Seeder (HS) and the conventional tillage (CT) sown plots and yield increase in HS over CT in Punjab, NW IGPs (Adapted from Sidhu et al. (2008))

Study years	Wheat yield (t ha ⁻¹)		Yield increase in HS over CT(%)
	Happy Seeder	Conventional tilled	
2007–2008	4.59	4.50	2.0
2008–2009	4.54	4.34	4.6
2009–2010	4.42	4.30	2.8
Mean	4.56	4.42	3.24

reported that the ZT method practiced for seven years under the R–W rotation resulted in higher grain yield and greater economic returns, compared with CT. Sidhu et al. (2008) studied the root growth and root architecture traits between the CT and ZT sown wheat and found no significant difference in the Indian Punjab. Zero tillage has now been the most credible RCT for improving crop and water productivity, particularly in the context of changing climate, although this requires at least 3–5 years to achieve significant positive yield effects.

Brar and Walia (2007) reported that CT favored the germination of grassy weeds in wheat under R–W system as compared to ZT, while a reverse was observed for broad-leaved weeds. In contrast, under CT, weed seeds are higher in number in deeper soil profile which would depend on the tilling depth of the machinery used. Due to reduced soil moisture and nutrient availability in lower soil layers, weed seed germination is reduced to a greater extent under ZT compared to CT (Bhatt 2015; Bhatt and Kukal 2017; Bhatt et al. 2020) (Table 6). On the other hand, there is experimental evidence which shows that residue mulch under ZT (as with the HS) helps to check weed population because of restricted furrow opening (Chhokar et al. 2007). Even the weed seeds that emerge from soil remain snubbed under residue mulch. Due to decreased light interception, weed growth is retarded significantly. Long-term adoption of ZT gradually reduces the weed seed bank in the soil (Carr et al. 2013). The shading and allelopathic effects significantly

Table 6 The combined effect of tillage (*P* puddling, *CT* conventional tillage, *ZT* zero tillage) and establishment methods (viz. direct-seeded rice and mechanical transplanted rice) on weed biomass (t ha^{-1}) in wheat and rice under a R–W system (Adapted from Bhatt (2015))

Establishment methods	Tillage (Rice)	Wheat			Rice		
		CT	ZT	Mean	CT	ZT	Mean
Direct-seeded rice	P	0.10	0.19	0.45	0.72	0.76	0.74
	CT	0.25	0.48	0.36	0.86	1.11	0.98
	ZT	0.05	4.04	2.04	1.11	1.46	1.29
Mean		0.13	1.77	0.95	0.89	1.11	1.00
Mechanical transplanted rice	P	0.06	0.90	0.48	0.74	0.83	0.79
	CT	0.21	1.38	0.79	0.96	1.02	0.99
	ZT	0.09	2.58	1.34	1.15	1.54	1.35
Mean		0.12	1.62	0.87	0.95	1.16	1.04

LSD ($p < 0.05$)

Tillage (Wheat), 0.69 for wheat and 0.13 for rice; Establishment method (Rice), NS for both rice and wheat; Tillage (Rice), 0.29 for rice and 0.09 for wheat; Tillage (Wheat) × Establishment method (Rice), NS for both rice and wheat; Establishment method (Rice) × Tillage (Rice), 0.41 for rice and NS for wheat; Tillage (Wheat) × Tillage (Rice), 0.41 for rice and 0.4 for wheat

reduce the seed germination and retard the emergence and growth (Brar and Walia 1989).

Conclusions, research gaps and technological interventions

Conclusions

This review has identified the unsustainability issues and problems in the R–W system of the NW IGPs while also recognizing the role of this important cropping system to achieve the food security of the increasing population of the region and South Asia. Few important conclusions have emerged from this review. First, RCTs developed and evaluated in the NW IGPs are highly site- and context-specific. For examples, the DSR is not a viable option for light-textured soils due to severe Fe deficiency and high weed infestation. The mechanical transplanting rice (MTR) requires high skills for nursery raising and machine operating. In the water-stressed regions, cultivation of short-duration rice varieties with late transplanting is real water-saving technologies. The tensiometer-based irrigation scheduling in laser-leveled fields together with use of appropriate crop varieties could save a substantial amount of irrigation water with increased IWP. The surface retention of rice residue and wheat establishment with a Happy Seeder have overwhelming significance in increasing SOC sequestration and enhancing the system sustainability in terms of reduced energy, water and C footprints. Enhancing the SOC helps increase nutrient availability and improvement in the soil physicochemical and hydrothermal properties for the long-term sustainability of the R–W system. This review has shown that the energy-saving RCTs such as LLL, SMP-based irrigation scheduling, PRBs, ZT, MTR and DSR

could be recommended for the NW IGPs but would require wider evaluation across sites and soils. Further, an integrated approach is required for the long-term sustainability of the system for addressing issues related to land degradation, declining groundwater and reduced IWP, economics, and increasing energy use and C footprints, and for increasing livelihood security in the current context of changing climate. Reduced or zero tillage with full straw loads of the previous crop could help achieve the R–W system sustainable and profitable while meeting the ever-increasing food demand from shrinking land and water resources.

