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REVIEW

Challenges and opportunities in productivity and sustainability of rice cultivation system: a critical review in Indian perspective

Neeraj Kumar[1] · R. S. Chhokar[1] · R. P. Meena[1] · A. S. Kharub[1] · S. C. Gill[1] · S. C. Tripathi[1] · O. P. Gupta[1] · S. K. Mangrauthia[2] · R. M. Sundaram[2] · C. P. Sawant[3] · Ajita Gupta[3] · Anandkumar Naorem[4] · Manoj Kumar[5] · G. P. Singh[1]

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Abstract

Rice–wheat cropping system, intensively followed in Indo-Gangetic plains (IGP), played a prominent role in fulfilling the food grains demand of the increasing population of South Asia. In northern Indian plains, some practices such as intensive rice cultivation with traditional method for long-term have been associated with severe deterioration of natural resources, declining factor productivity, multiple nutrients deficiencies, depleting groundwater, labour scarcity and higher cost of cultivation, putting the agricultural sustainability in question. Varietal development, soil and water management, and adoption of resource conservation technologies in rice cultivation are the key interventions areas to address these challenges. The cultivation of lesser water requiring crops, replacing rice in light-textured soil and rainfed condition, should be encouraged through policy interventions. Direct seeding of short duration, high-yielding and stress tolerant rice varieties with water conservation technologies can be a successful approach to improve the input use efficiency in rice cultivation under medium–heavy-textured soils. Moreover, integrated approach of suitable cultivars for conservation agriculture, mechanized transplanting on zero-tilled/unpuddled field and need-based application of water, fertilizer and chemicals might be a successful approach for sustainable rice production system in the current scenario. In this review study, various challenges in productivity and sustainability of rice cultivation system and possible alternatives and solutions to overcome such challenges are discussed in details.

Keywords Rice production · Factor productivity · Residue management · Groundwater table · Conservation agriculture · Global warming

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✉ Neeraj Kumar
neerajkumarsaini.126@gmail.com;
Neeraj.Kumar2@icar.gov.in

[1] ICAR- Indian Institute of Wheat and Barley Research, Karnal, Haryana 132001, India

[2] ICAR-Indian Institute of Rice Research, Hyderabad, Telangana 500030, India

[3] ICAR- Central Institute of Agricultural Engineering, Bhopal, Madhya Pradesh 462038, India

[4] ICAR- Central Arid Zone Research Institute, Regional Research Station-Kukma, Bhuj, Gujarat 370105, India

[5] Indian Institute of Soil and Water Conservation, Regional Centre, Chandigarh 160019, India

Introduction

Rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) is the largest cropping system practised in South Asian countries (Nawaz et al. 2019). About 85% of this cropping system falls in Indo-Gangetic plains (IGP), covering nearly 13.5 million hectares (mha) area (Saharawat et al. 2012). India alone covers approximately 76% of IGP, spreading in the states of Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal. Being staple food crops in the country, rice and wheat played a key role in minimizing the gap between food grains demand and production. In recent years, country witnessed surplus food grains production through an integrated approach of high-yielding varieties, disease and pest management, nutrient management, irrigation water management and better mechanization. Rice and wheat production was reported as 34.6 million tonnes (mt) and 11

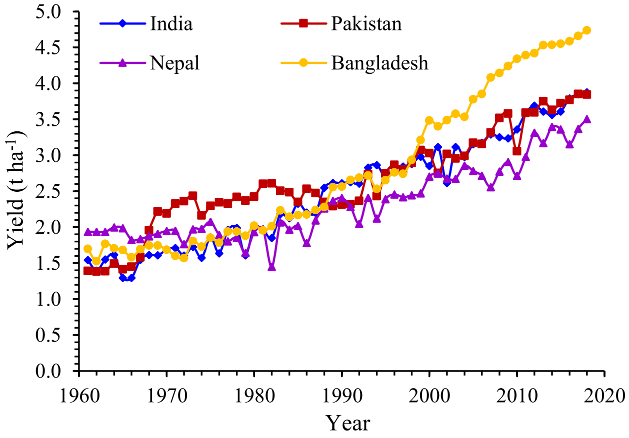


Fig. 1 Trend of rice yield in South Asia (*Source: FAOSTAT*)

mt, respectively, during 1960–1961, which is expected to rise to 122.3 and 109.5 mt, respectively, during 2020–2021 (PBAS 2019; PIB 2021). In the last one decade, slow growth in crop productivity has been registered, which may further decline in near future due to some ongoing resource guzzling practices. The trend of rice yield in South Asia is presented in Fig. 1. From 1998 onwards, Bangladesh witnessed a noble growth in rice yield, surpassing India and Pakistan, and continues to uphold the growing trend. It was due to intensive use of modern technologies such as cultivation of high-yielding varieties, adoption of improved irrigation technologies and balanced fertilizer application (Ahmed 2004; Shew et al. 2019). In past few years, rice productivity in India looks stagnant, even it may decline in future due to over-exploitation of natural resources (Ladha et al. 2009), low seed replacement rate (UPSDR 2019), poor management of irrigation water, fertilizer and crop residue (Ladha et al. 2009), same cropping pattern over the years (Nambiar and Abrol 1989) and lack of awareness about consequences of faulty cultivation practices among farmers (Dis et al. 2015; UPSDR 2019). The problem is not limited to India but also extends to other countries of IGP, where intensive tillage practices and confined agro-biodiversity degraded natural resources to a great extent. Researchers questioned the sustainability of rice–wheat cropping system under present challenges of stagnant yield (Ladha et al. 2003a), soil degradation (Bhandari et al. 2002; Tripathi and Das 2017), declining water table (Humphreys et al. 2010) and environmental pollution (Bijay-Singh et al. 2008). The trend of the area covered under rice cultivation in South Asia is shown in Fig. 2. In IGP, most of the rice cultivated area falls under Indian Territory, but this area was bounded within 40–45 mha during 1988–2018. The stagnant and limited spatial coverage of rice area is due to unavailability of irrigation facility, high water requirement of the crop, declining water table, labour-intensive cultivation, poor feed quality of by-product (straw), degradation of soil structure and irregular nature of rainfall. In fact, rice cultivation using the conventional method is believed as water-, energy- and capital-exhaustive practice (Bhatt et al. 2016).

India, a home to 17.7% of the world population, is the prime consumer of water requiring 3000 billion cubic meters annually (Vyas et al. 2019). India is the largest consumer of groundwater accounting for about 230 km^3 of groundwater use every year (TWB 2012). India receives nearly 4000 billion cubic meters of precipitation every year. However, only 48% of this water is stored in the surface and groundwater bodies due to losses in various hydrological processes such as runoff, water discharge through rivers to oceans, evaporation and evapotranspiration (Verma and Phansalkar 2007; Dhawan 2017). A major portion (88–90%) of groundwater extracted is used for irrigation purpose in agricultural fields (Siebert et al. 2010; GoI 2014). Rice crop requires huge amount of water than other cereal crops, and it consumes about 3000–5000 L of water to produce 1 kg of rice (Bouman 2009; Geethalakshmi et al. 2011). Tuong and Bouman (2003) reported that around 75% of global rice is produced by raising the seedlings in a nursery followed by transplanting operation in puddled field. In addition to excessive water, capital and energy demand, this practice of rice cultivation is associated with soil degradation (Bhatt et al. 2016), loss of ecosystem (Nawaz et al. 2019) and environmental pollution (Jimmy et al. 2017).

In the current scenario, when degradation of soil structure, declining soil health, residue handling issues and harmful emissions from rice cultivated fields are taking place, the sustainability of rice production system is questionable. In India, rice is cultivated on 44 mha area, accounting 20% of total rice production worldwide (Oo et al. 2018). It is estimated that India needs to produce 130 mt rice by 2030 to meet the demand of the growing population (Gujja and Thiyagarajan 2009). To achieve the projected demand, use of high-yielding varieties, expansion of rice cultivation area and wet tillage would be required, but latter two practices would further increase the irrigation water demand and greenhouse gas emissions (Oo et al. 2018). Considering all these aspects, an attempt has been made to critically review the challenges and opportunities in productivity and sustainability of rice cultivation system in Indian perspective. Also, attempts were made to highlight the possible alternatives and solutions to overcome the present challenges in rice cultivation system. The key challenges and intervening areas in rice cultivation system are discussed in details under the following sections:

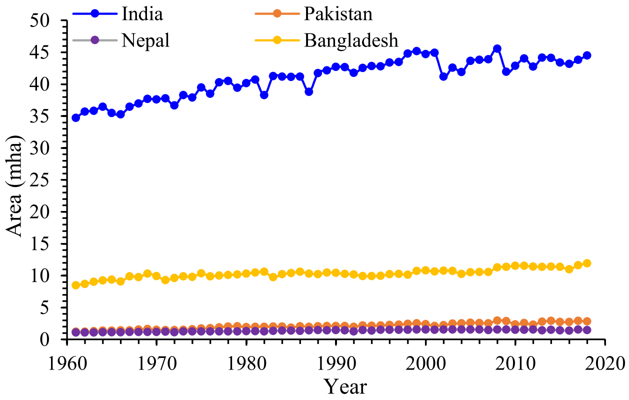


Fig. 2 Trend of rice area in South Asia (*Source: FAOSTAT*)

