Agricultural Innovation and Sustainable Development: A Case Study of Rice–Wheat Cropping Systems in South Asia

Abstract: The rice–wheat cropping system is the main food bowl in Asia, feeding billions across the globe. However, the productivity and long-term sustainability of this system are threatened by stagnant crop yields and greenhouse gas emissions from flooded rice production. The negative environmental consequences of excessive nitrogen fertilizer use are further exacerbating the situation, along with the high labor and water requirements of transplanted rice. Residue burning in rice has also severe environmental concerns. Under these circumstances, many farmers in South Asia have shifted from transplanted rice to direct-seeded rice and reported water and labor savings and reduced methane emissions. There is a need for opting the precision agriculture techniques for the sustainable management of nutrients. Allelopathic crops could be useful in the rotation for weed management, the major yield-reducing factor in direct-seeded rice. Legume incorporation might be a viable option for improving soil health. As governments in South Asia have imposed a strict ban on the burning of rice residues, the use of rice-specific harvesters might be a pragmatic option to manage rice residues with yield and premium advantage. However, the soil/climatic conditions and farmer socio-economic conditions must be considered while promoting these technologies in rice-wheat system in South Asia.

Keywords: rice–wheat cropping system; South Asia; water requirements; nitrogen; direct seeding

1. Introduction

Rice–wheat cropping systems (RWCS) provide staple food to 15% of the world’s population [1]. The major issue for the sustainability of conventional RWCS in South Asia is soil quality degradation associated with resource scarcity [2]. Other factors include water scarcity, low soil organic matter, nutrient imbalances, labor/energy crises, complex insect and weed flora, herbicide-resistant weeds, and greenhouse gas (GHG) emissions [3]. Moreover, conventional puddled transplanted rice (PTR) cultivation has over-exploited the groundwater leading to an alarming fall in the water table in South Asia [4].

The conventional rice production systems are no longer suitable as they require large amounts of water (3000–5000 L of water to produce one kg of rice) [5,6]. It has been reported that 15–20 Mha of conventional rice production systems will face water shortages by 2025 [7]. In some parts of Pakistan and India, groundwater tables are declining by 1.0–3.5 m and 6 m year\(^{-1}\), respectively [8].

Puddling, as practices in conventional rice-wheat system, increases the soil bulk density, which causes soil compaction [9] and affects root development in post-rice crops [3]. Nitrogen uptake in puddled rice fields declines by 12–35% in the following wheat crop due to subsoil compaction [10]. The evolution of herbicide resistant weeds and shift in weed flora (a mixture of broadleaf and grassy weeds) have further exacerbated the scenario in
RWCS to harvest optimum crop yields [11]. Little seed canary grass (*Phalaris minor* Retz.) has been reported to decrease wheat yields by 10–65% with occasional crop failure [12], while smartweed (*Polygonum hydropiper* L.) can reduce the rice and wheat yields by 15–25% and 15–30%, respectively [13]. Furthermore, the rice and wheat monocultures in RCWS have increased disease and pest problems [14] and has caused macro- and micro-nutrient deficiencies [3,15,16].

In this scenario, resource conservation technologies, such as direct-seeded rice (DSR), no-till wheat, and laser-assisted land leveling, can be used to improve the sustainability of yields in RWCS [3]. Several studies reported that residue retention and no-tillage enhance the nitrogen and carbon pools in soil [17,18].

In this case study focuses on the problems of conventional RWCS (i.e., nutrient mining, GHG emissions, and reduced profits) and alternative options such as DSR, use of advanced rice harvesters for harvest, no-till wheat, precision agriculture, and crop rotation to improve the yields, sustainability, and the conservation of scarce natural resources.

### 2. Review Methodology

We searched more than 180 articles, including 10 review and 170 research articles, using four databases: Scopus, Web of Science, Google Scholar, and Center for Agriculture and Bioscience International (CABI). These databases are large collections of mainstream articles and are widely used for searching. The different keywords as (rice–wheat cropping system, greenhouse gases emission, direct-seeded rice, zero tillage wheat, agricultural innovation systems, profit margin in the conventional rice-wheat cropping system, crop rotation, precision agriculture, nutrient mining, agricultural sustainability, and rice-specific harvesters) were used to search the articles from these databases. To take additional information from these articles, we used references from these articles as well. The articles other than South Asia and published before the year 2000 were not included in this review.

