



# Challenges and technological interventions in rice–wheat system for resilient food–water–energy–environment nexus in North-western Indo-Gangetic Plains: A review

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Received: 26 August 2022 / Accepted: 23 January 2023  
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## Abstract

Rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system in north-western Indo-Gangetic Plains performed a crucial role in the national food security. However, the widespread and intensive cultivation of this system has led to serious problems such as declining groundwater table (~1 meter year<sup>-1</sup>) with sharp increase in number of districts under over-exploitation category, residue burning, higher greenhouse gases emission and herbicide resistance in weeds, causing stagnant crop productivity and lesser profitability. In this review article, an attempt has been made to discuss the major issues pertaining to intensive rice–wheat cultivation amidst climate vagaries and futuristic approach to address these challenges. Different tillage- and crop-specific recommendations such as adoption of direct seeded rice, diversification with lesser resource guzzling crops such as maize (*Zea mays* L.) at least on the periodic manner especially in light-medium soils, inclusion of summer legumes and alternative tillage systems (permanent beds and zero tillage with residue retention) have been suggested to address these issues. However, crop performance under these techniques has been found to be location, soil and cultivar specific. The absence of aerobic tailored genotypes and weeds have been identified as the major constraints in adoption of direct seeded rice. The integrated strategies of conservation tillage, crop breeding program and resource conserving region- and soil-specific agronomic measures with crop diversification would be helpful in tackling the sustainability issues. It requires future efforts on developing crop genotypes suited to conservation tillage, effective weed control strategies and trainings and demonstrations to farmers to switch from conventional rice–wheat system to alternative cropping systems.

**Keywords** Crop residue · Conservation tillage · Greenhouse gases · Groundwater · Soil health · Diversification

## Introduction

Presently crop cultivation has three dimensions, viz. intensive resources-based crop production to feed the burgeoning population, more economic benefit and sustainability of resources for the future generations. In the last few decades, research had been crop production oriented with limited focus on declining natural resources and biodiversity. In recent time, stagnant crop productivity and deteriorated natural resources amidst climate change forced the researchers and stake holders to explore some alternative crop production strategies and management practices to keep the agricultural sustainability in long term. The problems of stagnant crop productivity, declining natural resources and increased environmental pollution witnessed predominantly in the regions with intensive adoption of conventional rice–wheat system (Ladha et al. 2007; Kumar et al. 2021),

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Communicated by Márton Jolánkai.

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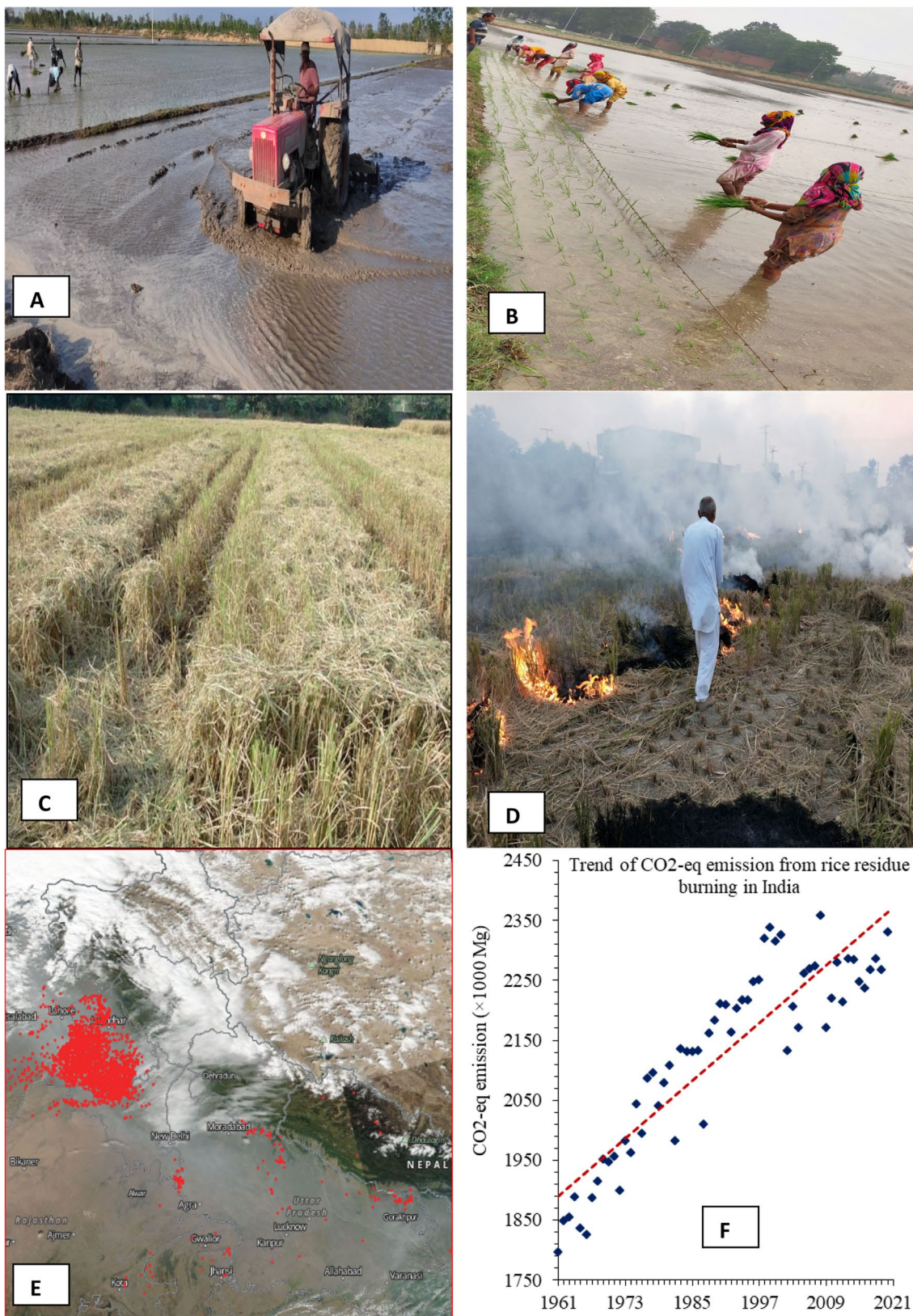
which occupied an area of 13.5 million hectares (m ha) in the Indo-Gangetic Plains of South Asia (Gupta and Seth 2007). In India alone, about 10.3 m ha area is under rice–wheat system, followed by Pakistan (2.2 m ha), Bangladesh (0.8 m ha) and Nepal (0.6 m ha). The critical phases and issues in conventional rice cultivation system are presented in Fig. 1. The conventional rice cultivation in north-western Indo-Gangetic Plains is characterized by intensive puddling followed by transplanting of 25–30 days old rice seedlings with stagnation of water in paddy fields for two to three weeks and thereafter replenish irrigation every two–three days upon infiltration of water into soil (Kumar and Ladha 2011; Anonymous 2020a). The long-term attachment of farmers with conventional practice of rice cultivation is due to its tangible benefits such as competitive advantage against weeds associated with differential size of rice seedlings against the concurrently germinating weeds and poor oxygen diffusion, hindering the weed germination (Rao et al. 2007; Kumar and Ladha 2011), assured anaerobic conditions with neutral soil reaction (Aggarwal et al. 1995) and higher availability of nutrients to plants with low or no iron deficiency. Although water percolation losses (14–16%) and crop water demand (10–25%) in rice are reduced after puddling, it comes at the expense of huge amount of water and energy accounted in puddling and other operations. In fact, conventional rice cultivation is considered as water-intensive practice and it requires a huge amount of water (about 2500 L) to produce 1.0 kg of rice (Bouman 2009). The total water requirement of rice–wheat system ranges from 1382 to 1838 mm and about 80% of which is consumed by rice crop only (Gupta et al. 2002) with about 50 and 1500 mm for nursery and after rice transplanting, respectively.

Researchers expressed concerns on sustainability of rice cultivation associated with high energy demand, deterioration of the groundwater table and escalating cost of groundwater pumping from deeper depth as a result of puddling and ponding practices (Humphreys et al. 2010; Chauhan et al. 2012). It is estimated that out of total energy input ( $52.4 \pm 1.3$  GJ ha<sup>-1</sup>) required for rice cultivation, irrigation water uses about 40% of total energy followed by 17.7% for electricity in pumping out of groundwater (Singh et al. 2019). This is also accompanied by increase in associated carbon dioxide (CO<sub>2</sub>) emissions emitted during the multiple wet tillage operations in puddling and water pumping in the cases where stationary diesel engines are used as power source. The practice of intensive puddling and continuous flooding in rice field also promotes methane (CH<sub>4</sub>) emission as a result of methanogenesis (Sapkota et al. 2015). Grace et al. (2003) reported that rice–wheat system emitted greenhouse gases with global warming potential of 13–26 Mg CO<sub>2</sub> ha<sup>-1</sup> per year in Indo-Gangetic Plains. The environmental threats of intensive rice cultivation are also encouraged by dominating chemical-based weed control strategies.