Underground water table depletion

India is the top user of groundwater around the world (Mukherjee et al. 2015), and it has about 25% share in global groundwater consumption. In fact, the groundwater consumption of India is higher than collective groundwater use of China and USA (Margat and van der Gun 2013). The unsystematic use of groundwater for irrigation caused widespread over-exploitation of groundwater resources (Rodell et al. 2009), which is not sustainable in long-term. In India, out of 160 mha cultivable land, only 68 mha cultivated area is covered with irrigation facilities, while about two-third area is still rain-dependent (Dhawan 2017). About 61.6% of irrigation water is extracted from groundwater through wells, dug wells, shallow tube wells and deep tube wells (Suhag 2016). The rate of groundwater level fall in India is probably the fastest globally (Aeschbach-Hertig and Gleeson 2012). During the last three decades, underground water levels in northern region of India have dropped from 8 to 16 m below ground level, and in rest of India, it has declined from 1 to 8 m below ground level (Sekhri 2013). Another estimate reports that north-western India lost 109 giga cubic meter of groundwater between 2002 and 2008 (Rodell et al. 2009). The rapid extraction and slow groundwater recharge caused groundwater table to fall at a rate of about 1 m per year (m y^{-1}) in Punjab and Haryana, which may fall more rapidly in the coming years (Humphreys et al. 2010; Singh et al. 2014). In many cities of north-western India, the groundwater table is declining at a rate of 1.6 m y^{-1} (Singh et al. 2015). The huge volumetric loss of groundwater and its faster declining rate might be the cause for India becoming a home for 25% of worldwide population living under water-scarce conditions (Mekonnen and Hoekstra 2016; Anonymous 2019a). The continuous decline of groundwater table has created water-stressed condition, affecting the per-capita water availability. In 1951, per-capita water availability was 5177 cubic meter per year (m^3 y^{-1}), which reduced to 1598 m^3 y^{-1} in 2011 as presented in Table 1. It has made India a water-stressed country according to international norms (Dhawan 2017; GoI 2018). Further, projected per-capita water availability is expected to fall to 1174 m^3 y^{-1} by 2051 (GoI 2018). Water stress to scarce condition would put enormous pressure on the sustainability of water-guzzling crops like rice. Traditionally grown rice requires around 200–240 cm of the water column from nursery preparation to harvesting stage (Humphreys et al. 2008; Chauhan et al. 2012). However, the actual amount of water applied by the farmers is much higher especially in light-textured soils (Timsina and Connor 2001). Over the years, flood irrigation has become a common practice, even water ponding is considered as necessary part of rice cultivation. Easily accessible and sufficient availability of irrigation water in north-western India turned out rice–wheat cropping system, a classical example of high productive system in non-ideal soils for rice cultivation, which are porous, coarse and highly permeable in nature (Chauhan et al. 2012). However, intensive cultivation of rice–wheat cropping system in these regions has forced the farmers to extract the groundwater with submersible pumps, which resulted in over-exploitation of groundwater. Singh and Kasana (2017) reported that area under the safe limit of groundwater (3.1–10 m) in Haryana state reduced from 44 to 34%, while the area under critical and over-exploited category of groundwater increased from 56 to 64% and 4 to 23%, respectively, during 2004–2012. The decline in groundwater of many districts of Haryana was in the tune of 0.7–1.1 m y^{-1}. It was concluded that variations in groundwater levels could be due to rice–wheat cropping systems, irregular distribution of rainfall, over urbanization, variation in hydrogeological setup and different aquifer conditions. The irregularity in annual rainfall of India is presented in Fig. 3. The deviation of annual rainfall from mean value could be very high during the drought years. Moreover, rainfall pattern makes this problem more complicated as during the monsoon season, events of excessive rainfall and the large interval between two consecutive rainfall events take place. In the absence of rainfall events at a certain interval, rice cultivation requires a huge amount of irrigation water, causing rapid extraction of groundwater, which is associated not only with water table depletion but also with carbon dioxide (CO_2) emissions, where engines and tractors are used as the prime mover for pumping unit. Undoubtedly, excessive rice cultivation in non-ideal soils, traditional rice cultivation practices and major dependency of irrigation on groundwater would put enormous pressure on natural resources. Furthermore, the excessive use of chemicals and fertilizers in rice cultivation under coarse-textured soils also poses other threats of soil and groundwater contamination with harmful chemicals.

Table 1 Change in population and per-capita water availability of India over the years

Year	Population (in millions)	Decadal change in population (%)	Per-capita water availability (m^3 y^{-1})	Decadal change in per-capita water availability (%)
1951	361	–	5177	–
1961	439	21.6	4987	−3.8
1971	548	24.8	4632	−7.7
1981	683	24.6	3498	−32.4
1991	846	23.9	2209	−58.4
2001	1029	21.6	1820	−21.4
2011	1210	17.6	1598	−13.9
2021*	1345	11.2	1421	−12.5
2031*	1463	8.8	1306	−8.8
2041*	1560	6.6	1225	−6.6
2051*	1628	4.4	1174	−4.3

*Estimated values

Sources: Anonymous (2019b), Babita and Kumar (2019)

Groundwater pollution

Groundwater pollution is a serious concern, which affects grain quality and health of human and animals. The excess and untimely use of N-fertilizer is associated with nitrate leaching, which pollutes the groundwater (Bhatt et al. 2016). In a study, researchers found higher nitrate content in groundwater of the regions where intensive rice–wheat cropping system was practised (Bajwa 1993). The problem of groundwater pollution is more serious in rice cultivating regions with coarse-textured soils, where frequent and heavy irrigation is applied. Bouman et al. (2002) found higher N leaching losses under wet season rainfed rice than irrigated rice. Pathak et al. (2009) observed higher cumulative leaching losses of nitrogen (46–69 kg N ha^{-1}) in rice field than the wheat field (16–22 kg N ha^{-1}). Rainfall plays an important role in N losses, which can be as high as 18% of applied nitrogen in high rainfall years (Pathak et al. 2009). Wang et al. (2015a) reported that intensive rice cultivation practice in subtropical China led to moderate ammonium-N (NH_4-N) pollution of shallow groundwater. It was concluded that flooded land and excessive N-fertilizer rate could lead to worse NH_4–N and nitrate–N (NO_3–N) pollution, respectively. Coarse-textured soils leach N more rapidly than heavy-textured soils, and N leaching under such soils is highly dependent on N-fertilizer application (Benbi 1990). Though it is very difficult to stop the nitrogen leaching completely, better management practices by adopting the proper irrigation and fertilizer scheduling can minimize the leaching losses and improve N-use efficiency (Singh et al. 1995). The cultivation of high water requiring crop like rice in arsenic-contaminated soils like in middle IGP of northern India carries the threat of groundwater contamination with arsenic (Srivastava et al. 2015). In many locations, arsenic content of groundwater under rice cultivation exceeded the acceptable limit (10 µg L^{-1}), raising the contamination level up to 312 µg L^{-1} (Srivastava et al. 2015). The application of such polluted groundwater for irrigation purpose can lead to other problems of soil and grain toxicity.

Soil and grain toxicity

It is extremely important to relook the practice of intensive rice cultivation under toxic soils and toxic irrigation water as it could lead to grain toxicity, affecting the human health. The practice of growing rice in arsenic-contaminated soils like in middle IGP escalates the possibility of soil and grains contamination with arsenic beyond the safe limit (Srivastava et al. 2015). It was reported that arsenic content in soil under rice cultivation exceeded the allowable limits of 20 mg kg^{-1}, raising the contamination level up to 35 mg kg^{-1}. Moreover, arsenic toxicity in the grains was found in the range of 0.179–0.932 mg kg^{-1}, leaving 8 of 17 varieties unsafe for human consumption. Dhillon and Dhillon (1991) found selenium toxicity in the soil and plants when selenium contaminated irrigation water was used for irrigation in rice–wheat cropping system under silty loam soils for a longer period. The intensive cultivation of frequent irrigation requiring crops like low land rice turned out one of the major factors responsible for the deposition of seleniferous material in the soil, leaving more than 100 ha area under selenium toxicity (Dhillon and Dhillon 1991). Sara et al. (2017) observed that arsenic and selenium content of soil increased with duration of rice monoculture system. The increase in arsenic and selenium concentration in soil caused toxicity in rice grain. The anaerobic condition in rice cultivation affects nutrient uptake

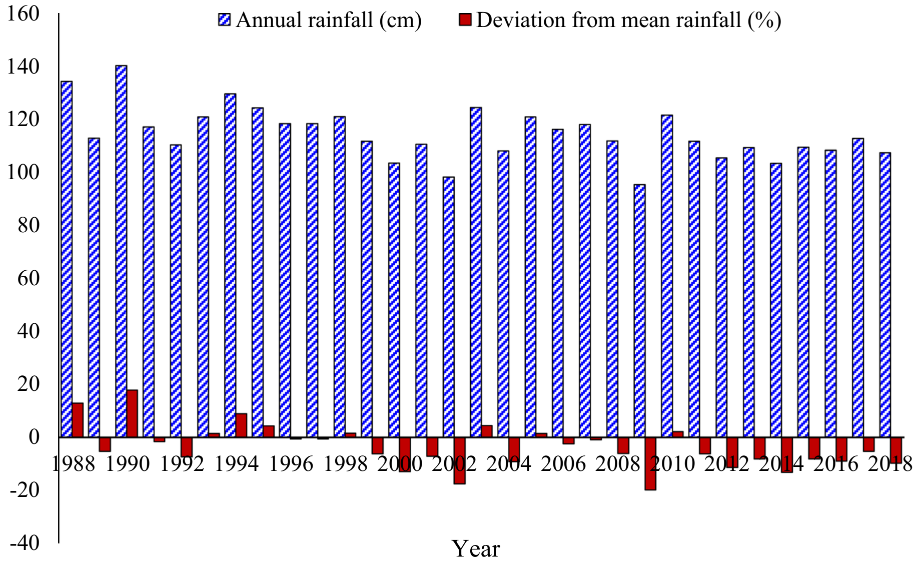


Fig. 3 Annual rainfall and deviation from mean rainfall of India during 1988–2018 Source: Somasundar (2014), Jaganmohan (2020)

by the plants and production of toxic substances (De Datta 1981). Tran (1998) also reported that long-term soil puddling and rice monoculture system increases the risk of soil toxicities. Shah et al. (2021) highlighted the toxic residues of pesticides and metalloids in rice grain under flooded rice cultivation system. Needless to say that intensive rice cultivation with puddling and flooding method projects the health risk associated with soil and grain toxicity in long-term. Sara et al. (2017) recommended to control these elements with prior importance by employing the different actions including crop rotations, soil amendments, etc.

Degradation of soil structure

Rice cultivation using conventional method requires intensive wet tillage primarily to reduce the percolation losses and to suppress the weed growth. The repeated puddling operation creates an impervious layer at 15–20 cm depth, which restricts water infiltration and root growth (Aggarwal et al. 1995; Kukal and Aggarwal 2003). The negative effects of subsurface compaction on the establishment, seed emergence, root growth and yield of succeeding crop are of major concern (Kukal and Aggarwal 2003). The puddling operation deteriorates the soil structure by damaging the soil aggregates, breaking the capillary pores and dispersing the fine clay particles (Aggarwal et al. 1995). Bakti et al. (2010) recommended that in fine-textured soil like clay having low percolation rate, puddling, which is capital intensive and detrimental to soil structure, should be minimized. It would be beneficial for soil health and its functionality to replace the puddled transplanted rice (PTR) with lesser intensive cultivation practices such as zero-till-based mechanized transplanting, direct-seeded rice (DSR) and strip tillage-based transplanting. The adoption of such rice cultivation practices under conservation agriculture (CA) either on a flat or permanent bed and diversified cropping systems with wetting and drying irrigation method could be effective to improve the soil structure (Singh et al. 2005a; Bakti et al. 2010; Chauhan et al. 2012).