### 3. Problems in Conventional Rice–Wheat Systems

#### 3.1. Greenhouse Gas Emissions

In the Indo-Gangetic Plains (IGP), conventional RWCS is the major source of atmospheric nitrous oxide ($N_2O$), carbon dioxide ($CO_2$), and methane ($CH_4$) emissions due to the use of intensive agricultural inputs [19], particularly the injudicious use of nitrogen fertilizers Table 1 [20,21], aerobic and anaerobic soil cycling [22], and residue burning. In northwest India, 2.5 M farmers burn 23 MMT of rice stubble each year (October to November) to prepare field for wheat crop, causing massive air pollution affecting millions of people across the IGP [23,24]. Annual residue burning emits GHGs, including $CO_2$ (379 Tg), carbon monoxide ($CO$: 23 Tg), $CH_4$ (0.68 Tg), NOx (0.96 Tg), and sulfur dioxide ($SO_2$) (0.10 Tg) [25]. The RWCS supplied with 75 kg N ha$^{-1}$ had mean annual emissions of $N_2O$ of 1.49 kg N ha$^{-1}$, or 2.97–3.04 kg N ha$^{-1}$ when supplied with >150 kg N ha$^{-1}$ [26].

Table 1. Greenhouse gas emissions from different rice production systems.

| Greenhouse Gas | Quantity Emitted from DSR | Quantity Emitted from Transplanted Rice | Reference |
|----------------|---------------------------|----------------------------------------|-----------|
| Methane ($CH_4$) | 0.49 mg m$^{-2}$ day$^{-1}$ | 3.10 mg m$^{-2}$ day$^{-1}$ | [27] |
| Nitrous oxide ($N_2O$) | 0.97 mg m$^{-2}$ day$^{-1}$ | 1.03 mg m$^{-2}$ day$^{-1}$ | |
| Carbon dioxide ($CO_2$) | 600 mg m$^{-2}$ day$^{-1}$ | 1800 mg m$^{-2}$ day$^{-1}$ | |
| Nitrous oxide ($N_2O$) | 0.90 kg ha$^{-1}$ | 0.56 kg ha$^{-1}$ | [28] |
| Methane ($CH_4$) | 23.3 kg ha$^{-1}$ | 32.8 kg ha$^{-1}$ | |
| Nitrous oxide ($N_2O$) | 18.9 kg ha$^{-1}$ | 28.4 kg ha$^{-1}$ | [29] |
| Nitrous oxide ($N_2O$) | 0.95 kg ha$^{-1}$ | 0.65 kg ha$^{-1}$ | |
| Nitrous oxide ($N_2O$) | 25 kg ha$^{-1}$ | 48 kg ha$^{-1}$ | [30] |
| Nitrous oxide ($N_2O$) | 0.12 kg ha$^{-1}$ | 0.11 kg ha$^{-1}$ | |
| Methane ($CH_4$) | 0.2 kg ha$^{-1}$ | 1.1 kg ha$^{-1}$ | [31] |
| Carbon dioxide ($CO_2$) | 1.2 kg ha$^{-1}$ | 1.3 kg ha$^{-1}$ | |
| Nitrous oxide ($N_2O$) | 0.6 kg ha$^{-1}$ | 0.4 kg ha$^{-1}$ | |
The flooding conditions in rice cause the anaerobic decomposition of organic matter, which produces methane (CH$_4$) in the soil [39]. Globally, rice contributes ~20% of the total CH$_4$ emissions [40]. The warming potential of CH$_4$ is 25–30 times greater than CO$_2$ [40,41]. In 2005, the concentration of atmospheric CH$_4$ reached 1774 ppb [40]. Several studies reported that PTR produces more CH$_4$ emissions than DSR, while DSR produces more N$_2$O than PTR [3]. In one study, DSR and PTR produced N$_2$O emissions of 1.2 t CO$_2$ eq ha$^{-1}$ and 0.4 t CO$_2$ eq ha$^{-1}$, respectively and CH$_4$ emissions of 0.1 t CO$_2$ eq ha$^{-1}$ and 0.6 t CO$_2$ eq ha$^{-1}$, respectively [42]. In conclusion, the adoption of monocultures in RWCS contributes to global GHG emissions due to intensive agricultural inputs use and residue burning.