The continuous cultivation of rice–wheat system along with faulty spray techniques have resulted in accelerated herbicide resistance in wheat associated weeds such as *Phalaris minor* and *Rumex dentatus* (Chhokar et al. 2018). Recently in rice also, first case of herbicide resistance in *Cyperus difformis* L. against bispyribac-sodium was reported in India (Choudhary et al. 2021). The effective dose of bispyribac-sodium required to control 50% of plants was found 19–96 g ha<sup>-1</sup> as compared to 10 g ha<sup>-1</sup> for susceptible.

In addition to the above discussed challenges, the alternate anaerobic (rice) and aerobic (wheat) regimes affect the soil characteristics and drive the dynamics of moisture and nutrient availability (Singh and Benbi 2020). Puddling causes the increase in soil bulk density leading to formation of hard pan (7 to 10 cm) in soil layer which causes depressed root rhizosphere of succeeding crop resulting in lower yields (Oussible et al. 1992; Aggarwal et al. 1995) and necessitate more tillage operations for succeeding crop (Kumar and Ladha 2011). In fact, conventional puddling and transplanting in rice fields followed by multiple tillage to create the fine seed bed for sowing of succeeding wheat are considered highly money-, water- and energy-intensive practice, resulting in the lower resource use efficiency (Saharawat et al. 2010; Chauhan et al. 2012). Studies have also confirmed significant yield reduction in other succeeding crops like chickpea (*Cicer arietinum* L.) and mustard (*Brassica sp.*) primarily due to compaction of soil and carry over effect of puddling in rice (Gangwar and Singh 2010).

The ill effects of puddling and other practices in conventional rice production do not come to end even after harvesting of crop. The burning of rice residue remains a common practice in north-western Indian Plains to clear the field in a rapid and economic way in response to limited availability and costly residue handling machines, higher cost on residue removal from the fields and unsuitability of rice residue for fodder purpose which enables farmers for timely sowing of wheat crop which otherwise causes yield decline in wheat upon delay. The nutrients contained about 5.5 kg nitrogen (N), 2.3 kg P<sub>2</sub>O<sub>5</sub>, 15–20 kg K<sub>2</sub>O, 1.2 kg sulfur (S), 3–4 kg calcium (Ca), 1–3 kg Mg and 400 kg of carbon (C) in each tonne of rice residue are majorly lost upon burning (Dobermann and Fairhurst 2002). In addition to nutrient losses, C, N and S in straw are converted to various gaseous emissions upon burning. *In-situ* rice residue burning also causes significant reduction in microbial population such as bacteria, fungi, actinomycetes, phosphate along with cellulose degraders immediately after burning (Kumar et al. 2019) and microbes related to biomass recycling fails to recover even after 60 days. The different estimations on total rice residue production and residue burned every year throughout the country, and in Haryana and Punjab states are presented in Table 1 (Jain et al. 2014; Lohan et al. 2018; Chaudhary et al. 2019). Similarly, rice, wheat and sugarcane



**Fig. 1** Critical phases/issues in conventional rice cultivation system, viz. water guzzling operation (puddling) resulting in soil compaction (A), laborious work of manual transplanting (B), presence of loose

straw after combine harvesting (C), gaseous emissions from residue burning (D), satellite image of burning spots as red dots (E), trend of CO<sub>2</sub>-eq emission from rice residue burning in India (F)

**Table 1** Different approximation on quantification of crop residue burning in India

Location	Amount of rice residue produced (m t per year)	Amount of rice residue burnt (m t per year)	References
India	153.35	41.52	Jain et al. (2014)
India	154 (gross potential and 43.50 surplus)	–	Hiloidhari et al. (2014)
Punjab and Haryana	18.45	14.42	Lohan et al. (2018)
Punjab	15.00	7.50	Sidhu et al. (2007)
Punjab	18–20	14.40–16.01	Roy and Kaur (2016)
Punjab	21–23	17.11–18.75	Kaur et al. (2006); Sangeet (2016)
Haryana	4.80	1.29	HARSAC (2018)

(*Saccharum officinarum* L.) constituted about 23, 48 and 23% of crops residues burnt in Pakistan (Azhar et al. 2019). Moreover, residue burning increased carbon dioxide emissions by 40% from 2000 to 2014 at an annual rate of 2.7% while other South Asian countries, i.e. Indonesia, Vietnam, Myanmar, Thailand and Philippines constituted about 36.0, 21.0, 15.0, 14.8 and 9.0%, respectively, to the amount of crop residue open burning, whereas, for crop-specific rice contributed to 19–97% followed by maize (2–78%) and sugarcane (0.4–26%) to the total crop residue burning (Oanh et al. 2018).

The expansion of rice area in Haryana and Punjab states of India in the last few decades and sharp decline in groundwater table further escalated these issues and placed this region under water-stressed category besides a huge source of greenhouse gases emissions as a result of water ponding and residue burning practices. The rigorous adoption of rice–wheat system has resulted in the depletion of the groundwater table in north-western India and current crop production is at the expense of natural resources (Rodell et al. 2009). The existing crop production system is becoming more fragile due to imbalanced use of fertilizers, extensive burning of crop residue in rice–wheat system and scarcity of available resources within each target ecosystem (Sidhu et al. 2007) and these intermingled issues with rice–wheat system emphasize importance of system diversification for ecological and human health.

## Materials and methods

Considering the issues pertaining to conventional rice cultivation coupled with climate vagaries and its menace on agriculture, it requires the urgent attention to explore the alternative crop production systems, resource conservation technologies and diversification of rice with lesser resource guzzling crops to conserve the natural resources for future sustainability. Therefore, present review study was undertaken to discuss the key issues in conventional rice

cultivation system amidst climate change and to explore the viable technological and strategic diversification options to address these challenges for agricultural sustainability in future. We have collected the information from about 140 research articles, reviews and reports oriented to rice–wheat system and possible diversification options in north-western Indo-Gangetic Plains especially in Haryana and Punjab states of India. In this regard, we searched databases (Google Scholar and Scopus) for existing literature with specific search terms (diversification, rice–wheat, Indo-Gangetic Plains, maize, pigeonpea (*Cajanus cajan* L.), summer mungbean [*Vigna radiata* (L.) Wilczek], etc.).

## Gravity of groundwater depletion in north-western Indo-Gangetic Plains

India is the largest consumer of groundwater as 60% of nation's total water supply met by groundwater. The dominant share (88–90%) of groundwater extracted is utilized for irrigation activities in agricultural fields (Siebert et al. 2010; GoI 2014). The increase in total irrigated area, uncertainty of rainfall, slow recharge rate of groundwater resources and increased cultivation of high water guzzling crop like rice have been the major reasons for rapid withdrawal of groundwater used for irrigation. For instance, the area under rice cultivation was 0.31 m ha in 1966 which was increased to about 3.10 m ha (ten times increase) in Punjab state, India. Similarly in Haryana state, India, where around 0.19 m ha of land was under rice cultivation in 1966, increased to 1.56 m ha (a seven-fold hike) in 2019. Further, the subsidized rate-based electricity in Haryana and Punjab states caused the overuse of water pumps (through whole night running) resulting in water ponding conditions each day during the initial phase of rice establishment and loss of excess water to side fields or paths.

The decline in water table depth was 0.2 m per year between 1973 and 2000 which increased to 1.0 m per year during 2000–2006 in many regions of Haryana and central

Punjab (Humphreys et al. 2010; Singh et al. 2014). The results of groundwater depletion rate especially of north-western Indo-Gangetic Plains computed using different techniques are presented in Table 2 which show the over-exploitation of groundwater, a cause of concern for the country. The district-wise decline in water level of Punjab is depicted in Fig. 2. Hira et al. (2004) found that decline rate (average annual rate) in groundwater table was 18 cm during 1982–87 and 42 cm during 1997–2002. During 2002–2006, decline rate increased to 0.75 m per year and worsened the condition (Singh 2006) and a hefty 0.83 m per year particularly in the year 2002–2003, with average decline of 52 cm annually for the Punjab state (Kaur et al. 2011). The area with water table depth greater than 10 m was increased from 20% (1998) to 58% (2006) due to shifting in paddy transplanting time to early and change in centrifugal pump to submersible pump (Kaur et al. 2011).

The depth of water table in Haryana districts is shown in Fig. 3. In Haryana also, average annual decline rate was recorded in districts Kurukshetra, Karnal, Kaithal and Fatehabad as 1.14, 0.93, 0.70 and 0.52, respectively (Singh and Kasana 2017). Moreover, increase in depth of water table (m per year) in major rice producing districts, i.e. Kurukshetra, Kaithal, Karnal, Fatehabad, Panipat and Sirsa were 0.34, 0.12, 0.23, –0.06, 0.25 and –0.34 during 1974 to 1995, but accelerated increase was found during 1995 to 2020 with 0.97, 0.92, 0.42, 0.82, 0.47 and 0.50 m per year, respectively. The periodical fluctuation in water table during 1974–2014 and 1974–2020 showed more fluctuation in water table from 2014 to 2020 in different districts of Haryana. Mainly two factors were responsible for this decline; one was increasing the area under tubewell irrigation from about 38.9% (1975–1976) to 61.2% (2011–2012) and second is the rice–wheat system as major cropping system (Singh 2015).