Soil health deterioration

The intensive tillage, puddling operation and excessively cultivation of rice–wheat cropping system deteriorated health, structure and nutrient balance of the soils in north-western India. Killebrew and Wolff (2010) reported that long-term intensive rice cultivation system led to soil salinization, nutrient deficiencies, soil toxicities and reduced capacity of the soil to supply the nitrogen to the plant roots. Such changes can lead to reduced yield and abandonment of paddy fields in long-term. In other studies, Boparai et al. (1992) and Mohanty and Painuli (2004) observed that long-term water submergence and mineral fertilization practices in conventional rice cultivation resulted in degraded soil quality in terms of disintegration of stable aggregates and reduced soil organic matter. The concerns have been expressed on the sustainability of high yield of crops due to intensive rice cultivation system and multiple harvests of crops in a year (Livsey et al. 2019). The sustainability of rice production under rice–wheat cropping system in Punjab has been reported at risk due to soil degradation and declining water table (Dhaliwal et al. 2020) along with inadequate crop residue recycling and lack of organic fertilization. These changes in soil–water environment led to micro-nutrients deficiencies and yield stagnation (Dobermann and Fairhurst

2002; Yadvinder-Singh and Bijay-Singh 2003). However, such negative impacts can be lowered by adopting rice in combination with leguminous crops and rice–oilseed crop rotation (Chen et al. 2012; Meetei et al. 2020). Moreover, shifting the rice monoculture to rice–fish farming showed positive effects on soil health in terms of labile pool of C fractions, microbial populations, nutrients and soil fertility in addition to environmental sustainability (Bihari et al. 2015). The problem of declining soil health becomes worse with the burning of rice residue, which results in 20–100% loss of precious nutrients retained in the residue (Singh et al. 2008). In response to nutrient losses with residue burning, farmers have to apply more fertilizers to obtain a similar crop yield, which raises the cost of cultivation. It needs urgent attention to improve the soil health in which residue retention on the soil surface and seeding with zero-till practice can play significant roles (Malik and Yadav 2008; Sidhu et al. 2008). Extending the resource conservation technologies (RCTs) for rice cultivation under conventional and CA along with soil water potential-based irrigation scheduling could be effective to improve the soil health and environmental quality (Dwivedi et al. 2003; Gupta and Sayre 2007; Jat et al. 2010).

Declining crop response

The decline in crop response to applied fertilizers is a serious concern, causing the farmers to apply fertilizers above the recommended dose in an injudicious way. Although crop response to P and K fertilizers can be realized only after 5–10 years, it is necessary to apply these fertilizers along with N as the application of N-fertilizer alone in long-term can cause yield decline in rice–wheat cropping system (Bhatt et al. 2016). The low fertilizer use efficiency due to fertilizer losses as surface runoff, leaching, volatilization and unfavourable soil moisture is one of the major reasons for declining crop response to applied fertilizers. Moreover, long-term practice of same cropping sequence like rice–wheat in IGP over the years, injudicious and unbalanced application of fertilizers, inappropriate timing of fertilizer application and low soil organic matter are other factors responsible for declining crop response to applied fertilizers (Chauhan et al. 2012; Bhatt et al. 2016). In rice–wheat cropping system, the net negative balance of NPK is 2.22 mt per annum for IGP (Tandon 2007). The current trend of decline in crop response to applied fertilizers would create more difficulties for any further improvement in crop productivity. Therefore, soil and water management, integration of green or brown manuring, growing of dual-purpose pulses and addition of organic manure along with inorganic fertilizers are required to reverse the trend and improve the crop response in long run.

Decreasing water productivity

In the scenario of depleting groundwater table, decreased water productivity is of major concern, which has been reported from different agro-climatic zones of the country (Humphreys et al. 2010; Bhatt 2015). Decreased water productivity along with deteriorating water table can hamper the objective of sufficient grains production in future. It requires urgent attention to increase the water productivity of crops especially C3 crops like rice, which are less water efficient. This can be achieved by grabbing the opportunities at biological, environment and management levels (Sharma et al. 2015). Rice (lowland) is a less water productive crop (0.2–1.2 kg m^{-3}) as compared to wheat (0.8–1.6 kg m^{-3}) and maize (1.6–3.9 kg m^{-3}) (Sharma et al. 2015). While the Punjab and Haryana states of India report the highest land productivity (4 tonnes per hectare) for rice, the water productivity is relatively low at 0.22–0.60 kg m^{-3}, even though these states have almost 100% irrigation coverage. It signifies the inappropriate use of irrigation water. Puddling and flooding operations in lowland rice production system consume a major portion of irrigation amount, causing lesser water productivity. The PTR requires 15–25 cm water column for saturation and flooding of soil (Tuong 1999). However, puddling method also reduces deep drainage losses by lowering the infiltration rate, which is generally high in the absence of puddling in coarse-textured soils (Sharma et al. 2004). The reduction in infiltration rate depends on soil texture, tillage intensity and puddling operations, water table and depth of floodwater (Gajri et al. 1999; Kukal and Aggarwal 2002). Bouman and Tuong (2001) reported that rice performs well in terms of yield when continuous flooding or saturated soil condition is maintained. Rice yield reduces when soil moisture drops below to saturation level. Technologies such as alternate wetting and drying (AWD), a system of rice intensification (SRI), bed planting, DSR and soil mulching have been adopted to reduce the water inputs and improving the water productivity (Tuong et al. 2005). Tabbal et al. (2002) reported that rice cultivation in saturated soil culture required 30–60% lesser water, which increased the water productivity by 30–115% over conventional practice. However, a yield penalty of 4–9% was levied on rice cultivation in saturated soil culture as compared to conventional practice. Water-saving in AWD method is attributed to a reduction in seepage and drainage losses (Tuong et al. 1994). This practice of irrigation is usually applied to DSR in which water required for raising the nursery and transplanting the rice is eliminated. However, the duration of DSR is longer than PTR, which would require higher water for evapotranspiration process than conventionally cultivated rice (Cabangon et al. 2002; Humphreys et al. 2010). Researchers asserted that net water savings depends on water saved from longer irrigation interval and additional water required in pursuance to deep drainage losses in DSR as compared to PTR. A few researchers reported that lesser irrigation amount was required in DSR than PTR with or without yield penalty (Jat et al. 2009; Yadav et al. 2010). The yield of DSR reduced rapidly when the soil was permitted to dry beyond soil moisture tension of 20 kPa (Yadav et al. 2010). These findings suggest that it is essential to reduce the unproductive water outflows to improve the water productivity of rice, which may be accomplished by soil water potential-based frequently irrigated DSR. Water-saving techniques such as micro-irrigation systems (sprinkler and drip irrigation) proved as cutting edge technology for improving the water use efficiency and conserving the water due to elimination of conveyance losses, evaporation from the water surface, runoff losses, etc. (Meena et al. 2015). Technologies such as CA should be promoted and practised on a large scale to improve the water productivity of crops. Agronomical practices such as rice cultivation on a raised bed with furrow irrigation, DSR with cultivars of high stress tolerance index, unpuddled transplanted rice and DSR with straw mulching would be effective approaches to increase the water productivity without much effect on the rice yield (Mahajan et al. 2011; Kar et al. 2018). Needless to say that India also need to review the present scenario of producing the higher water requiring crops such as rice and sugarcane in water-stressed areas (Dhawan 2017).

Declining factor productivity

The declining trend of total factor productivity in agriculture is a severe threat to sustainable farming and food security. In recent years, a significant portion of the cultivable land faced stagnation or negative growth in total factor productivity (Kumar and Mittal 2006). In low land of Asia, excessive tillage led to degradation of land resource base, which reduced the productivity growth of primary cereals like rice and wheat (Pingali and Heisey 2001). In north-western India, the rice–wheat cropping system has been associated with environmental degradation along with stagnant or declining crop productivity, thereby posing a threat to sufficient grain production (Aggarwal et al. 2000). A few researchers stated that declining factor productivity and degrading soil and water resources have threatened the sustainability of rice–wheat cropping system (Hobbs and Morris 1996; Ladha et al. 2003a). A more yield decline has been witnessed in rice as compared to wheat under rice–wheat cropping system (Ladha et al. 2003b). However, generally, it is argued that wheat yield suffers more after PTR due to soil structure degradation (Humphreys et al. 1994; Bhushan and Sharma 1999). Ladha et al. (2003b) suggested to adopt the suitable agronomic and soil management practices for sustaining and improving the crop productivity.

Diverse weed flora

Weeds are the major problem in rice cultivation. Effective weed management plays an important role in the overall profitability of any cropping system. The destruction of weeds with puddling is the main reason for ongoing traditional practice in rice cultivation. However, intensive rice cultivation over the years confined the eco-biodiversity and weed spectrum, and therefore, specific weeds develop more resistance against herbicides and compete with crop plants for water, nutrient and energy. Crop diversification can effectively change the weed spectrum and reduce weed infestation and resistance (Chhokar and Malik 2002). Unlike in traditional practice, DSR restricts the weed seed distribution and weed killing and leaves 60–90% weed seeds in the top layer of the soil (Swanton et al. 2000; Chauhan et al. 2006). The diverse weed flora consisting of grasses, broadleaved and sedges infest rice crop depending on the rice culture and management practices adopted as well as soil and climate conditions. The major weeds found in the rice fields in South Asia are mentioned in Table 2. *Echinochloa crus-galli* and *Echinochloa colona* are the major weeds found in different rice ecologies (aerobic as well as anaerobic rice) in Asian countries. There are many weeds such as *Dactyloctenium aegyptium, Digitaria sanguinalis, Digera arvensis*, *Trianthema portulacastrum and Cyperus rotundus,* which do not infest puddle transplanted rice but found in abundance in DSR and cause huge yield reductions (Chhokar et al. 2014). Overall, DSR has diverse weed flora due to alternate wetting and dry conditions. Further, the losses caused by weeds in rice depend upon weed densities, nature of weed flora, duration of weed competition as well as crop establishment methods (Diarra et al. 1985; Fischer and Ramirej 1993; Eleftherohorinos et al. 2002; Chhokar et al. 2014). Crop establishment methods such as direct seeding (under dry or wet conditions) or transplanting (under puddled or unpuddled conditions) have strong influence on weed diversity and intensity. Numerous studies have reported higher yield losses in direct seeding compared to transplanting in rice cultivation. (Walia et al. 2008; Chauhan 2012; Chhokar et al. 2014).