3.2. Nutrient Mining and Unwise Nutrient Use

Continuous monoculture cropping has threatened the long-term sustainability and has caused macro- and micro-nutrient imbalances in RWCS [3]. In the IGP, the mining of major nutrients, including nitrogen (N), phosphorus (P), potassium (K), and sulfur (S), has created a major nutrient imbalance in RWCS. The production of 1 t of rice/wheat depletes 20.1/24.5 kg N, 4.9/3.8 kg P, and 25.0/27.3 kg K, respectively, from the soil [43], which decreases the soil productivity [44] if these nutrients are not replenished. In the IGP, the removal of crop residues removes five times more K than that supplied through fertilizers [45].

Among the micro-nutrients, Zn deficiency is more common in rice, while manganese (Mn) deficiency is more prevalent in wheat [46]. In India, 49% of soil samples were Zn deficient, followed by 33% deficient in B, 12% in Fe, 5% in Mn, and 3% in Cu [47]. In the IGP, most rice and wheat farmers apply N fertilizers following blanket recommendations based on crop response data, leading to under- or over-fertilization as there is wide spatial variability in the indigenous nutrient supply capacity of soils in different agro-ecologies [26]. Diagnostic surveys of the IGP showed that farmers apply more N and P fertilizers than recommended while under/overlooking the supply of K, other secondary macronutrients, and micro-nutrients [48]. The inadequate and imbalanced use of nutrients reduces nutrient use efficiencies and profitability and increases environmental hazards [49]. In conclusion, the continuous growing of rice and wheat has resulted in the mining of major (N, P, K, and S) and trace (Zn, B, and Fe) nutrients due to over- or under-fertilization.

3.3. Reduced Profit Margins

The PTR has smaller profit margins than DSR due to the high labor costs Table 2 [50]. With industrialization, the migration of people to cities reduced labor availability for agricultural activities, which increased labor costs. Labor shortages delay the transplantation of rice seedlings into puddled fields [51], delaying maturation, and decrease yields [3].
Table 2. Profit margins in different rice production systems.

| Name of Input                              | Type of Soil          | Unit Cost in DSR ha$^{-1}$ ($) | Unit Cost in Transplanted Rice ha$^{-1}$ ($) | Reference |
|--------------------------------------------|-----------------------|-------------------------------|---------------------------------------------|-----------|
| Farmyard manure                            | Sandy loam clay       | 18.40                         | 13.26                                       | [52]      |
| Fertilizer                                 | Sandy loam clay       | 97.56                         | 80.88                                       |           |
| Plant protection measures (weeds, insect pests and disease control) | Sandy loam clay       | 54.63                         | 42.09                                       |           |
| Land preparation                           | Sandy loam clay       | 59.01                         | 69.49                                       |           |
| Human labor charges                        | Reclaimed alkali soils| 163.01                        | 174.56                                      | [53]      |
| Machine use charges                        | Reclaimed alkali soils| 60.62                         | 103.34                                      |           |
| Cost of seeds                              | Reclaimed alkali soils| 15.86                         | 7.49                                        |           |
| Cost of plant protection chemicals         | Reclaimed alkali soils| 31.03                         | 38.21                                       |           |
| Irrigation charges                         | Reclaimed alkali soils| 36.57                         | 47.15                                       |           |
| Micronutrients                             | Sandy loam clay       | 14.25                         | 12.49                                       | [52]      |
| Irrigation                                 | Sandy loam clay       | 84.07                         | 152.13                                      |           |
| Nursery and transplanting/seed and sowing  | Sandy loam clay       | 21.53                         | 65.11                                       |           |
| Cost of weedicides                         | Reclaimed alkali soils| 33.61                         | 26.78                                       | [54]      |
| Preparatory Tillage                        | Reclaimed alkali soils| 61.74                         | 97.21                                       |           |
| Pre-Sowing Irrigation                      | Reclaimed alkali soils| 12.80                         | 15.70                                       |           |
| Harvesting/threshing                       | Reclaimed alkali soils| 49.06                         | 49.06                                       |           |
| Plant protection                           | Reclaimed alkali soils| 76.52                         | 80.23                                       |           |
| Hoeing and weeding                         | Reclaimed alkali soils| 37.04                         | 18.92                                       |           |
| Irrigation                                 | Reclaimed alkali soils| 76.50                         | 125.82                                      |           |
| Fertilizer application                     | Reclaimed alkali soils| 6.12                          | 6.60                                        |           |
| Nitrogen                                   | Reclaimed alkali soils| 17.21                         | 19.48                                       |           |
| Phosphate                                  | Reclaimed alkali soils| 15.20                         | 20.04                                       |           |
| Zinc sulphate                              | Reclaimed alkali soils| 7.96                          | 8.47                                        |           |
| TYM                                        | Reclaimed alkali soils| 56.30                         | 56.30                                       |           |
| Seed                                       | Reclaimed alkali soils| 13.76                         | 7.26                                        |           |
| Cost of fertilizers                        | Reclaimed alkali soils| 49.41                         | 48.50                                       | [53]      |