Research gaps

This review has identified the following key research gaps for increasing the productivity and addressing the sustainability issues of R–W system in the NW IGPs.

- Most research focused only on a single RCT and that too within one crop or season, without studying the effect of that RCT on the preceding or the succeeding crop. Therefore, future research needs to focus on the integration of different RCTs within a cropping system basis while assessing the sustainability of the system in terms of water, energy, economics and livelihood security. In future, the determinations of different soil water balance components, viz. irrigation, rainfall, seepage, drainage and ET, under different establishment methods must be included during the planning stage of any research studies.
- There is a need to study the residual effect of the RCTs on the irrigation water requirement of rice or wheat or R–W system and to enhance the IWP. In most studies, the intervening period (the fallow period between two

crops) has been ignored or given less emphasis. The research needs immediate focus on studying the system as a whole including the intervening period rather than focusing on rice or wheat alone while planning studies on IWP in R–W system.

- c. There is an urgent need to study the variations in soil moisture with different tillage and crop establishment methods such as ZT or CT for wheat, DSR and MTR. Drum-seeded rice or un-puddled transplanted rice is other options that require thorough evaluation in the NW IGPs. Emphasis needs to be given to study these technologies in the R–W system context under diverse soil-textural classes and agro-climatic conditions.
- d. Double ZT has been an important RCT for improving soil physicochemical properties, but due to the presence of significant weed biomass, ZT requires immediate attention for finding efficient control measures. The appropriate herbicides need to be tested and advocated for efficient weed control measures in DSR and ZT wheat.

Technological interventions

The following technological interventions for R–W system need to be evaluated and promoted in the NW IGPs to achieve higher land and water productivity, improve soil health, mitigate GHGs emissions and lessen water and C footprints.

1. The promotion of RCTs, such as ZT, HS, LLL, PRBs and SMP-based irrigation scheduling which are cost and resource-efficient and eco-friendly can help increase productivity, profitability and sustainability of the R–W system. There is a need to ensure large-scale initiatives that integrate awareness, technical know-how, on-farm demonstrations, subsidy on agri-machinery for crop residue management and rice transplanting and financial incentives to farmers who retain crop residues on their fields. Rice–wheat farmers can be benefited with the adoption of Happy Seeder technology for wheat seed drilling into standing rice stubbles.
2. There should be a clear understanding that these technologies are site- and context-specific and hence should not be generalized. The DSR should be promoted only on the medium- to heavy-textured soils and not on the light-textured soils. To promote DSR on light-textured soils with low Fe availability, there is a need to strengthen the rice breeding research for developing Fe-efficient varieties. The agricultural extension agencies could play a key role in educating the farmers with the conduct of front-line demonstrations and on-farm testing by highlighting the effect of foliar application of ferrous sulfate on rice grown in light-textured Fe-deficient soils.

3. The promotion of short-duration rice and wheat varieties helps saving water due to their shorter life cycle in the field, but farmer adoption has been low due to their lower yields. Some new short-duration rice and wheat cultivars should be bred and recommended to the farmers for their adoption. Timely rice transplanting after June 20 is important as it coincides with monsoon and results in reduced ET losses due to increased relative humidity. This could sustainably handle the problem of rapidly declining under-ground water, particularly in the water-stressed semiarid region to enhance crop and water productivity. The large-scale adoption of short and medium-duration rice varieties in the NW IGPs can significantly impact the water and energy footprints of rice cultivation.
4. Farmers need to be provided incentives for adoption of rice residue management technologies which can also encourage others for managing residues into their fields rather than burning in open fields; such interventions would improve soil health and reduce GHGs emissions.
5. For the *in situ* management of rice residue before wheat sowing, the Happy Seeder machine needs to be promoted as a cost-effective technology; this machine also helps in reducing energy and water use and adds organic matter to the soil.
6. There is an urgent need to encourage farmers to increase SOC in their fields through residue retention; residues can regulate soil evaporation, soil temperature and soil moisture dynamics and help increase C sequestration of R–W soils.
7. Farmers need to be encouraged for the adoption of integrated approach such as delayed transplanting of short-duration rice cultivars followed by wheat seeding into standing rice stubbles for the long-term sustainability of crop, land and water productivities of the R–W system.
8. The extension efforts need to strengthen, disseminate and popularize the RCTs among farmers and encourage them for their widespread adoption.

Funding No financial support existed in this review article.

Compliance with ethical standards

Conflict of interest The authors declared that they have no conflict of interest.

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