Table 2 Major weed flora of rice fields in South Asia

Grass weeds	Broadleaved	Sedges	References
Dactyloctenium aegyptium (L.) Willd (Crow footgrass); *Digitaria sanguinalis* (L.) Scop (Large crabgrass); *Echinochloa colona* (L.) Link (Jungle rice); *Echinochloa crus-galli* (L.) Beauv (Barnyard grass); *Eleucine indica* L. Gaertn (Goose grass); *Eragrotis japonica* (Thunb.) Trin (Pond lovegrass); *Oryza sativa* L. (Wild rice); *Panicum repense* L. (Torpedo grass); *Paspalum distichum* L. (Seashore paspalum/Knotgrass)	*Ammennia baccifera* (Monarch redstem); *Commelina benghalensis* L. (Day flower); *Digera arvensis* Forsk; *Eclipta alba* (L.) Hassk (False daisy); *Ludwigia parviflora* L. Roxb (Water primerose); *Marselia quadrifolia* L. (*Water* clover); *Monochoria vaginalis* (Pickerel weed); *Phyllanthus niruri* L. (Gale of the wind); *Physalis minima* (Little gooseberry); *Portulaca oleracia* L. (Common purslane); *Trianthema portulacastrum* L. (Horsepurslane)	*Cyperus difformis* L. (Smallflower umbrella-sedge); *Cyperus. esculentus* (Yellow nutsedge); *Cyperus rotundus* L. (Purple nutsedge); *Fimbristylis miliacea* (L.) Vahl (Fringerush); *Scirpus maritimus* L. (Salt-marsh bulrush)	Rao et al. (2007), Kumar and Ladha (2011), Chhokar et al. (2014)

Based on the large number of farm trials (Gharade et al. 2018), weeds in India caused a loss of about 15–66% in DSR and 6–30% in PTR. Similarly, other workers also reported that weeds cause worldwide, 30–100 per cent rice grain yield reductions in DSR (Oerke and Dehne 2004; Rao et al. 2007; Kumar and Ladha 2011; Chhokar et al. 2014). The higher yield reductions in DSR compared to PTR are due to infestation of diverse weed flora in abundance and their emergence before or along with the crop as well as in several flushes, whereas in PTR crop has an advantage of about one-month-old seedlings over weeds (Chhokar et al. 2014; Rao et al. 2007). Moreover, standing water during the initial stages reduces weeds germination and also improves the herbicides effects. Hill and Hawkins (1996) reported that same relative *E. crus-galli* density caused a 20% yield reduction in PTR compared to 70% in DSR. Besides yield losses, weed infestation also reduces rice quality (Menzes et al. 1997). Worldwide, rice is grown under different ecologies ranging from an upland to lowland situations, but maximum area is occupied with PTR, where fields are flooded during the most of the crop duration. The depth of the water influences the type and density of the weed flora (Kent and Johnson 2001; Kumar and Ladha 2011). However, the scarce and costly labour for transplanting is forcing to shift towards the DSR. The labour problem has been aggravated recently due to Covid-19 pandemic in northern India (Haryana and Punjab) and as a result, many farmers shifted from PTR to DSR. However, for long-term success of DSR, two pre-requisites are selection of suitable varieties and efficient weed management (Chhokar et al. 2014).

In DSR, single pre- or post-application of herbicide fails to control the diverse weed flora and combination of herbicides either in tank mixture or in sequence is required to have effective control of broad-spectrum weeds. The application of pre-emergence pendimethalin or oxadiargyl followed by either bispyribac or penoxsulam in combination with ethoxysulfuron or pyrazosulfuron controls the diverse weed flora in DSR. Fenoxaprop + safener (Rice Star) effectively controls the problematic weeds, *Dactyloctenium aegyptium* and *Digitaria sanguinalis.* Also, the ready mixture of triafamone + ethoxysulfuron as well as penoxsulam + cyhalofop can be utilized for diverse weed flora control. The sole dependency on herbicide is not desirable due to the risk of evolution and spread of herbicide resistant weeds. Weedy rice or red rice (*O. sativa* f. *spontanea*) has turned out as a major challenge in rice cultivation where PTR has been replaced with DSR (Kumar and Ladha 2011). In fact, weedy rice problem in Malaysia has left some farmers to switch back to transplanting method of rice cultivation to control it. Therefore, for effective weed management in long-term, herbicides in mixtures and rotations should be supported with multiple non-chemical weed control strategies such as stale seed bed, competitive cultivars, crop rotation, use of weed free seed and mechanical weeding to remove the weeds before seed setting. In addition, the development and large-scale adoption of herbicide-tolerant rice in future will simplify and provide cost-effective diverse weed flora control in DSR.

Labour scarcity

The labour scarcity and higher labour cost are the emerging challenges in rice production system (Lauren et al. 2008). The labour shortage causes the delay in rice transplantation, which may reduce the yield by 30–70% upon delay of 1–2 months (Rao and Pradhan 1973). The problem of a labour shortage during the rice transplantation and wheat-sowing season arises due to engagement of labour in assured working scheme like MGNREGA by Government of India. Rice transplantation is very laborious, tedious and time-consuming operation, which requires 300–350 man-h ha^{-1} (Bhatt et al. 2016). It has also been observed that manual random transplanting of rice results in lesser seedlings per unit area compared to the recommended level of 30–40 plants per square meter. Mechanical transplanting of rice is being adopted, which requires only 40 man-h ha^{-1} to tackle the issues of labour scarcity, higher labour cost and delay in rice transplantation (Mohanty et al. 2010). After harvesting the rice with combine harvesters, the problems of critical window period between rice harvest and wheat sowing, labour scarcity and higher labour cost involved in manual residue handling encourage the farmers to adopt the practice of residue burning to avoid any delay in wheat sowing. The farmers of Punjab and Haryana regions are more concerned about timely seeding of wheat as its yield is reduced by 26.8 kg day^{-1} ha^{-1}, when sowing is done after 30th November (Tripathi et al. 2005). The research focus on machinery development, subsidiary on residue handling machines and ban on crop residue burning by Government of India have prompted the farmers to adopt alternate practices for residue management. However, it would require more research focus on machinery development for multi-cropping systems, awareness of farmers about consequences of residue burning, set-up of industries engaged in manufacturing of residue-based products at block level and schemes like incentives for supplying the raw materials, i.e. crop residues to such industries.

Table 3 Residue production from various crops in India over the years

Year	Residue production (in million tonnes)			
	Rice	Wheat	Maize	Sugarcane
1950–1951	28.81	8.40	3.98	21.68
1960–1961	48.41	14.30	9.38	41.80
1970–1971	59.11	30.98	17.23	48.02
1980–1981	75.08	47.20	16.01	58.62
1990–1991	104.01	71.68	20.61	91.60
2000–2001	118.94	90.58	27.69	112.46
2010–2011	134.37	112.93	49.98	130.10
2011–2012	147.42	123.34	50.05	137.20
2012–2013	147.32	121.56	51.20	129.66
2013–2014	149.31	124.61	55.80	133.81
2014–2015	147.67	112.49	55.59	137.69
2015–2016	146.17	119.98	51.91	132.41
2016–2017	153.58	128.06	59.57	116.31
2017–2018	157.86	129.83	66.13	144.36
2018–2019	162.99	132.85	62.63	152.06

Residue production has been calculated from yield data of rice, wheat, maize and sugarcane (Source: PBAS 2019) with their residue-to-product ratio as 1.4, 1.3, 2.3 and 0.33, respectively

Residue management challenges

In India, more than 686 mt of crop residue is generated every year, of which 234 mt is surplus (Hiloidhari et al. 2014). Around 368 mt crop residue is generated from cereal crops in which rice and wheat contribute approximately 154 and 131 mt, respectively (Hiloidhari et al. 2014). Along with the crop production, residue generated from the agriculture sector is increasing every year as given in Table 3. Among the various crop residues, management of rice residue and sugarcane trash has been very challenging due to its poor feed quality owing to higher silica content, narrow window period between rice harvest and wheat sowing, higher cost of residue handling machines, labour-intensive operation of residue removal and lack of storage and energy generation systems. These challenges force the farmers of north-western India to adopt the injudicious practice of residue burning as an economical option for timely sowing of wheat into combine harvested rice fields. Such unfair practices degrade the environment by contaminating the air with carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and particulate matter. In fact, air quality index of National Capital Region of India falls sever to emergency level during the rice-harvest and wheat-sowing season (APRC 2018). Crop residue burning is also associated with other problems such as loss of nutrients retained in the residue, global warming and soil health deterioration.

Hence, the farmers have been suggested to use the rice residue for manure, energy production, biogas production, ethanol generation, gasification, biochar and mushroom cultivation according to easily accessible option to them (Fig. 4). A few researchers reported that incorporation of residue in the soil is an effective in-situ residue management option, which improves the soil health in long-term (Kumar and Goh 2000; Sidhu and Beri 2005; Bijay-Singh et al. 2008). However, higher energy requirement and temporary immobilization of nitrogen are the key challenges in this method, which increases the cost of cultivation (Singh et al. 2005b, 2020). The surface retention of rice residue by direct seeding the wheat or other crops with resource conserving machines such as zero-till drill, strip-till drill, mulcher, punch planter, Happy Seeder and Rotary Disc Drill emerged as more promising option for residue management (Sidhu et al. 2007, 2015; Sharma et al. 2008). Researchers reported multiple benefits of reduced soil erosion, improved soil organic carbon, reduced water losses through evaporation and less emergence of weeds in direct seeding of wheat under residue covered field (Ding et al. 2002; Humphreys et al. 2010; Sidhu et al. 2015). Busari et al. (2015) concluded that conservation tillage either zero tillage or reduced tillage along with anchored crop residue can build up a better soil environment along with lessened impact on the environment, leading to climate resilience crop production system. The non-conventional seeding practice, i.e. direct drilling, allows in-situ management of crop residue and timely seeding of crops. It also provides the yield advantage to crops, while saving the time, water (10–15%) and diesel (70–80%) along with reduced impact on the environment (Erenstein and Laxmi 2008; Erenstein 2009; Mishra and Singh 2012). Despite multiple benefits, the adoption of these technologies is not very impressive at farmers' field. Therefore, more efforts on the development of suitable seeding machines for multi-cropping systems under conventional and CA and their popularization are required for effective in-situ residue management on large scale at farmers' field. Custom hiring service needs to be promoted at block and village level to overcome the issue of costly residue handling and seedling machines for farmers belonging to small- and medium-land holdings. Moreover, utilization of crop residue for industrial and energy applications requires infrastructure development, establishment of residue collection centres at block level, build-up of strong supply chains, policy interventions,