Considering these issues, Government of India has also taken concrete steps including ‘The Preservation of Subsoil Water Act, 2009’ with the objectives to conserve irrigation water, prohibits early transplanting of rice to reduce unproductive evaporation water losses and irrigation demand (Dangar et al. 2021). This subsequently reduced the annual rate of water table fall from 84 cm per year (2000–2008) to 50 cm per year (2008–2014). The transplanting time was again revised in 2014 to June 15 and further in 2018 to June 20. However, presently, the annual groundwater recharge is less than the annual groundwater consumption in Haryana, India leading to depletion of groundwater table. In India, recently a study showed that with current depletion rates cropping intensity may shrinkage by 20 and 68% at national scale and in groundwater depleted regions, respectively (Jain et al. 2021). Under these scenarios, to sustain the crop productivity, alternative agro-techniques and diversification options need to be identified and delivered on the large scale. Further to sustain the rice production, systematic integration

of developing high-yielding and water stress-tolerant rice cultivars with improved resource conserving technologies will be needed under shrinking cultivable area, water and labor availability.

## Technological refinements to improve sustainability of rice–wheat system

In recent years, tremendous efforts have been made to rectify, ameliorate the challenges and sustainability threats imposed by rice–wheat system. These technological refinements are devoted to discover the efficient and viable alternatives of ongoing crop establishment practices and strategic diversification in rice–wheat system with maize, pigeonpea and other lesser resource requiring crops.

### Scaling up of resource conservation technologies

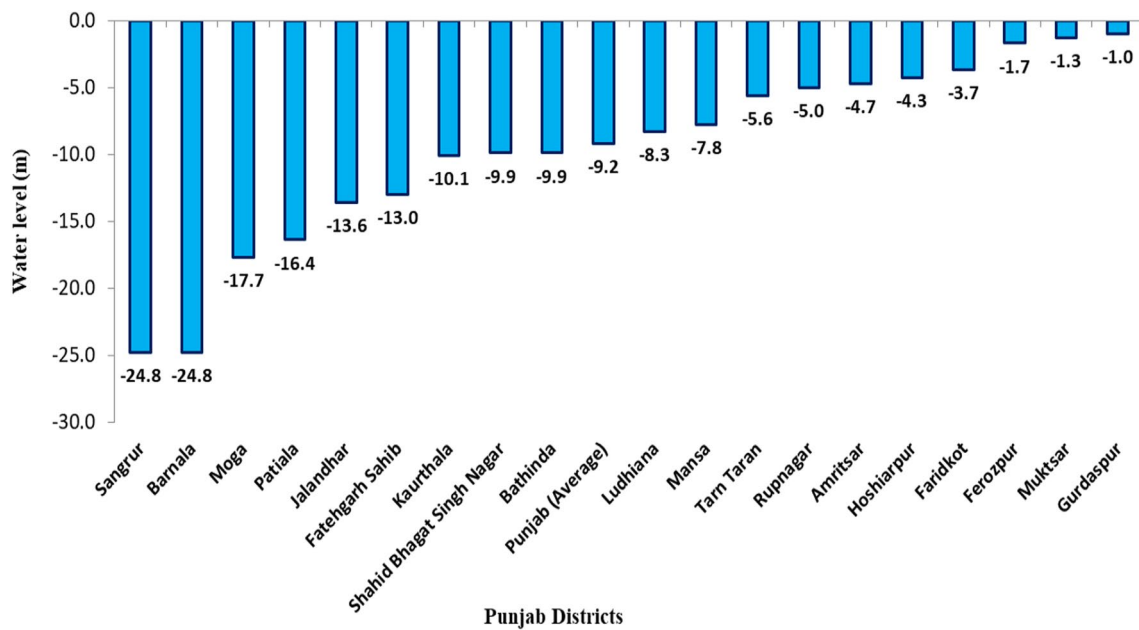
In the last few years, different resource conserving technologies (Table 3), viz. reduced tillage, laser land leveling, no-till with or without residue retention, brown manuring, nutrient management tools as leaf color chart, furrow-irrigated raised beds (FIRBs), subsurface drip irrigation in wheat have been validated under irrigated conditions in the Indo-Gangetic Plains to alleviate the ill effects of intensive rice–wheat system (Kumar and Ladha 2011; Jat et al. 2019, 2021; Singh et al. 2020). The multifarious benefits of these technologies such as reduced fuel cost, least labor requirement, improved water infiltration and timely sowing of crops resulting in higher yields, lesser weed infestation associated with depletion of seed bank and less disturbance, 15–20% water saving, improved input use efficiency and increased profitability attracted farmers’ attention and adoption of alternative practices at their fields (Gupta and Seth 2007; Sidhu et al. 2007; Saharawat et al. 2010; Chauhan et al. 2012).

### Direct seeded rice

Direct seeded rice is a cost-effective technology alternative to puddled transplanted rice to address the labor scarcity and water depletion issues. It eliminates the water guzzling operation, i.e. puddling in crop establishment which requires about 200 mm water. The advantages of direct seeded rice in terms of reduced labor requirement, lesser risk of terminal drought, crop intensification through early maturity and higher water use efficiency over puddled transplanted rice are well documented (Malik and Yadav 2006; Rao et al. 2007; Pathak et al. 2011). However, performance of direct seeded rice is highly sensitive to cultivar, soil and agro-climatic conditions (Rao et al. 2007; Kumar and Ladha 2011). The water saving of different matrices, viz. 3–4 irrigations, 450 mm water in and 20%, have been reported in

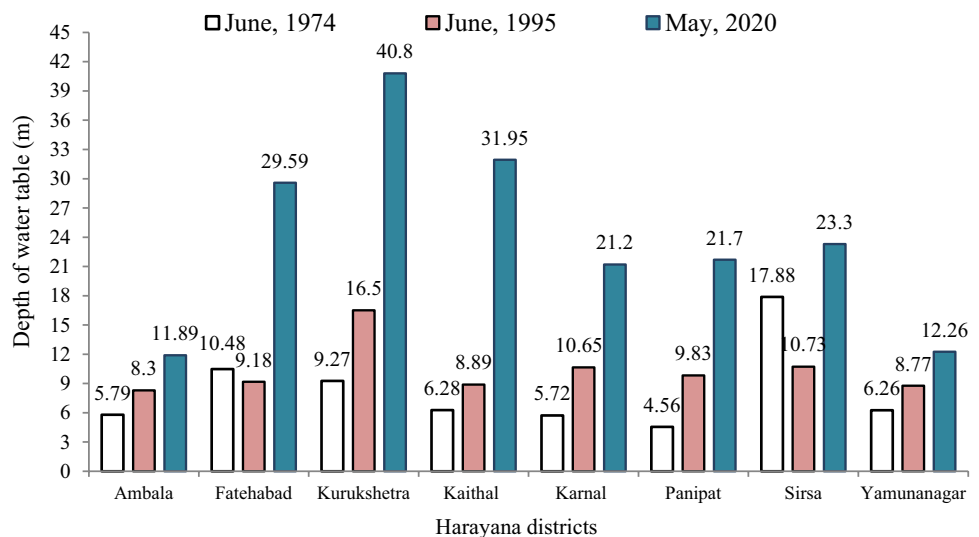
**Table 2** Studies on quantification of groundwater depletion in India particularly north-western Indo-Gangetic Plains

Study year	Region/Location	Method	Annual mean groundwater depletion/losses	References
1974–85, 1986–97 and 1998–2005	Central region of Punjab (India)	Open wells during pre-monsoon and post-monsoon	9, 20 and 65 cm per year, respectively	Singh (2006)
2002–2008	North-western India (particularly Haryana, Punjab and Rajasthan)	Gravity recovery climate experiment satellites (GRACE)	About 13–17 km <sup>3</sup> per year amount of groundwater is being extracted a net loss of 109 km <sup>3</sup> of water	Rodell et al. (2009)
1998–2006	Punjab (India)	Groundwater table maps, which were prepared, based on the spatial data analysis using Geographic Information System (GIS)	An average annual fall of 52.0 cm	Kaur et al. (2011)
2003–2012	North-western India	GRACE Satellites	During 2003–2007 (29.4 ± 8.4 km <sup>3</sup> per year), while 2003–2012 (20.4 ± 7.1 km <sup>3</sup> per year)	Chen et al. (2014)
2004–12	Haryana (India)	Geographic Information System from the groundwater level data of 893 observation well	Average annual decline of above 32 cm per year, with the strongest decline in Kurukshetra district (108.9 cm per year)	Singh and Kasana (2017)
2000 and 2019	Punjab (India)	Pre-monsoon water level data of observation wells	Average depletion rate 8.91 m with the highest values for district Barnala (20.38 m)	Sidhu et al. (2021)
2005–15	Haryana and Punjab (India)	GRACE satellites	1.13 cm for Haryana and 0.92 cm for Punjab	Singh et al. (2021)
1997–2018	Malwa region of Punjab (India)	Groundwater level data of 90 observation wells / piezometers	> 30% of tubewells in the eastern parts of Malwa having depletion rate 40 cm per year during pre- and post-monsoon, while in south-western > 20% of wells had increased groundwater level	Sahoo et al. (2021)



**Fig. 2** Average decline in water level (m) in different districts of Punjab during 2000 to 2019 (India Water Resources Information System, Anonymous 2020b)

**Fig. 3** The periodical scenario of water table depth in different districts of Haryana during 1974 to 2020 (Anonymous 2020c)








direct seeded rice with reference to puddled transplanted rice (Bouman et al. 2005; Pathak et al. 2013; Brar et al. 2021). Likewise, alternate wetting and drying technique in rice cultivation saves substantial amount of irrigation water due to lesser seepage losses than continuous ponding conventional rice cultivation. Gill et al. (2006) reported water productivity of 0.40–0.46 kg grain m<sup>-3</sup> for direct seeded rice as compared to 0.29–0.39 kg grain m<sup>-3</sup> for puddled transplanted rice. Yadav et al. (2011) noted that direct seeded rice had significantly higher irrigation water productivity as compared to puddled transplanted rice, irrigation with scheduling at 20 kPa soil matric potential in rice. Therefore,

in the medium to heavy textured soils, direct seeded rice coupled with alternate wetting and drying technique could be employed to conserve the water. The large-scale adoption of direct seeded rice is likely to favor the groundwater recharge through more water infiltration which may help in groundwater recharge in monsoon season.