All the values in $ are converted according to rate of 10 January 2021; 1 Pakistani rupee = 0.0062$; 1 Indian Rupee = 0.014$.

Late transplantation of rice due to labor shortage causes heat stress during the reproductive stage; temperatures >33.7°C at anthesis causes panicle sterility due to poor anther dehiscence [55] and >34°C during grain formation substantially reduce grain yield [56]. Temperatures >35°C (above optimal) during reproductive development affect flowering and grain formation in rice [57].

4. Agricultural Innovations for Sustainable Development of Rice–Wheat Systems

Adaptation of innovative agricultural practices, such as conservation agriculture (CA), improves and sustains the productivity of RWCS and preserves scarce natural resources, such as water, energy, environmental quality, time, and labor [58]. The adaptation of CA-based systems is most beneficial in extreme climatic conditions, mitigating the negative impact of climatic stresses, such as water and heat stress, and increasing crop yields (0.4–0.8 t ha$^{-1}$ per season), when compared with the conventional system [59].

The CA improves energy efficiency and carbon sequestration and reduces GHG emissions [2,60–62]. The incorporation of crop residues favors N immobilization (biotic and abiotic), which conserves active soil N by, (i) decomposing crop residues for a source of C for microorganisms and as an energy source to strengthen their metabolism which results in N immobilization in biomass, and (ii) incorporating N into the soil organic matter through ammonium fixation by clay minerals, nitrosation of nitrite with phenolic compounds, and condensation of ammonia with phenol [63].

Immobilized N can serve as temporary N sink [63]. Residue retention increases total organic C and available nutrients, mainly available P (16%), available K (12%), available sulfur (6%), and DTPA-extractable Zn (11%), relative to no-residue retention [64]. The adoption of resource-conserving technologies, such as DSR, harvesting rice with advanced rice harvesters, no-till wheat, crop rotation, and precision agriculture for better nutrient
management, can mitigate climate change, reduce environmental pollution, and conserve natural resources.

4.1. Direct-Seeded Rice

In the IGP, increasing shortages of energy, water, and labor force farmers to switch from conventional PTR to a smart seeding system, i.e., DSR. In many studies, DSR produced higher yields, maximum profitability, and water-saving (25%) than PTR [62,65,66] with improved soil health (Table 3). DSR is an economically feasible alternative as it reduces production costs by 11–17% (with 25–30% irrigation water saving) and saves INR 5000 (on fuel and labor) [67] for the same yields as PTR [62]. In a study, DSR used 7–13.9% less water than the conventional PTR system [68]. Other studies in South Asia have reported that DSR uses 20–57% less water than PTR [69,70]. Rice produced through DSR also matures earlier than PTR, requires less water, and enables the timely sowing of following wheat and other crops [51].