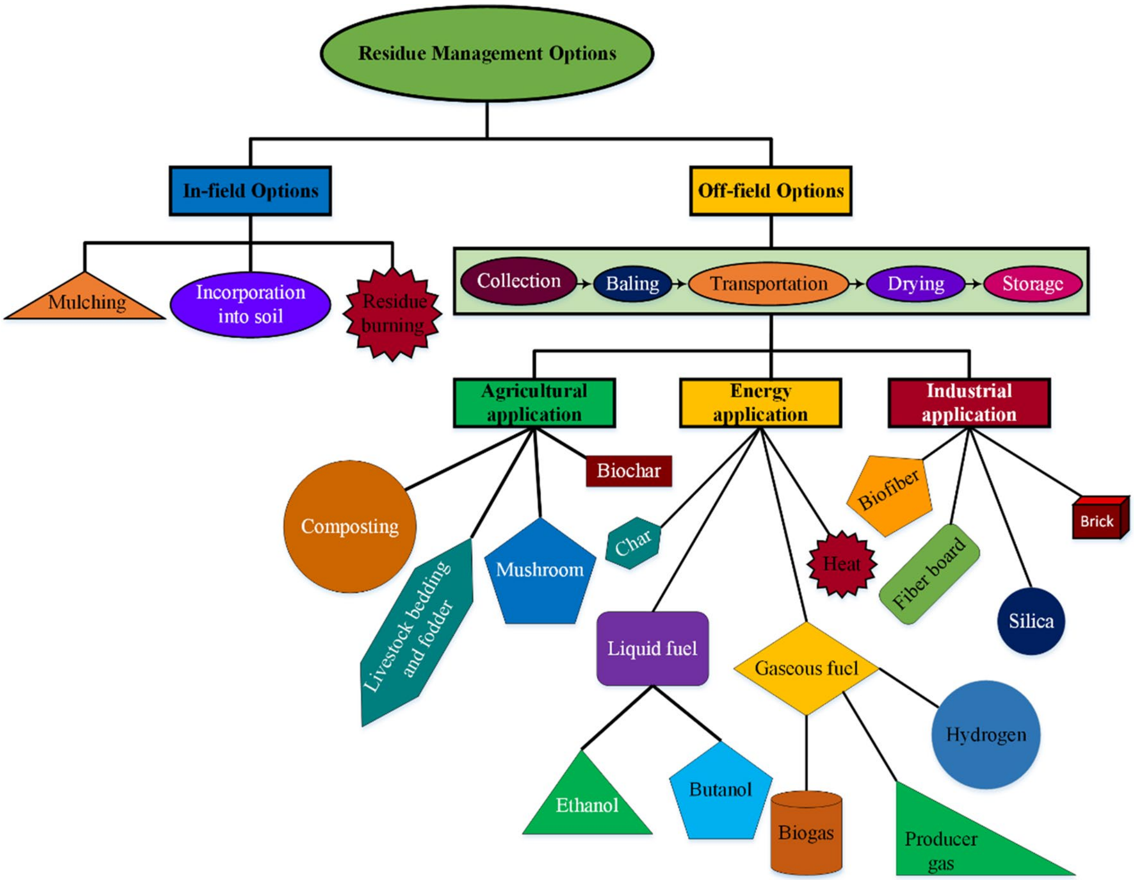
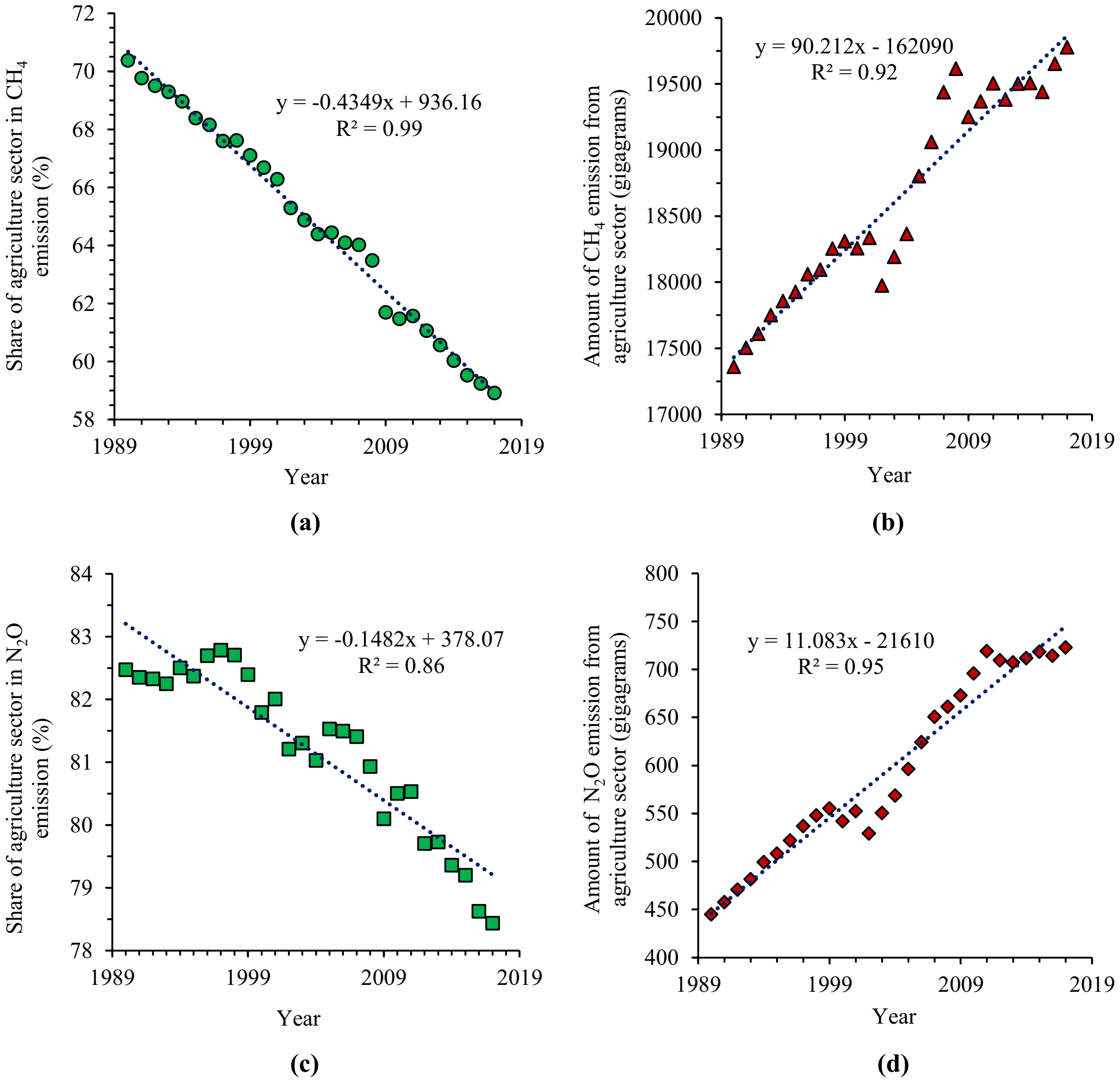


Fig. 4 Different in-field and off-field options for residue management



(a) (b)

(c) (d)

Fig. 5 Figure depicting (**a**) share of agriculture sector in CH_4 emission, (**b**) amount of CH_4 emission from agriculture sector, (**c**) share of agriculture sector in N_2O emission, (**d**) amount of N_2O emission from agriculture sector (*Source: FAOSTAT*)

large-scale trainings and incentives to farmers to drive the sustainable residue management mission.

Environmental pollution

The agriculture sector has been a major source of methane (CH_4) and nitrous oxide (N_2O) emissions, primarily driven from flood-based rice cultivation (Kritee et al. 2018), use of synthetic fertilizers (Zschornack et al. 2018) and residue burning practices (Jain et al. 2014). Such emissions can raise the global warming potential to 10 times in rice season than winter (Zschornack et al. 2018). It is estimated that agriculture is the largest sector, contributing about 44% of anthropogenic methane emissions (Janssens-Maenhout et al. 2019). The graph plotted using the data taken from FAO shows a consistent decrease in the contribution of the agriculture sector to CH_4 emission during 1990–2017 (Fig. 5a). However, interestingly amount of CH_4 emission emitted from agriculture sector consistently increased for the same period (Fig. 5b). Needless to say that other sectors emitted CH_4 emissions in a faster way than agriculture. But changes in agricultural practices such as increased cultivable area especially under rice cultivation, an overdose application of fertilizers and residue burning have elevated CH_4 emissions significantly. Similarly, the amount of N_2O emission emitted from agriculture sector consistently increased during 1990–2017 (Fig. 5c and 5d). Apart from CH_4 and N_2O emissions, the traditional practice of rice cultivation significantly contributes to other greenhouse gas emissions, too. Puddling operation in mechanized rice cultivation consumes much amount of fuel and thereby raises CO_2 level in the environment. Also, more water requiring crops are responsible for higher CO_2 emission as compared to other crops in the areas where stationary diesel engines or tractors are used for pumping out the water. The burning of 1 L of diesel supplies 2.67 kg of CO_2 to the environment. The problems of environmental pollution from rice cultivation are not limited to its growth period but also after harvesting of rice. Economic constraints, unavailability of suitable residue handling machines and poor feed quality of rice residue encourage the farmers to adopt the unfair practice of residue burning for quick in-situ management of residue and timely seeding of wheat. It creates a huge burden on the environment during the rice-harvesting and wheat-sowing season. Kumar et al. (2019) estimated the loss due to residue burning by taking nutrient losses, yield loss, soil biodiversity, irrigation, health and other factors into consideration. It was observed that residue burning in north-western India caused losses to the tune of Rs. 8953 per hectare. As far as CH_4 and N_2O emissions are concerned, better water management practices can lower these emissions from the rice fields. CH_4 emission reduces significantly with intermittent irrigation approach, while N_2O emission rises under such conditions, thereby creating a trade-off between CH_4 and N_2O emissions (Yue et al. 2005). However, CH_4 emission plays a dominant role in greenhouse gas emissions. The excessive use of fertilizer, chemicals and non-renewable energy in PTR raises other emissions of CO_2, oxides of nitrogen (NO_x), oxides of sulphur (SO_x) and heavy metal (Jimmy et al. 2017). It is important to optimize N-fertilizer doses to improve its uptake efficiency and to reduce the losses and emission load on the environment (Ju et al. 2009; Qiao et al. 2012). A shift in cultivation method from PTR + residue retention to non-puddled transplanting using strip tillage + residue retention can mitigate 15–30% greenhouse gas emissions (CO_2 equivalent emission) along with the benefit of carbon storage in the soil (Alam et al. 2016, 2019). The adoption of cultivation practices such as DSR on flat or permanent beds, zero-till mechanized transplanting and strip tillage + transplanting can alleviate harmful impacts of puddling method on the environment. However, it requires more research efforts to address weed control, soil-borne pathogens and grain quality challenges of rice cultivated under non-puddled practices (Kumar et al. 2011). A shift from intensive cereal–cereal production system to leguminous-cereal cultivation or replacing rice–wheat with maize–wheat cropping system periodically under zero-till or CA practice could be beneficial for sustainable food grain production. The integrated approach of adopting low duration and lesser water requiring varieties, water management, residue management and RCTs in rice cultivation can mitigate the environmental pollution.