The literature suggests that yield increment and water savings in direct seeded rice compared to puddled transplanted rice are not universal; as these results are specific to soil, site and climatic conditions and therefore, direct seeded rice should be advocated accordingly. Further, productivity constraints in direct seeded rice in South Asian countries

**Table 3** Important resource conservation technologies tested under rice–wheat system (Gupta and Seth 2007; Saharawat et al. 2010; Chauhan et al. 2012; Chaudhary et al. 2019)

Technology	Impact/particulars
<i>Tillage and residue management (crop establishment)</i>	
	Zero tillage without residue: Timely sowing of crop with higher yield, saving of fuel, irrigation water and time, less weed proliferation, reduced germination of <i>Phalaris minor</i> , lesser risk of crop lodging, improved nutrient use efficiency, increased profitability and lower environmental pollution (Erenstein and Laxmi 2008)
	Zero tillage + residue retention with Happy seeder: Timely sowing of crop with higher yield and other benefits like reduced fuel cost, soil temperature moderation, recycling of straw back to soil, irrigation water and time saving, lesser weed infestation, reduced germination of <i>Phalaris minor</i> due to restricted soil disturbance and surface retention of straw, and increased profitability (Sidhu et al. 2007)
	Residue incorporation with Super seeder: Timely sowing of crop through residue incorporation into soil and reduced input cost over conventional tillage. Requires additional nitrogen (N) in case of crop residue of high C N ratio to overcome the temporary N immobilization, higher draft and power requirement over residue retention practice. Likely to increase crop lodging incidence associated with sub surface compaction
	Furrow-irrigated raised beds: Cultivation of crops on raised beds with application of irrigation water through the furrows between the beds with benefits of irrigation water saving, efficient use of fertilizer, lower seed rate, less lodging and facilitating the mechanical/manual weeding, thereby reducing the herbicide use (Jat et al. 2005)
	Mechanical rice transplanting: Ensures proper spacing and recommended plant population with timeliness in operation resulting in increased yield lesser labor requirement and reduced cost of cultivation



**Table 3** (continued)

Technology	Impact/particulars
	<p>Direct seeded rice: A cost-effective technology alternative to puddled transplanted rice reduces the problems of labor scarcity, risk of terminal drought and facilitates crop intensification through early maturity of crop but with a penalty on yield while requiring more/less water depending upon the soil texture</p>
<p><i>Water management</i></p> 	<p>Laser land leveling: A remarkable innovation in the water conserving technique which saves 25–30% water and increases water and nutrient use efficiency through uniform depth of water, improves germination and crop stand, increases cultivable area, yield, enhances resource use efficiency and farm profitability (Jat et al. 2009)</p>
<p><i>Nutrient management</i></p> 	<p>Leaf color chart: Crop need-based nitrogen application reduces nitrogen fertilizer requirement, and reduced nitrogen losses with associated reduction in environmental pollution</p>
	<p><i>Sesbania</i> green manuring: Improves soil carbon and nutrient status along with increase in crop and system productivity (Yadav et al. 2019)</p>
	<p>Inclusion of zero tillage-based mungbean in rice–wheat system: Inclusion of short-duration mungbean after wheat harvest increases the productivity of rice–wheat system, reduces fertilizer requirement of succeeding crops and improve soil health</p>

had also been reported due to proliferation of many aerobic weeds viz. *Leptochloa chinensis*, *Digitaria sanguinalis*, *Dactyloctenium aegyptium*, *Echinochloa colona* and *Cyperus* spp. (Mahajan et al. 2009; Kumar and Ladha 2011). In addition to these, the most noteworthy constraint in productivity remains with nonavailability of aerobic tailored varieties as

the varieties designed for conventional puddled system fail to reflect their potential yields underwater unsaturated (aerobic) soils. The yield losses in direct seeded rice are mostly associated with poor weed management due to lack of effective pre- and post-emergence herbicides, sub-optimal irrigation scheduling, micro-nutrient (such as iron) deficiencies

associated with aerobic conditions and culture of direct seeded rice adoption in non-ideal (light) soil (Kumar and Ladha 2011; Bhullar et al. 2016; 2018).

It is evident from the results presented in Table 4 that grain yield losses under direct seeded rice under different climatic and soil conditions are highly variable (1.8–45.5%) as compared to conventional rice cultivation. However, the recent advances in direct seeded rice cultivation with short-duration varieties PUSA 1509, PR 126 and hybrids have made this technology popular among the farmers in some pockets of Haryana and Punjab, India. Rice seed can be directly sown in moist workable soil conditions by using a seed drill machine capable of simultaneous sowing and pre-emergence herbicide application (Anonymous 2020a). The scarcity of migrant laborers across the north-western states in India, Covid-19 induced labor shortage and rising wage rates at the time of rice transplanting are forcing the farmers to shift from conventional rice cultivation to direct seeded rice. Consequently, about 5.62 lakh ha area was sown through direct seeded rice technique in Punjab, India during *kharif* 2021, showing a sharp increase from 62,000 ha in *kharif* 2019 (Chaba 2021). However, excessive problem of weed infestation and under performance of rice cultivars under

aerobic conditions (direct seeding) may force the farmers to switch back to transplanted rice. So, proper weed management of diverse weed flora that emerges in flushes and realization of equivalent yields as in transplanting rice still remains the major challenges in the direct seeded rice cultivation.

Recently, new non-genetically modified imazethapyr herbicide-tolerant genotypes containing mutated acetolactate synthase inhibitor (ALS inhibitor) gene, i.e. Pusa Basmati 1979 and Pusa Basmati 1985 are proposed to tackle the challenges of weeds under direct seeded rice in India. Further, a recent study showed that sequential application of imazethapyr herbicide is required for effective control of diverse weed flora in herbicide-tolerant rice (Yadav et al. 2022) that may leads to increase in selection pressure. The reports from other imidazolinone-tolerant cultivars adopted countries showed limited potential of these practices in modulating weed problem in long term. The sole reliance on these practices have resulted in the rapid evolution of imidazolinone-resistant weedy rice, problem of gene flow and accelerated development of resistance in other weed species (Kumar et al. 2008; Avila et al. 2021). Further, matter of concern is that first case of herbicide resistance in *Cyperus difformis* L. against bispyribac-sodium (ALS inhibitor) in

**Table 4** Yield comparison between puddled transplanted rice and direct seeded rice under different soil types

Soil type	Grain yield (kg/ha)		Percent change in yield under direct seeded rice over puddled transplanted rice	References
	Puddled transplanted rice	Direct seeded rice		
Silty clay loam	5300	5400	(+) 1.9	Hobbs et al. (2002)
	5224	5593	(+) 7.1	Sharma et al. (2004)
	5486	5024	(-) 8.4	Sharma et al. (2005)
	5655	5224	(-) 7.6	Tripathi et al. (2005)
	6356	6092	(-) 4.2	Tripathi et al. (2005)
Silty loam	6100	5600	(-) 8.2	Hobbs et al. (2002)
	8100	6820	(-) 15.8	Gathala et al. (2011)
Sandy loam	5600	5300	(-) 5.4	Hobbs et al. (2002)
	4930	4900	(-) 0.61	Sharma et al. (2005)
	7500	6400	(-) 14.7	Jat et al. (2009)
	7720	8300	(+) 7.5	Gangwar et al. (2009)
	5975	4795	(-) 19.8	Chhokar et al. (2014)
	6100	5400	(-) 11.5	Kahlon and Dhingra (2019)
	6552	5960	(-) 9.0	Singh et al. (2020)
Sandy clay loam	5300	3600	(-) 32.1	Kukkal et al. (2014)
	4467	3033	(-) 32.1	Singh et al. (2001)
Clay soil	4130	4500	(+) 9.0	Tripathi and Chauhan (2001)
	7080	4180	(-) 41.0	Ram et al. (2006)
Loamy sand	3220	2872	(-) 10.8	Mahajan et al. (2009)
	5458	5345	(-) 2.1	Walia et al. (2014)
Loam	3720	3620	(-) 2.7	Sharma et al. (1995)
Fine silty	4175	3340	(-) 20.0	Farooq et al. (2008)

India (Choudhary et al. 2021) was reported recently having the similar mode of action.