Global warming

Global warming is an emerging serious threat to agriculture sector. Greenhouse gases like CH_4, CO_2 and N_2O trap the short wave radiation, causing a net increase in the global temperature. The comparative assessment of different crops should be made not only based on yield potential but also their emission intensity, i.e. net return to the environment. For instance, the production of 1 kg rice returns 0.71 kg CO_2 equivalent (CO_2-eq) emissions to the environment as compared to 0.27 kg CO_2-eq emissions per kg production of other cereals (*Source: FAOSTAT*). In addition to this, huge amount of residue generated from rice and sugarcane crops creates management challenges and farmers burn the residue for timely sowing of wheat especially in IGP. The total carbon present in rice residue converts to CO_2 (70%), CO (7%), CH_4 (0.66%) and particulate matter, while 2.09% nitrogen to N_2O gas upon burning (NPMCR 2014). The burning of crop residue is not only associated with air pollution but also with loss of precious nutrients retained in the crop residue. During the crop residue burning, almost 100% carbon, more than 90% nitrogen, 20–25% phosphorus and potassium and about 60% sulphur are lost in the form of various gases and particulate matter (Singh et al. 2008). The gases emitted from crop residue burning can cause radiation imbalance, leading to harmful effects such as more aerosols in the region, acid rain and ozone layer depletion. Hence, like in other crops, farmers should adopt residue management and RCTs in rice cultivation as well for a sustainable farming. Ma et al. (2019) found that global warming potential (GWP) and greenhouse gas intensity (GHGI) reduced by 12.6–59.9% and 10.5–65.8%, respectively, by returning the wheat crop waste to the soil in the form of straw, straw-derived biochar and straw with straw-decomposing microbial inoculants over no straw return practice. Sapkota et al. (2017) and Chen et al. (2021) highlighted the use of no-tillage with residue retention practice to combat the global warming potential in rice–wheat and rice–rice cropping systems. The return of crop residue to the soil should be in the form of mulching as residue incorporation into soil can raise CH_4 emissions by 3.2–3.9 times of straw-induced SOC sequestration rate, thereby worsening the GWP rather than mitigating climate change (Xia et al. 2014). In a different study, Pittelkow et al. (2014) found that potential yield of rice along with minimal yield-scaled GWP is achievable by using the optimal doses of N-fertilizer. Nemecek et al. (2012) highlighted the lowest GWP for sugar crops (< 0.05 kg CO_2-eq kg^{-1}) followed by root crops (< 0.15 kg CO_2-eq kg^{-1}) and vegetable and fruits (< 0.35 kg CO_2-eq kg^{-1}). Cereals (except rice) and pulses were found to have medium GWP (< 0.6 kg CO_2-eq kg^{-1}), while oil crops (cotton, peanuts) and rice exhibited the highest GWP (1.2–2.4 kg CO_2-eq kg^{-1}). Needless to say that it would be beneficial to the environment and agroecosystem to replace the higher GWP posing cereal crop with vegetable, sugar or root crops in cereal–cereal cropping system. The better water management techniques replacing the continuous flooding in rice cultivation might be effective to reduce the GWP further from rice-based cropping systems (Jiang et al. 2019a).

Abiotic stress challenges in rice

Rice can be grown in most diverse ecologies; however, its growth and productivity are severely affected by abiotic factors such as heat stress, cold stress, salinity, flood and drought (Biswal et al. 2019). The severity and intensity of these abiotic stresses are increasing due to climate change (Pereira 2016). With the continuous increase in greenhouse gases and extensive human interference in the environment, adverse effects of climate change are likely to increase. The prediction models have shown severe rice yield losses under intensive climate warming scenarios (Zhao et al. 2016). Increased concentration of CO_2 and fluctuations in temperature and precipitation would impact the rice growth and productivity severely due to significant effects of these factors in photosynthesis and other important metabolic processes (Liu et al. 2017; Wang et al. 2020). A recent study suggested that elevated levels of CO_2 also affected protein, iron, zinc and vitamins content of rice cultivars grown in Asia, thereby posing a serious challenge to human health (Zhu et al. 2018). Temperature is one of the most critical abiotic factors which influences the rice production, productivity and grain quality directly. Heat stress affects rice growth and metabolism and has severe impact on all the growth phases, especially seedling and reproductive stage (Sailaja et al. 2015; Bhogireddy et al. 2021). In a recent study, Zhao et al. (2017a) estimated the global yield loss of rice by 3.2% for every 1 °C increase in global mean temperature by compiling the extensive published results from different analytical methods. On the contrary, positive effects of temperature and increased CO_2 on rice growth were predicted in Madagascar (Gerardeaux et al. 2012) suggesting that climate change may bring better scenario for rice cultivation in this region.

Little efforts have been made towards mapping the quantitative trait locus (QTL) for heat stress tolerance (Shanmugavadivel et al. 2017; Kilasi et al. 2018). Moreover, further characterization of these QTLs to understand the mechanisms and causal genes has not been very impressive. Few genes like *ERECTA* (ER), a homolog of Arabidopsis receptor like kinase and α2 subunit of the 26S proteasome have been identified as potential regulators imparting heat stress tolerance in rice (Li et al. 2015; Shen et al. 2015). The *O. glaberrima* allele of *TT1* was shown to be more efficient in degradation of cytotoxic denatured proteins during the heat stress. Another gene *OsDPB3-2* (*LOC_Os03g63530*) imparts heat stress tolerance in rice through positive regulation of dehydration-responsive element binding protein 2A (DREB2A). Notably, the overexpression of DPB did not show any phenotypic aberrations suggesting that it can be used as candidate gene for improving thermotolerance in rice (Sato et al. 2016).

Similarly, stress due to cold temperature at seedling and booting stages can cause severe loss to rice grain production (Xiao et al. 2018). In rice, a pathway mediated by *CBF/DREB1* play a crucial role in cold tolerance (Chinnusamy et al. 2007; Ritonga and Chen 2020). Other transcription factors such as *OsMYB4*, *MYBS3*, *OsbHLH002* and *OsMAPK3* positively regulate the cold stress tolerance response in rice (Su et al. 2010). Fujino et al. (2008) identified that *qLTG3–1* (Os03g0103300) encoding protein of unknown function is important for germination at low temperature. Cultivars harbouring tolerant allele of *qLTG3–1* or overexpressing rice lines showed low-temperature germinability phenotype, suggesting variations in promoter region of tolerant and susceptible alleles. In a crucial study, a gene responsible for cold tolerance of japonica rice was cloned and characterized through QTL analysis. *COLD1* (Chilling Tolerance; LOC_Os04 g51180) was found to be a key player associated with chilling tolerance, which acts through activation of Ca^{++} channel by interacting with G protein and regulating G protein signalling at plasma membrane (Ma et al. 2015). Interestingly, a single nucleotide polymorphism (SNP) at the 15th nucleotide of the 4th exon of *COLD1A* was attributed to difference in low-temperature-tolerant japonica and susceptible indica cultivars. The susceptible genotypes had T/C instead of A present in tolerant genotypes, which resulted in Met187/Thr187 (susceptible) to Lys187 (tolerant) substitution. The tolerant allele was suggested to be derived from *O. rufipogan* wild rice (Ma et al. 2015). An SNP in coding sequence of *LOC_Os10g34840* was identified through genome-wide association study of 1033 rice accessions, which contribute low-temperature tolerance at seedling stage. This SNP at 18,598,921 (G in tolerant while A in susceptible) caused Gly (tolerant) to Ser (susceptible) substitution (Xiao et al. 2018). Another such gene *Os09g0410300* was shown to contribute cold tolerance at seedling stage, and the phenotype was attributed to nucleotide variations present in its promoter resulting in tolerant and susceptible alleles of a gene (Zhao et al. 2017b). In addition to genes for cold tolerant at seedling stage, few genes imparting tolerance at vegetative and booting/reproductive stages have also been characterized. *Ctb1* (cold tolerance at booting stage) encoding a F box protein and *CTB4a* encoding a conserved leucine rich repeat receptor like kinase have

Table 4 Genetic engineering approaches for developing abiotic stress tolerance in rice

Gene	Gene description	Gene source	Phenotype	Reference
Overexpression				
HVA1	LEA (Late Embryogenesis Abundant) protein	*Hordeum vulgare*	Salinity and drought tolerance	Xu et al. (1996)
OsLEA3-2	LEA protein	*Oryza sativa*	Salinity and Drought tolerance	Duan and Cai (2012)
OsPIP1	Aquaporin (plasma membrane intrinsic protein)	*Oryza sativa*	Salinity tolerance	Liu et al. (2013)
OsTSP1	Trehalose-6-phosphate synthase	*Oryza sativa*	Salinity, drought, and cold tolerance	Fan et al. (2012)
HSP70	Heat shock protein	*Citrus tristeza virus* (CTV)	Salinity tolerance	Hoang et al. (2015)
sHSP18.6	Heat shock protein	*Oryza sativa*	Heat, drought, salt and cold tolerance	Wang et al. (2015b)
pdc1	Pyruvate Decarboxylase	*Oryza sativa*	Submergence tolerance	Quimio et al. (2000)
PYL10	ABA receptor	*Oryza sativa* (Nagina22)	Drought and cold tolerance	Verma et al. (2019)
Rab7	ABA pathway protein	*Oryza sativa*	Drought and heat tolerance	El-Esawi et al. (2019)
OsMYB6	Transcription factor	*Oryza sativa*	Drought and salinity tolerance	Tang et al. (2019)
RNA interference (RNAi)				
OsmiR156k	Regulatory non-coding small RNA	*Oryza sativa*	Cold tolerance	Cui et al. (2015)
miR390	Regulatory non-coding small RNA	*Oryza sativa*	Cadmium tolerance	Ding et al. (2016)
miR319	Regulatory non-coding small RNA	*Oryza sativa*	Cold tolerance	Yang et al. (2013)
miR159	Regulatory non-coding small RNA		Drought tolerance	Zhao et al. (2017a, 2017b)
miR393	Regulatory non-coding small RNA	*Oryza sativa*	Sensitive to salinity and alkalinity	Gao et al. (2011)
miR164b	Regulatory non-coding small RNA	*Oryza sativa*	Drought and salt tolerance	Jiang et al. (2019b)
Genome editing				
dst	DST protein	*Oryza sativa*	Drought and salinity tolerance	Kumar et al. (2020b)
OsRR22	Transcription factor	*Oryza sativa*	Salinity tolerance	Zhang et al. (2019b)
OsMYB30	Transcription factor	*Oryza sativa*	Cold tolerance	Zeng et al. (2020)

been cloned and demonstrated their role in conferring cold tolerance at booting stage (Zhang et al. 2017). The tolerant allele of *CTB4a* contained 5 SNPs (at positions 2536, 2511, 1930, 780 and 2063) in its promoter, which helps in better expression of gene in tolerant genotypes (Zhang et al. 2017). In another study, a gene contributing cold tolerance at vegetative growth stage was mapped and characterized (Lu et al. 2014). The Low-Temperature Growth 1 (*LTG1*) encoding a casein kinase I regulates cold tolerance through auxin dependent pathway. The tolerant allele of *LTG1* has a SNP, i.e. T at 1070 in place of A in susceptible allele, causing amino acid substitution Iso357 (in tolerant) to Lys357 (in susceptible) (Lu et al. 2014). A few genetic engineering approaches for developing the abiotic stress tolerance in rice are presented in Table 4.