Nevertheless, comprehensive studies are needed regarding the comparative saving of irrigation water in direct seeded rice keeping in view the farmers' practice of early seeding during the peak evapotranspirative demand in summers and consequent frequent irrigations. Assessment and quantification of nutrient leaching in direct seeded rice is also required considering the use of higher amount of fertilizers, besides more percolation of water as compared to puddled transplanted rice. There is need to examine the soil–water dynamics in rice–wheat system instead of individual crops as increased water productivity in direct seeded rice could affect the water productivity of succeeding crop. Future research efforts on developing short-duration, deep rooted, resistant to abiotic stress (adverse soil conditions and lodging); and biotic stress (brown leaf spot, blast and grain discoloration) rice varieties and mechanical-based weed management module would be helpful to address some of the existing challenges and to switch the farmers from conventional rice cultivation to direct seeded rice.

### Opportunistic diversification of rice–wheat system with inclusion of summer legume

A short window of about 65–70 days, i.e. after harvesting of wheat and before transplanting of rice, can be utilized as an opportunity to include short-duration legume crop such as mungbean. Inclusion of short-duration mungbean after wheat harvest has the potential to increase productivity of rice–wheat system as shown in Table 5, besides improving the physical and chemical properties of soil. The photo-thermo insensitivity varieties with short maturity duration

(55 to 65 days), high yield ( $> 2 \text{ t ha}^{-1}$ ), synchronous maturity and resistance to major disease were developed to strategically fit the mungbean in rice–wheat system. Earlier, detailed agronomic practices and information related to varieties were provided by Gupta and Pratap (2016). Numerous studies reported higher nutrient use efficiency (Sharma and Prasad 1999), water use efficiency from 1.4 to 2.3 kg grain  $\text{m}^{-3}$  (Laik et al. 2014), benefit cost ratio from 1.47 to 2.40 (Venkatesh et al. 2015; Pooniya et al. 2018) with inclusion of summer mungbean in rice–wheat system. The incorporation of mungbean or *Sesbania* green manuring into soil also resulted in recycling of 77–113 kg N  $\text{ha}^{-1}$  and improved plant nitrogen uptake by 12–35 kg  $\text{ha}^{-1}$  per year, besides increasing the productivity of rice–wheat system by 0.5–1.3 t  $\text{ha}^{-1}$  per year (Sharma and Prasad 1999) over rice–wheat system without summer crop. However, area under short-duration mungbean after wheat harvest did not gain much success due to non-availability of extra early synchronous maturity short-duration varieties, escalating cost of manual picking, untapped mechanization potential for timely sowing and harvesting, abnormal rainfall during the crop growth are some of the important constraints that limiting potential productivity and large-scale adoption of mungbean in the rice–wheat system.

### Strategic diversification of conventional rice–wheat system to conservation agriculture-based maize-wheat system in light-medium textured soils

Maize has been a promising substitution to rice crop especially in regions with light-medium textured soils and high depletion rate of groundwater due to its lesser resource

**Table 5** Increase in yield and soil organic carbon with inclusion of legume (mungbean) in rice–wheat system in Indo-Gangetic Plains

Studies	Location	System yield ( $\text{t ha}^{-1}$ )		Percent increase in yield	Organic carbon	
		Rice–wheat	Rice–wheat-mungbean		Rice–wheat	Rice–wheat-mungbean
Laik et al. (2014)	Patna, Bihar, India	8.5 <sup>a</sup> (8.4)	15.1 <sup>a</sup> (11.2)	77.8 (33.2)	–	–
Sharma and Sharma (2005)	New Delhi, India	8.0 <sup>a</sup>	8.9 <sup>a</sup>	11.3	–	–
Pooniya et al. (2018)	New Delhi, India	9.4	10.8	15.0	0.52% or 12.5 Mg C/ha	0.56% or 13.8 Mg C/ha
Sharma et al. (2000)	New Delhi, India	8.4	10.0	19.0	–	–
Mandal et al. (2003)	New Delhi, India	7.9	9.3	17.7	8.75 g/kg soil	10.33 g/kg soil
Hazra et al. (2018)	Kanpur, Uttar Pradesh, India	6.2	8.4	36.6	17.29 total organic carbon Mg/ha	20.55 total organic carbon Mg/ha
Venkatesh et al. (2015)	Kanpur, Uttar Pradesh, India	8.3	10.4	25.5	0.28%	0.32%

<sup>a</sup>Rice equivalents based

requirement. The replacement of rice in rice–wheat system with maize can increase the crop and water productivity of cropping system, sustain the soil health and reduce the overall environmental footprints (Jat et al. 2013; Parihar et al. 2016). Moreover, due to deepening of water table associated with faster depletion of groundwater and escalating cost of water pumping from deeper depths for irrigation in puddled transplanted rice (Sharma et al. 2015), the area under maize-wheat system has potential to grow in the north-western Indo-Gangetic Plains (Jat et al. 2013, 2015). Maize-wheat system uses annually 47% lower total energy input than rice–wheat system because of saving in 81 and 73% energy accounted for tillage operation/crop establishment and; irrigation and fertilizers management, respectively (Kumar et al. 2018). The area under maize has been decreasing after 1970 in Haryana and Punjab, India due to adoption of rice–wheat system after green revolution.

### Maize-based system to amplify the water productivity

Maize crop requires about 600 litre water to produce 1 kg grain, which is about 75% lesser than water required for production of 1 kg rice grain (Bouman 2009). For sustaining natural resource base, maize has emerged as a viable alternative to replace the conventional rice in Indo-Gangetic Plains (Sharma et al. 2015). Based on the rice equivalent yield, the water productivity of maize ( $5.0\text{--}5.6\text{ kg m}^{-3}$ ) has been reported as 3.5 to 5.0 fold higher than wheat and about 8 to 22 fold higher than rice (Gathala et al. 2013). Maize-wheat

system has higher water productivity because of reduced water losses from bare soil as a result of large coverage of maize canopy and absence of puddling and ponding of water operations as in case of rice. Sharma et al. (2015) found the water productivity of maize as  $1.6\text{--}3.9\text{ kg m}^{-3}$  while being  $0.8\text{--}1.6\text{ kg m}^{-3}$  for wheat and  $0.2\text{--}1.2\text{ kg m}^{-3}$  for lowland rice.

A large number of research studies have been conducted to examine the yield and water productivity on crop (wheat) and system basis in maize-wheat system under different crop establishment methods with a comparison to conventional rice–wheat system and results are detailed in Table 6. It is evident from the presented results that productivity of wheat and overall system under maize-wheat pattern in loam to clay-loam soil with either crop establishment practice was higher than the wheat yield found in conventional rice–wheat system. Further overall system productivity within maize-wheat system was the maximum under permanent raised beds + residue retention followed by zero tillage and conventional till fresh bed. Parihar et al. (2016) also reported that maize establishment on permanent raised beds can save the irrigation water and improve crop and water productivity in maize-wheat system in Indo-Gangetic Plains. However, superficial reshaping of beds before the sowing of maize in rainy season remains the key requirement for sustainability of permanent raised beds in maize-wheat system (Govaerts et al. 2005). The integrated approach of conservation tillage, recycling of residue back to soil and smart irrigation in maize-wheat system can lead to drastic increase in system productivity and profitability over

**Table 6** Productivity of water ( $\text{kg m}^{-3}$ ), wheat crop and overall system ( $\text{t ha}^{-1}$ ) under maize-wheat system with different establishment methods with reference to rice–wheat system

References	Soil type	Productivity	Conventional till- rice–wheat system	Conventional till fresh bed—maize-wheat system	Zero tillage— maize-wheat system	Permanent raised bed— maize-wheat system (+ RR)
Choudhary et al. (2018a)	Loam	Water	0.44	1.01	–	1.45
		Wheat	4.76	4.82	–	5.80
		System	11.78	11.71	–	13.61
Gathala et al. (2013)	Loam	Water	0.36	–	0.89	–
		Wheat	4.96	–	5.84	–
		System	12.30	–	13.4	–
Jat et al. (2021)	Clay loam	Water	0.42	0.99	–	1.35
		Wheat				
		System	11.24	11.46	–	13.31
Choudhary et al. (2018b)	Clay loam	System	11.10	11.20	12.30	12.80
Choudhary et al. (2018c)	Clay loam	Wheat	5.00	4.92	–	5.22
		System	12.09	11.23	–	12.40
Kumar et al. (2018)	Reclaimed alkali with loam	Water	0.37	–	1.00	–
		Wheat	5.00	–	5.90	–
		System	12.30	–	14.30	–

rice–wheat system. Jat et al. (2019) observed 20% increase in system productivity, 49% hike in profitability and 85% saving of irrigation water with conservation agriculture-based subsurface drip irrigation and fertigation in maize–wheat system as compared to conventional rice–wheat system. In a different study, Sandhu et al. (2019) studied the effect of furrow irrigation-residue removal, drip irrigation-residue removal, drip irrigation + residue retention (50% maize upper straw and 25% lower wheat straw) under sandy loam soil and found that drip irrigation + residue retention saved 168 mm of water in maize and 88 mm of water in wheat. Therefore, in this treatment, the water productivity was 259% higher for maize and 66% more in case of wheat than furrow irrigation-residue removal treatment. Also, treatment having drip irrigation + residue retention demonstrated 13.7 and 23.1% increase in grain yield of maize and wheat, respectively, compared to those under furrow irrigation-residue removal practice. Considering the severity of declining water resources problem in north-western Indo-Gangetic Plains, various water conserving techniques have been tested, refined and optimized over the years for different crops of which conservation agriculture-based maize cultivation with drip irrigation emerged as a potential crop substitution to rice due to lesser water requirement with lower noxious impact on the environment. Further, the continuous cultivation of maize would be helpful to promote the micro-irrigation system in succeeding crops as well.