Genetic resources and molecular approaches of rice improvement

Rice is one of the most widely adapted crops due to the vast genetic diversity and its wild relatives (Singh et al. 2018). There are 22 wild and 2 cultivated species (*Oryza sativa* and *Oryza glaberrima)* under the genus *Oryza* (Vaughan 1989). The *O. sativa* covers most of the area under rice cultivation and has been classified into five major groups: *indica*, aromatic *japonica*, tropical *japonica*, temperate *japonica* and *aus* (Garris et al. 2005). These genomic resources conserved by national and international organizations have been used in crop improvement programs and also for basic research. A total of 132,000 accessions of rice were maintained by International Rice Genebank Collection Information System (IRGCIS) of International Rice Research

Institute (IRRI) as on December 2019. A large number of indigenous, exotic and wild rice accessions are also maintained by National gene bank of India of National Bureau of Plant Genetic Resources (NBPGR), New Delhi. Among the crops, rice is the first to have complete genome sequence, which helped in developing genetic resources for gene discovery, molecular markers and crop improvement (IRGSP 2005). Recent efforts of sequencing of 3,000 rice accessions from 89 countries have helped in identification of superior alleles and haplotypes for rice breeding programs (T3RGP 2014). Genomic information of 3,010 diverse Asian cultivated rice including 3000 rice accessions of 3 K rice genome project was used to identify 29 million SNPs, 2.4 million small indels, 10,000 novel full-length protein-coding genes and more than 90 thousand structural variations, which will serve as an extremely important genetic resource for breeding and biotechnology research (Wang et al. 2018). Several databases and genomic resources of rice are available in public domain for gene/allele discovery, molecular marker designing and basic studies (Kamboj et al. 2020). These resources have facilitated the QTL discovery and gene cloning for marker-assisted breeding programs and transgenic research. Novel resources such as gene activation mutants, EMS mutants and T-DNA-tagged rice mutant populations are powerful genetic resources for functional genomics and crop improvement (Yi and An 2013; Mohapatra et al. 2014; Reddy et al. 2020). Recently, a genomic resource based on CRISPR/Cas9 (clustered regularly interspaced short palindromic repeats–associated nuclease 9) genome editing has been developed wherein more than 34,000 genes of rice have been targeted (Lu et al. 2017). Many high-throughput sequencing-based genomic resources for abiotic stress-related traits are discussed by Bansal et al. (2014). Transcriptomic and micro-RNA-based genomic resources for abiotic stress traits are also available in rice (Bansal et al. 2014; Mangrauthia et al. 2016, 2017). Such resources have been utilized in various molecular approaches such as marker-assisted breeding, genome-wide association studies, cis-and transgenic and genome editing for crop improvement (Varshney et al. 2020). Marker-assisted selection and introgression have been used for developing biotic and abiotic stress-tolerant rice genotypes (Das et al. 2017). Three major bacterial blight resistance genes (*Xa21, xa13 and xa5*) were introduced through marker-assisted breeding to produce a bacterial blight resistant rice cultivar, Improved Samba Mahsuri (Sundaram et al. 2008). Transgenic rice lines for various traits have been developed using a number of genes and genetic elements (Fraiture et al. 2016). Recently, genome editing is projected as the potential breeding technique due to its precision and efficiency (Aglawe et al. 2018). Several traits and genes of rice are being targeted and improved using the CRISPR/Cas technology of genome editing (Zafar et al. 2020).

Grain quality challenges in rice

Rice grain quality is a permutation of several traits such as appearance, cooking, nutritional and milling qualities (Yu et al. 2008). Several factors such as cultivars, production and harvesting conditions, post-harvest management, milling and marketing techniques determine the rice grain quality. Rice endosperm is composed of 80–90% starch with 6–28% amylose content and 5–7% proteins, which serve as energy and protein source of the global population especially in developing countries. The grain appearances *vis-à-vis* cooking, eating and milling quality are largely determined by the combination of several starch properties such as gelatinization temperature, amylose content and gel consistency (Bao et al. 2008). Various approaches including genetic and molecular utilized to improve the starch properties of rice have been extensively reviewed by various researchers (Fujita 2014; Birla et al. 2017). The off-putting nutritional value of rice proteins is mainly due to the deficiency in certain amino acids such as lysine and tryptophan (Ufaz and Galili 2008). Compared to maize, efforts towards increasing the content of deficient amino acids such as lysine and tryptophan have not been extensively attempted in rice due to limited genetic variability, and side-effects of nutrient enrichment on germination and abnormal plant growth. Also, due to the absence of expression of some of the enzymes of the carotenoid pathway, rice is not able to synthesize and accumulate sufficient quality of carotenoids. Therefore, efforts have been put forth to genetically alter the rice plants to produce golden rice that produces b-carotene in the endosperm giving rise to a characteristic yellow colour (Ye et al. 2000). Similarly, micro-nutrients such as Fe and Zn, vitamins such as folate and thiamine, antinutritional factor such as phytate and other bioactive compounds have been recently reviewed by Birla et al. (2017) and Custodio et al. (2019).

Owing to sufficient production, studies during the past have focussed towards quality traits including nutritional quality. It is usually agreed that rice quality depends on both genetic and environmental factors (Cheng et al. 2003). Increase in the night temperature is linked to poor grain quality such as decreased head rice ratio, increased chalkiness and reduced grain width (Shi et al. 2016; Li et al. 2018). Being complex polygenic traits, chalkiness and amylose content, protein content, grain length, grain width and aspect ratio of rice are highly influenced by environmental conditions such as light, temperature and humidity, and certain cultural practices particularly during the grain-filling stage (Siebenmorgen et al. 2013; Li et al. 2018). Similarly, fertilizer application, plant density and irrigation management especially during the grain-filling period significantly affect the rice grain quality (Huang et al. 2016; Wei et al. 2018). However, little is known about the role of optimized

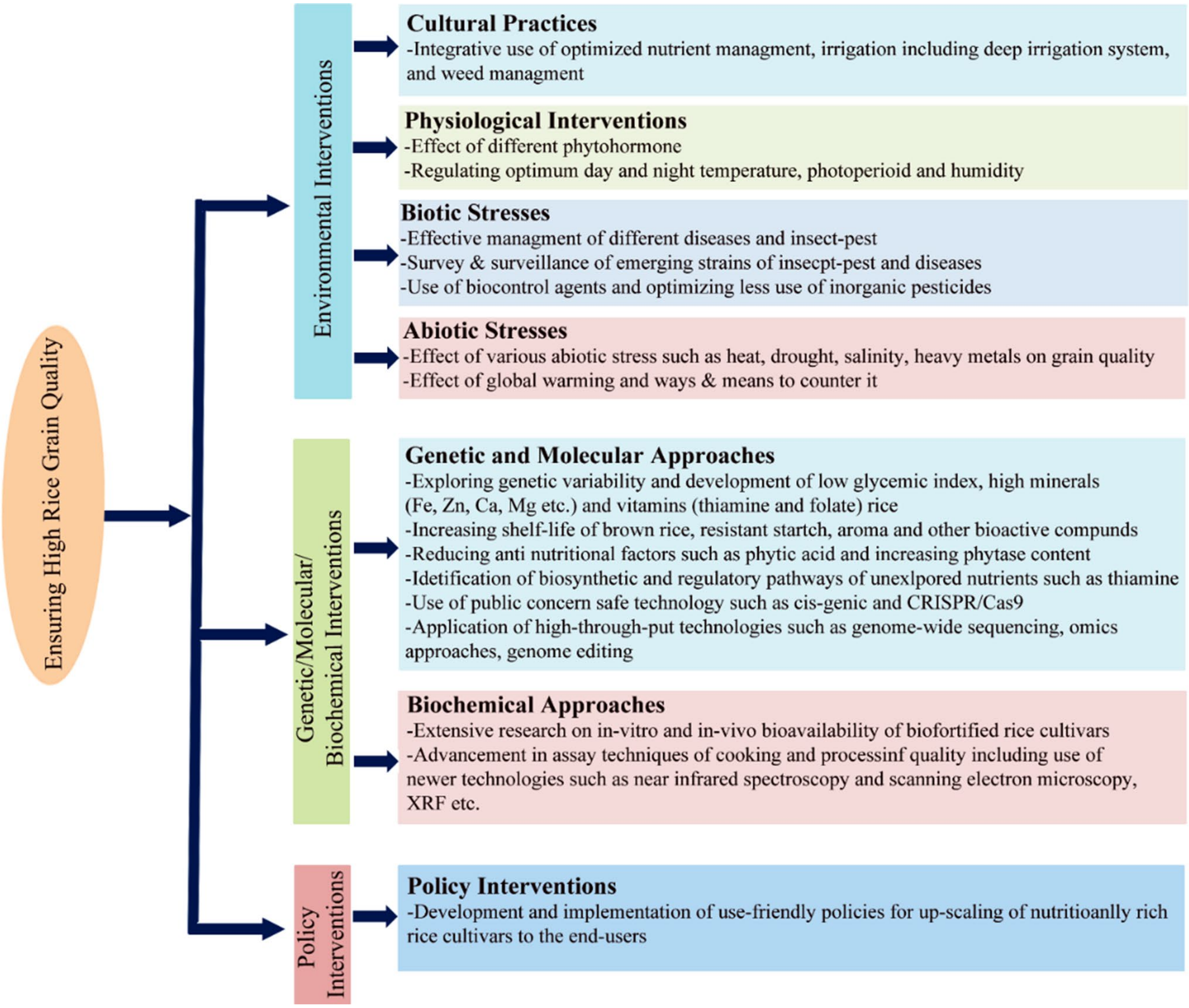


Fig. 6 Key intervention areas to ensure consumer pro high rice grain quality

cultivation managements on rice grain quality (Zhang et al. 2019a). Besides, deep flood irrigation has been shown to reduce the chalky grains due to the increased supply of carbohydrates to the panicles (Chiba et al. 2017). In the recent, several reports have suggested the significant harmful effect of global warming on crop quality (Morita et al. 2016; Ishigooka et al. 2017). Taken together, systematic work on rice cultivation in varying environmental conditions in combination with genetic studies has widened our current understanding of rice grain quality. Even though, there are significantly more challenges coupled with opportunities to work on enhancing the quality of rice grain, the various approaches to improve rice grain quality are explicitly shown in Fig. 6.