### Maize-based cropping system to restore the soil health and crop productivity

The cropping system, tillage methods and residue recycling play key role in soil physicochemical and biological properties. Irrespective of the tillage methods, soil labile carbon pools, activities of enzymes and heterotrophic microbial counts are reported to be higher in maize followed by cowpea (*Vigna unguiculata* L.), while least in the rice (Neogi et al. 2014). Choudhary et al. (2018c) also found that dehydrogenase activity and alkaline phosphatase activity increased by 210 and 49%, respectively, in maize–wheat–mungbean system as compared to rice–wheat–fallow system with residue removal. Furthermore, significant rise was observed in the mean population of actinomycetes, fungi and bacteria by 98, 68, 28%, respectively, under the maize–wheat–mungbean system over base treatment (rice–wheat system). Overall, microbial biomass carbon, microbial biomass nitrogen, dehydrogenase activity, alkaline phosphatase activity and microbial counts were 37, 51, 45, 8.8 and 5–17% higher in conservation agriculture-based maize–wheat–mungbean system as compared to rice–wheat–mungbean system. The dehydrogenase activity has been identified as a suitable indicator to quantify the changes in

microbial activity, which in turn promotes plant and microbial growth by releasing nitrogen, phosphorus and sulfur on decomposition (Jat et al. 2015). The integration of zero tillage with residue retention increased microbial biomass carbon ( $1990 \mu\text{g g}^{-1}$  dry soil) and microbial biomass nitrogen ( $729 \mu\text{g g}^{-1}$  dry soil) in maize–wheat system, while the lowest activity of microbial biomass carbon and nitrogen were recorded under conventional rice–wheat system ( $646$  and  $210 \mu\text{g g}^{-1}$  dry soil, respectively). Similarly, the maximum microbial count and microbial biomass nitrogen values were found higher in zero tillage and residue retention than conventional tillage and residue removal (Govaerts et al. 2007). The increased biological activities and microbial biomass under zero tillage + residue retention are associated with more availability of substrate or carbon source for microbial growth. Wang et al. (2008) reported 48 and 73% increase in microbial count and microbial biomass nitrogen, respectively, in maize–wheat system over rice–wheat system due to relatively higher rate of residue recycling with variable soil edaphic conditions. Jat et al. (2017) described the behavior of soil chemical and physical properties under maize and rice-based cropping systems and reported that 29.4% more water stable aggregates, lower bulk density and lesser soil penetration resistance under permanent raised bed-based green gram, resulting in improved infiltration over conventional tillage practice. Maize-based diversification under conservation tillage techniques significantly modified the physical properties of soil resulting in 16–33% higher water stable aggregates ( $> 250 \mu\text{m}$ ), 11.0–11.3% reduction in bulk density and 11.2–12.0% declining penetration resistance under zero tillage and permanent raised bed scenario (Parihar et al. 2016). From fertilizer application perspective, site-specific nutrient management can be an additional choice in conservation agriculture-based maize–wheat system to further enhance the resource use efficiency and soil health. The effect of tillage practice was also witnessed on maize yield. Majumdar et al. (2012) recorded higher yield of maize sown under zero-till practice with site-specific nutrient management over conventionally sown maize crop even at similar nitrogen application rates, resulting in higher net returns and nitrogen use efficiency. The addition of residue retention with zero tillage increased the yield attributes of maize along with lower weed infestation and higher economics returns over zero tillage without residue (Khedwal et al. 2017). Jat et al. (2013) and Das et al. (2018) also reported that conservation agriculture practices involving zero tillage on flat and permanent beds increased the productivity and profitability along with saving of energy and water in maize-based cropping system. Conservation agriculture with precise nutrient and irrigation management strategies can further improve the productivity, economic gain and resource use efficiency (Parihar et al. 2016; Jat et al. 2019; 2021).

## Maize-based cropping system to lessen the greenhouse gases emission load on environment

The crop establishment method, cropping system followed and management of nutrient, water and pests are the key agronomical components responsible for emittance of greenhouse gases from agricultural fields. Methane is the second most important greenhouse gas after carbon dioxide (CO<sub>2</sub>) and a single molecule of methane (CH<sub>4</sub>) traps nearly 28 times as much heat, as does the CO<sub>2</sub>. The studies on methane emission measurement indicated that CH<sub>4</sub> emission is primarily dependent on parameters such as frequency of water drainage, soil types, soil temperature (Parashar et al. 1991) along with organic and inorganic fertilization (Singh and Benbi 2020). The formation of plough-pan or hard pan in wet tillage under conventional rice cultivation holds the water and blocks the soil pores, resulting in increased CH<sub>4</sub> emission. Further, these all processes depend upon decomposition rate of soil organic matter and soil redox potential (Saini and Bhatt 2020; Singh and Benbi 2020). For instance, the production of 1 kg of rice returns 2.6 times more CO<sub>2</sub> equivalent emission to the environment than other cereals. Singh and Benbi (2020) reported emission of 0.2 kg CO<sub>2</sub> equivalent per kg grain in rice–wheat system as compared to 0.1 kg CO<sub>2</sub> equivalent per kg grain in maize-wheat system. In puddled transplanting fields, intermittently flooding with single and multiple aerations reduced methane emission and lower global warming potential by about 18.1 and 27.6%, respectively, as compared to continuously flooded fields (Singh and Benbi 2020). The conventional rice cultivation showed higher CH<sub>4</sub> emission (50–250 mg m<sup>-2</sup> d<sup>-1</sup>) than direct seeded rice (< 50 mg m<sup>-2</sup> day<sup>-1</sup>). The total cumulative soil flux of CO<sub>2</sub>, nitrous oxide (N<sub>2</sub>O) and CH<sub>4</sub> emissions in terms of CO<sub>2</sub> equivalent was 27% more in conventional rice–wheat system than direct seeded rice followed by zero-till wheat along with residue retention (Sapkota et al. 2014). A 34% reduction in global warming potential was observed on substitution of puddled transplanted rice with direct seeded rice. Irrigation and nutrient management systems followed by farmers and conventional tillage make significant contribution to greenhouse gases emission (Sapkota et al. 2014). Rice residue burning is largely practiced in northern India and burning of 1 Mg rice straw releases about 280 kg CO<sub>2</sub>-C, 3 kg CH<sub>4</sub> and 0.07 kg N<sub>2</sub>O-N with a global warming potential of 1118 kg CO<sub>2</sub> equivalent. In the scenario of climate change, global warming potential or emission intensity of various crops should be assigned as key factor, responsible for long-term sustainability of crop production and environment.

It is evident from Table 7 that rice crop poses extreme high global warming potential (0.50–5.65 kg CO<sub>2</sub>-eq kg<sup>-1</sup>) over others, viz. maize (0.18–0.45 kg CO<sub>2</sub>-eq kg<sup>-1</sup>),

soybean (*Glycine max* L.) (0.10 kg CO<sub>2</sub>-eq kg<sup>-1</sup>) and sugarcane crop (0.09 kg CO<sub>2</sub>-eq kg<sup>-1</sup>). Maize-based cropping systems seem to be the best alternative to rice-based cropping systems to address the challenges of increased gaseous emission load on the environment and declining resources like in north-western Indo-Gangetic Plains. The lower global warming potential in maize is associated with alternation in crop establishment practices, i.e. absence of puddling, continuous ponding of water and residue burning in addition to reduction in fuel consumption on elimination of wet tillage and intensive tillage for succeeding crop as followed in conventional rice-based cropping systems. In the scenario of declining natural resources and climate change, it is also crucial to make the selection of crops not only based on the yield but also their net returns to the environment.

## Pigeonpea (*Cajanus cajan* L.)-based diversification of rice–wheat system

Pigeonpea-based diversification of rice–wheat system has the potential to ameliorate the current situation by more nitrogen additions in soil, lower water requirement and eliminated subsurface soil compaction as witnessed in conventional rice cultivation (Dahiya 2002; Singh and Dwivedi 2006; Das et al. 2016). However, the potential benefits can be realized with adoption of high-yielding and super-early maturing (< 90 days) varieties of pigeonpea to fit it in non-traditional areas for diversification purpose (Vales et al. 2012). Singh and Dwivedi (2006) reported lower cost associated with optimum doses of nitrogen fertilizer for wheat under pigeon pea-wheat system (128–133 kg ha<sup>-1</sup>) compared to rice–wheat system (139–173 kg ha<sup>-1</sup>) associated with nitrogen fixation and lower nitrogen demand of former system. Moreover, pigeonpea-wheat system also reduced NO<sub>3</sub> leaching to deeper soil profile layers as nitrate-N concentration was lower for pigeonpea-wheat system (5.8–6.0 mg kg<sup>-1</sup>) compared to rice–wheat system (6.5–8.1 mg kg<sup>-1</sup>) associated with its higher fertilizer demand (120–180 kg N ha<sup>-1</sup>). The continuous adoption of rice–wheat system increased the bulk density of soil over initial value and effects were more pronounced at 30–45 cm soil depth, while pigeonpea maintained the soil bulk density, thereby eliminating the problem of subsurface soil compaction. This facilitated higher wheat root growth and root penetration to deeper soil depths subsequently increasing the wheat grain yield by 2.7–47.0% under pigeonpea-wheat than rice–wheat system (Singh and Dwivedi 2006). Das et al. (2016) reported higher productivity of pigeonpea-wheat system in addition to higher water use efficiency by planting the crops on permanent narrow beds along with retention of residue. Unlike rice, pigeonpea crop introduced positive effects on root volume and root weight of succeeding wheat

**Table 7** The global warming potential of various crops

Study region	Crop	Global warming potential (kg CO <sub>2</sub> -eq kg <sup>-1</sup> product)	Source
Worldwide	Maize ( <i>Zea mays</i> L.)	0.45	Audsley et al. (2009)
	Lentil ( <i>Lens culinaris</i> L.)	1.10	
	Beans ( <i>Phaseolus vulgaris</i> L.)	0.61	
	Chickpea ( <i>Cicer arietinum</i> L.)	0.77–0.80	
	Groundnut ( <i>Arachis hypogaea</i> L.)	0.65	
	Millet	0.47	
	Potato ( <i>Solanum tuberosum</i> L.)	0.26–0.51	
	Rice ( <i>Oryza sativa</i> L.)	3.50	
Worldwide	Sugarcane ( <i>Saccharum officinarum</i> L.)	0.09	Nemecek et al. (2012)
	Wheat ( <i>Triticum aestivum</i> L.)	≈0.60	
	Cotton ( <i>Gossypium</i> sp.)	≈1.40	
	Onion ( <i>Allium cepa</i> L.)	≈0.20	
	Rye ( <i>Secale cereale</i> L.)	≈0.50	
	Rice ( <i>Oryza sativa</i> L.)	1.20–2.40	
China	Sugarcane ( <i>Saccharum officinarum</i> L.)	≈0.05	Wang et al. (2015)
	Rice ( <i>Oryza sativa</i> L.)	0.80–0.95	
	Wheat ( <i>Triticum aestivum</i> L.)	0.20–0.30	
India	Maize ( <i>Zea mays</i> L.)	0.18–0.22	Vetter et al. (2017)
	Wheat ( <i>Triticum aestivum</i> L.)	0.34	
	Rice ( <i>Oryza sativa</i> L.)	5.65	
	Potato ( <i>Solanum tuberosum</i> L.)	0.22	
	Onion ( <i>Allium cepa</i> L.)	0.10	
	Sugarcane ( <i>Saccharum officinarum</i> L.)	0.09	
	Pulses	0.75	
Groundnut ( <i>Arachis hypogaea</i> L.)	0.38		

crop. The net economic returns under pigeonpea-wheat system were also greater compared with rice-wheat system due to reduction in input cost (Singh et al. 2005). Nawab et al. (2011) also reported significantly higher yield of wheat in rotation with pigeonpea as compared to other cropping systems (rice-wheat, maize-wheat, sunflower-wheat and sorghum-wheat). Zero tillage increased pigeonpea and wheat yield by 5.4 and 2.3%, respectively as compared to conventional tillage. Further, with the inclusion of crop residue (3 t ha<sup>-1</sup>) under zero tillage yields increased by 14.3 and 34.4% in pigeonpea and wheat, respectively (Sepat et al. 2014). Generally, rainfall during flowering time led to reduce crop yield associated with excessive vegetative growth and subsequent poor pod setting in pigeonpea (Gora et al. 2022). Further, very few studies were conducted that deliver the information regarding potential of pigeonpea in rice replacement, subsequent economic and environmental benefits. So, the future studies on development of extra early maturing, resistance to insect pest and diseases varieties, trainings and field demonstrations and incentives to farmers along with assured support price especially in Haryana and Punjab, India pigeonpea-based cropping systems would be helpful to address the issues of declining natural resources.

### Miscellaneous productive diversification options

The adoption of alternate cropping pattern instead of rice-wheat system could be more profitable and sustainable, if designed based on location and environmental conditions with improved agronomic practices. Tripathi and Singh (2008) studied eight crop sequences for six years to find out the diversification options for conventional rice-wheat system based on the productivity and profitability. Diversification of rice-wheat system (once in 3 years) increased net returns when all crops (except rice) were grown on raised-bed in a system approach. The addition of pulses or oilseed in rice-wheat system once in 3 years or system intensification by growing pea in between rice and wheat or greengram after wheat harvesting provided higher net returns and sustainable value index as compared to conventional rice-wheat system. The maximum sustainable value index (0.92) and net returns were recorded in rice-Indian mustard-greengram-rice-wheat-green-gram-rice-wheat-green-gram crop sequence. Further, growing of berseem (*Trifolium alexandrinum* L.) in the rotation reduced the weed population in the subsequent

wheat cycle. The diversified cropping sequence, i.e. pigeon-pea–wheat–rice–wheat–rice–wheat, rice–Indian mustard–greengram–rice–wheat–greengram–rice–wheat–greengram and rice–vegetable pea–wheat–greengram increased organic carbon content (0–15 cm) by 20, 25 and 37%, respectively, as compared to continuous rice–wheat system after six years. The combined analysis showed that rice–vegetable pea–wheat–greengram sequence produced 27.9% higher wheat equivalent yield than rice–wheat system. A study on ten rice-based cropping sequences at Varanasi, Uttar Pradesh (India) showed that rice–berseem–cowpea fodder sequence had resulted in higher grain yield, gross returns, net returns and energy productivity to the tune of about 13.9, 13.9, 46.6 and 13.8%, respectively, along with rice–potato (*Solanum tuberosum* L.)–green gram (Banjara et al. 2022). Yadav et al. (2022) reported higher profitability, sustainability and employment generation with enterprise mix diversification system with average net-income from crop (including fodder), vegetables and fruits and subsidiary components was 15.3% higher than conventional rice–wheat system. Further, higher benefit cost ratio (> 4) was observed with fruit and fisheries in enterprise mix diversified system. In a different study, Tripathi et al. (2021) reported maize–potato–wheat combination best in terms of system productivity with a value of 16.49 t ha<sup>-1</sup>. Maize–wheat–green gram crop sequence was the most profitable by having higher land use efficiency (87.7%) and net returns (1577.1 \$ ha<sup>-1</sup>). Soil health parameters were also improved under the maize–mustard–green gram system with increase in organic carbon content by 28.7% and available nitrogen by 34.9%. Vegetable-based cropping system also provides opportunity to increase the cropping intensity as these crops are generally harvested earlier than cereal crops and drive higher net returns than rice–wheat system (Walia et al. 2011). Further, optimal cropping systems could also be designed to regulate the weed emergence, growth and reproductive responses. A study showed that *Phalaris minor* (reduced by 80.5, 86.1, 88.8, 88.8, 66.6, 86.1, 88.8, 91.6 and 96.6% on shifting to maize–wheat, maize–wheat–summer mungbean, maize–potato–summer mungbean, maize–potato–onion (*Allium cepa* L.), cotton (*Gossypium* sp.)–wheat, cotton–african sarson (*Brassica carinata* A. Braun), cotton–gobhi sarson transplanted (*Brassica napus* sub sp. *Oleifera* var. *annua*), summer groundnut (*Arachis hypogaea* L.)–toria (*Brassica rapa* var. *toria*) + gobhi sarson and summer groundnut–potato–pearl millet (*Pennisetum glaucum* L.), respectively, from conventional rice–wheat system (*Phalaris minor* count of 36 plants m<sup>-2</sup>) in Punjab, India conditions (Walia et al. 2011). Moreover, the maximum rice equivalent yield was recorded by maize–potato–onion (32.0 t ha<sup>-1</sup>) followed by groundnut–potato–bajra (fodder) and maize–potato–summer mungbean with cumulative values of 10.0 to 19.1 t ha<sup>-1</sup> additional rice equivalent yield and saved 75.6–122.3 cm

irrigation water compared to rice–wheat system. The production efficiency and net returns were found the highest in maize–potato–onion system. However, vegetables-based systems are highly energy and labor intensive so efforts are needed towards mechanization for uprooting or harvesting of vegetables and availability of disease-resistant genotypes. Moreover, price stabilization, insurance and minimum monetary-based support would be pre-requisites for promoting the diversification and replacing the rice with perishable crops. The various diversification options are presented in Table 8, which can be used to improve the sustainability and cropping intensity in north-western Indo-Gangetic Plains. This strategy can be employed with the integration of short-duration high-yielding crop varieties under conservation tillage or alternate crop establishment methods and effective crop protection measures.