Way forward with conservation agriculture and resource conservation technologies

Conservation agriculture (CA) is an alternate farming practice, which emphasizes on minimum soil disturbance, soil cover with crop residue ($\geq 30\%$) and crop rotation (Hobbs et al. 2008). It has the potential to address the sustainability issues in rice production system. Many farmers partially adopted CA mainly in the form of zero-till-based direct seeding and direct rice transplantation on untilled or unpuddled field. The minimum soil disturbance component of CA or zero-till-based seeding provides multiple benefits of reducing the negative impact of tillage and heavy machinery on soil structure, while saving time, labour and fuel along with lesser harmful air pollutants (Sharma et al. 2003; Malik and Yadav 2008). Soil cover component of CA acts as an effective moisture conserving

Table 5 Effect of CA practices on soil organic carbon, yield and other aspects in different cropping systems

Source	Cropping system	Soil type	Treatments	Effect on organic carbon	Yield	Other benefits
Das et al. (2013)	Cotton–wheat Maize–wheat–green gram	Sandy loam	Tillage treatments: Zero tillage (ZT) with flat and bed planting Conventional tillage (CT) with flat and bed planting Residue treatments: No residue cotton/maize residue wheat residue cotton/maize + wheat residue	26% higher than CT	Similar	–
Choudhury et al. (2014)	Rice–wheat	Sandy loam sodic soil	Combination of tillage (conventional and conservation) and residue management (with and without) coupled with the system of rice cultivation (PTR and DSR)	33.6% higher with DSR in zero-tilled wheat with residue retention	8.3% higher equivalent wheat yield	Increased water-stable macro-aggregates
Guo et al. (2015)	Rice–wheat	Silty clay loam	Treatment included CT and NT (no-tillage) with and without returning of wheat residue	NT with residue returning increased soil organic carbon over CT	–	Higher microbial biomass carbon over CT
Parihar et al. (2016)	Maize-based cropping systems	Sandy loam	Tillage treatments included zero tillage, permanent raised beds and CT Crop rotations included maize–wheat–mungbean, maize–chickpea–sesbania, maize–mustard–mungbean and maize–maize–sesbania	Increased by 23–35% over CT	Higher maize equivalent yield in zero tillage after the initial two years	Water-stable aggregates, soil microbial biomass carbon and soil enzymatic increased, while penetration resistance and bulk density decreased under CA

Table 5 (continued)

Source	Cropping system	Soil type	Treatments	Effect on organic carbon	Yield	Other benefits
Bera et al. (2018)	Rice–wheat	Sandy loam	Tillage and crop establishment methods in rice included ZT-DSR, CT-DSR, ZT-Direct-transplanted rice and PTR Tillage and residue treatments in wheat included CT and ZT wheat with the removal of both crops residue(CTW-R and ZTW-R) and ZT wheat with the removal of wheat residue but retaining rice residue (ZTW + R)	7–9% higher over other treatments	6–10% higher wheat yield in ZTW + R over CTW-R and ZTW-R	Higher soil enzyme activities in ZT-DSR coupled with ZTW + R
Das et al. (2018)	Maize–wheat	Sandy clay loam	Treatments included CT, ZT on flatbed (with and without residue), permanent narrow bed (with and without residue) and permanent broad bed (with and without residue)	Higher	Up to 29% higher grain yield in maize and comparable wheat yield over CT	Overall 59% and 11% higher water productivity in maize and wheat, respectively, 12% higher net returns in zero tillage on the permanent broad bed (with residue) over CT
Jat et al. (2018)	Rice–wheat Rice–wheat–mungbean Maize–wheat–mungbean	Loamy	Treatments involved CT-based rice–wheat, PTR-ZT-based wheat and mungbean and CA-based rice–wheat–mungbean and maize–wheat–mungbean	Higher	Similar	Soil bulk density and penetration resistance reduced while infiltration rate improved Increased available N, Zn and Mn under CA over CT
Mondal et al. (2019)	Rice–wheat–mungbean Rice–potato + maize–mungbean	Silty clay	Treatments included DSR-ZTW- ZT mungbean, PTR-ZTW-CT mungbean and UPTR-CT potato + maize–ZT mungbean	Increased	Similar	Subsurface compaction reduced and soil aggregation improved Macro- and water-stable aggregates and steady-state infiltration rate increased

Table 5 (continued)

Source	Cropping system	Soil type	Treatments	Effect on organic carbon	Yield	Other benefits
Patra et al. (2019)	Rice–wheat–mungbean Maize–wheat–mungbean	Loamy	Treatments involved CT-based rice–wheat–mungbean, CA-based rice–wheat–mungbean and maize–wheat–mungbean and PTR-ZT-based wheat and mungbean	Higher	–	Increased total nitrogen in CA-based cropping systems
Parihar et al. (2019)	Maize–wheat–mungbean	Sandy loam	Tillage treatments included zero tillage, permanent beds and CT 30% (maize and wheat) and 100% (mungbean) residue retained in zero tillage and permanent beds/incorporated in CT Nutrient strategies included control, farmer fertilizer practice, recommended fertilizer and site-specific nutrient management treatments	Higher as compared to CT	–	–
Sinha et al. (2019)	Rice–wheat Rice–maize	Sandy clay loam	Treatments included three rice crop establishment practices (PTR, unpuddled transplanted rice and DSR) and CT and ZT practices in wheat and maize crop	Increased	Similar	–
Dey et al. (2020)	Rice–wheat	Clay loam	Treatments involved CT rice–CT wheat, CT rice–ZT wheat, DSR–CT wheat, DSR-ZT wheat (with and without residue) and DSR–ZT wheat on a raised bed with residue	20–40% higher in DSR-ZT wheat with residue over CT rice–CT wheat	–	Improved C quality in terms of the nutrient supply and buffering capacity

technique by reducing the evaporation rate. Moreover, it also provides physical protection to the soil from rainfall, runoff and wind-induced erosion, while improving the structure, organic carbon and physico-chemical properties of soil (Kassam et al. 2009; Rockström et al. 2009). The crop rotation in CA promotes the biodiversity and helps in soil nutrient balance and weed spectrum (Kumar et al. 2020a). The threat of pest and disease incidence is also reduced with regular crop rotation (Farooq et al. 2011). The effects of CA practice on soil organic carbon, yield and other parameters under different cropping systems are presented in Table 5. CA practice in rice-based cropping systems can provide a beneficial effect on soil properties like soil organic carbon, bulk density, soil compaction, microbial biomass, infiltration rate, soil enzymatic activities, macro- and water-stable aggregates, water productivity, etc., with a similar or higher yield than CT practice. Laik et al. (2014) reported 46–54% and 10–24% higher yield of wheat and rice, respectively, in wheat–cowpea–rice cropping system under CA over conventional practice. The water productivity and benefit–cost ratio were also higher under this cultivation practice. Gathala et al. (2015) concluded that it is uncertain to have yield advantage in rice-based cropping systems under CA establishment methods; however, in terms of cultivation cost, labour cost and net profit, CA-based cultivation methods are advantageous over CT practice. Haque et al. (2016) observed lesser cultivation cost and higher profit for minimum tillage unpuddled transplanted rice under CA as compared to conventionally grown rice. In a different study, Mohammad et al. (2018) reported higher crop and water productivity of DSR under CA over CT practice. Chaki et al. (2021) found that system production, water productivity and nitrogen use efficiency of wheat–mungbean–rice cropping system increased by 5.4, 40 and 5%, respectively, under CA over conventional practice in fine-textured soils. However, grain and water productivity of rice depleted under CA over conventional practice in coarse-textured soils. From the cited studies, it is evident that CA offers savings in time, labour, water and input cost, while improving the soil characteristics and diminishing GWP simultaneously. In the scenario of declining factor productivity coupled with climate change, it is extremely imperative to bring the rice crop under CA for long-term sustainability of crop production system. The use of RCTs such as leaf colour chart and normalized difference vegetation index (NDVI) sensors-based fertilizer application and electrostatic and variable rate spraying for chemical applications need to be integrated with CA for a sustainable rice cultivation system. Further research efforts are required on developing suitable rice cultivars and variety selection for CA and development of cost-effective RCTs such as zero-till rice transplanter and seeder integrated with pre-emergence herbicide applicator. The future studies on weed, nutrients and pest dynamics and quality aspects of rice under CA are desirable for effective weed and pest control and to have comparable rice yield as with PTR. In line with this, policy interventions, large-scale training and field-level demonstrations would also be required to accelerate the adoption of CA among farmers.

Conclusions

The continuous rice cultivation with traditional method imposed serious threats to natural resources and agricultural sustainability. In the scenario of declining factor productivity, crop response and water table and rising air pollution, researchers and policymakers need to intervene through a systematic and integrated approach to produce more rice with less water in a sustainable way. The cultivation of some alternative and lesser water requiring crops should be encouraged by various measures like incentives and minimum support price for the regions of light-textured soils and rainfed condition. Resource use efficiency needs to be enhanced through multi-dimensional approach on varietal development, soil and water management, adoption of resource conserving machines and need-based application of fertilizers and chemicals for sustainable rice cultivation in medium-to-heavy soils. The integrated resource conserving approach like delayed direct seeding of short duration, high-yielding and stress tolerant rice varieties with a zero-till seeder or transplanting such varieties with zero-till transplanter under CA with drip irrigation system should be encouraged for rice cultivation. However, more research studies and analysis are required to explore the yield aspect and profitability with promising results to convince the farmers for shifting from PTR to a new rice cultivation system. Policy reforms are needed to stop the subsidy on methods and systems that contribute to low water productivity on a system basis. Reforms on water security to users, the decentralization and privatization of water management functions to suitable levels, water pricing, markets in tradable property rights and introducing water conserving technologies for irrigation purposes should be in vogue.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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