### Constraints in diversification

Based on above discussion, it can be realized that continuous rice cultivation with traditional method is primarily the root cause of unabated depletion of groundwater resources in the north-western India. In addition, burning of rice residue has led to environmental and health hazards associated with aggravated emission of greenhouse gases, deterioration of soil physical properties along with addition of new herbicide resistance weed species and emergence of insect pests. To address the current situation, direct seeded rice is being proposed as a cost-effective technology alternative to puddled transplanted rice to check the accelerated groundwater depletion, labor scarcity, escalating cost involved in rice cultivation and to facilitate the crop intensification. But the performance of direct seeded rice has been found to be location, cultivar and soil specific. The yield aspects, absence of aerobic tailored genotypes and weed problems have been the major constraints in the large-scale adoption of direct seeded rice.

The opportunistic diversification with inclusion of summer mungbean after wheat harvest in rice–wheat system has the potential to partially alleviate soil related problems associated with adoption of monotonous rice–wheat system. However, there is need to develop extra short-duration varieties of summer mungbean tolerant to biotic and abiotic stresses. Further, assured procurement of rice and wheat, and its unavailability on other diversifying crops may lead farmers to stick with rice–wheat system despite its destructive impact on natural resources due to assured market price. In relation to strategic diversification, maize is a potential substitution to rice due to elimination of puddling, water ponding and residue burning activities in addition to reduced energy requirement and lesser global warming potential. However, besides lacking of sound maize cultivation



**Table 8** Diversification options of rice-wheat system for north-western Indo-Gangetic Plains in India

Cropping system/Time	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	
Rice-wheat		Rice				Wheat							
Rice-wheat-mungbean summer		Rice				Wheat							Summer mungbean
Rice-vegetable-pea-wheat-summer mungbean		Rice				Vegetable pea		Wheat					Summer mungbean
Maize-wheat		Maize				Wheat							
Maize-wheat-mungbean summer		Maize				Wheat							Summer mungbean
Maize-potato-wheat		Maize				Potato		Wheat					
Maize-potato-wheat-summer mungbean		Maize				Potato		Wheat					Summer mungbean
Pigeonpea-wheat		Pigeonpea				Wheat							
Maize-mustard-mungbean summer		Maize				Mustard							Summer mungbean
Rice-mustard-mungbean summer		Rice				Mustard							Summer mungbean

practices among the farmers, impressive replacement of rice with maize in north-western Indo-Gangetic Plains could be meagre due to high rainfall amount in continuous raining period during the summer months and increased events of extreme heavy rainfall in a short span of time, leading to water stagnation and complete crop failure due to its sensitivity to water logging. Moreover, climate vicissitude in recent times made occurrence of such events very frequently. For instance, rainfall scenario of a rice dominating district (Karnal) from Haryana state, India showed erratic and variable distribution of rainfall (378 to 1248 mm) from June to September during 2011 to 2020 (Fig. 4).

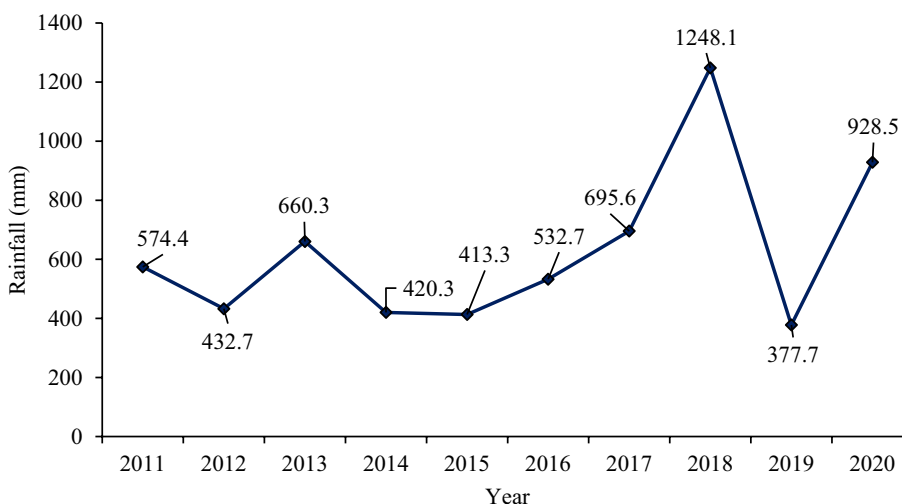
In such situations, the other options for diversification include replacement of rice with leguminous crops such as pigeonpea and mungbean, which can ameliorate natural resources by addition of nutrient in soil through biological nitrogen fixation, and lower water and environmental footprints besides acting as a biological chiseler to break the subsurface soil compaction associated with continuous

cultivation of puddled transplanted rice. The development of extra early maturing photo-thermo insensitive cultivars of these crops with higher production potential would be helpful to expand the diversification area under rice-wheat system without any delay in succeeding crops. The active policies such as assured procurement with minimum support price, subsidized electricity and submersible pumps in huge domain restrict the adequate shift in cropping system.

### Conclusions and future perspective

The issue of declining natural resources has far reaching impact which is further escalated by climate change and its menace on agriculture. The problem of deteriorating natural resources and stagnant crop productivity are dominantly present in regions having intensive cultivation of traditional rice-wheat system like north-western Indo-Gangetic Plains. There is enormous potential to address these challenges

**Fig. 4** Rainfall (mm) received in Karnal district of Haryana, India during June to September of 2011–2020



through agronomic management by making alternation in crop establishment methods and adoption of resource conservation technologies in rice–wheat system as well as opportunistic diversification of rice–wheat system with inclusion of leguminous crop and possible substitution of rice with lesser resource requiring crops. There is need to refine the agronomical practices for direct seeded rice along with genetic tailoring for anaerobic germination, emergence from deeper depth, higher vigour with more source to sink translocation of photosynthates during the grain filling stage and promotion of mechanical-based weed control. The large-scale adoption of short-duration and stature rice varieties may bring significant decline in groundwater draft besides producing the optimum biomass and providing the enough time for sowing of succeeding crop with effective *in-situ* residue management. Moreover, rescheduling the transplanting time considering the changes happening in monsoon arrival time in the region and technological support with the aspects of short-duration varieties, better performing genotypes under late transplanting would be helpful to increase the water and nutrient productivity in conventional rice–wheat system. In existing rice–wheat system, the substitution of conventional rice varieties with short-duration scented (*Basmati*) rice (110–125 days) can also reduce the burden on groundwater resources due to its lower water demand (< 120 cm) over short-medium duration rice varieties and long-duration (> 140 days) non-scented rice varieties such as PUSA 44 (> 150 cm) as major growth phase of medium-short-duration *Basmati* rice coinciding with monsoon rainfall and reproductive phase with lower evapotranspiration period of the season. Conclusively, groundwater depletion may be brought down to a large scale with the adoption of direct seeded rice, short-duration and high-yielding varieties of improved source to sink relation, monsoon-based scheduling in transplanting time and optimized water management techniques.

In addition to amendments in agronomical measures of existing rice–wheat system, the substitution of rice especially in light-medium textured soils with conservation agriculture and permanent raised bed-based maize crop can alleviate the burden on groundwater, soil and environment. The maize with permanent bed planting system can mitigate the risk associated with water logging from heavy rainfall. The establishment of processing industry for value-added maize products such as baby corn, sweet corn and soup, can raise the maize demand as feedstock in intensive rice cultivating regions and may engage more farmers in maize cultivation besides employment generation. The other cropping systems, viz. rice–Indian mustard–greengram, rice–vegetable pea (*Pisum sativum* L.)–wheat–greengram, maize–wheat–greengram, maize–mustard–greengram, maize–potato–wheat, rice–potato–wheat and soybean–wheat, need to be

optimized and advocated to farmers to increase the system productivity and profitability. The future research efforts on developing water logging-resistant maize varieties and effective measures for new emerging issues such as recent infestation of insect pest (fall army worm) would be helpful to bring the more area under maize cultivation. Further, vegetable-based systems require rigorous efforts on mechanization due to their energy and labor-intensive nature, development of climate-resilient genotypes, establishment of cold storage units, insurance and minimum monetary-based support and strengthening of supply chain between farmer and consumers to promote the vegetable-based diversification options among farmers. Crops with limited diversification options need to be cultivated using cluster-based approach for marketing and value addition purpose. The short-duration vegetables such as pea, potato and carrot (*Daucus carota* L.) should be the main target to include after rice harvesting and before wheat sowing (late sown). Also, there is enormous opportunity to introduce the summer mungbean or green-manure legumes such as *Sesbania* in between wheat and rice crop on a large area with subsidized seed price in order to improve the soil quality through awareness and field demonstration programs to farmers. Apart from cropping system perspective, adoption of soil/water conserving technologies like conservation tillage (zero and reduced tillage), recycling of crop residue back to soil, micro-irrigation systems, integrated nutrient management, etc., would be helpful to lessen the burden on natural resources and to uphold the agricultural sustainability amidst the rising risk of climate change.

**Acknowledgements** Authors are highly thankful to Department of Agronomy, CCS Haryana Agricultural University, Hisar, Haryana, India for providing them an opportunity to write this review.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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