Table 3. Soil quality in different rice production systems.

| Soil Property                        | Unit       | Soil Type       | Value in DSR | Value in Transplanted Rice | Reference |
|--------------------------------------|------------|-----------------|-------------|---------------------------|-----------|
| Total organic carbon                 | g kg⁻¹     | Silt clay       | 7.24        | 7.25                      | [64]      |
| Aggregate associated carbon          | g kg⁻¹     | Silt clay       | 12.56       | 11.94                     |           |
| Aggregate size class (0.25–2 mm)     | %          | Silt clay       | 48          | 48.9                      |           |
| Mean weight diameter                 | mm         | Silt clay       | 1.61        | 1.61                      |           |
| Aggregate ratio                      |            | Silt clay       | 5.06        | 5.58                      |           |
| Water stable macro-aggregates        |            | Silt clay       | 83.2        | 83.8                      |           |
| Water-holding capacity               |            | Loam            | 0.346       | 0.331                     |           |
| Available water                       | cm³ cm⁻³   | Loam            | 0.170       | 0.164                     | [71]      |
| Geometric mean diameter              | mm         | Loam            | 0.86        | 0.80                      |           |
| Soil moisture potential (75 kPa)     |            | Loam            | 0.166       | 0.170                     |           |
| Crack depth (60 kPa)                 | cm         | Loam            | 13          | 23                        |           |
| Bulk density (6–10 cm)               | Mg m⁻³     | Clay, silt, sand| 1.60        | 1.61                      |           |
| WSA (>0.25 mm)                       |            | Clay, silt, sand| 67.24       | 64.44                     |           |
| Steady-state infiltration rate       |            | Clay, silt, sand| 0.33        | 0.29                      |           |
| Water stable micro-aggregates        |            | Silt clay       | 16.8        | 16.2                      | [64]      |
| pH                                   |            | Silt clay       | 7.39        | 7.41                      |           |
| Electrical conductivity              | dS m⁻¹     | Silt clay       | 0.79        | 0.75                      |           |
| Available N                          | kg ha⁻¹    | Silt clay       | 195.5       | 185.0                     |           |
| Available P                          | kg ha⁻¹    | Silt clay       | 28.4        | 27.5                      |           |
| Available K                          | kg ha⁻¹    | Silt clay       | 264.3       | 222.4                     |           |
| Crack width (60 kPa)                 | cm         | Loam            | 3           | 7                         | [71]      |
| Crack length (60 kPa)                | cm         | Loam            | 300         | 420                       | [71]      |
| Total nitrogen                       | g kg⁻¹     | Sandy loam      | 0.29        | 0.27                      | [73]      |
| Total soil organic carbon            | g kg⁻¹     | Sandy loam      | 3.40        | 3.14                      |           |
| Soil microbial biomass carbon        | μg g⁻¹     | Sandy loam      | 155.6       | 150.28                    |           |
| Soil microbial biomass nitrogen      | μg g⁻¹     | Sandy loam      | 586.3       | 551.78                    |           |
| Soil aggregates (>0.25 mm)           |            | Silt loam       | 60          | 51                        | [69]      |
| MWD of soil aggregates               | mm         | Silt loam       | 1.56        | 1.33                      |           |
| Bulk density (0–7 cm)                | Mg m⁻³     | Silt loam       | 1.60        | 1.50                      |           |
| Penetration resistance (5–10 cm)     | MPa        | Silt loam       | 1.2         | 0.75                      |           |

WSA, water stable aggregates; MWD, mean weight diameter.

In DSR, the crop is directly sown into the field, avoiding transplantation injuries, thus reducing exposure to terminal drought due to timely stand establishment [74]. Moreover, DSR improves soil health for post-rice winter cereals [3] by enhancing total porosity and decreasing soil bulk density [9], enabling deeper root penetration and facilitating nutrient
and water uptake [3]. In RWCS, DSR has been reported to reduce methane emissions and production costs, with increased profitability (Table 1; [51]).

Weeds are a major challenge in DSR; however, the application of weedicides can control the issue. For example, pre-emergence application of pendimethalin (1.5 kg ha$^{-1}$) followed by bispyribac-Na (25 g ha$^{-1}$) at post-emergence and hand weeding 35 days after sowing provided better weed control and higher rice yields (123–130%), net returns (327–806%) and net benefit: cost ratios than PTR [75]. However, diversification of weed flora has been reported in DSR in Pakistan which are very difficult to control and many farmers are afraid to plant rice in the DSR system. This needs the immediate attention of the government agencies in the region.

In conclusion, switching from PTR to DSR in RWCS increases profitability reduces production costs and GHG emissions, and is environmentally friendly, apart from the weed management issue during early growth.

4.2. Zero-Tillage Wheat

Using zero tillage (ZT) wheat in RWCS benefits the timeliness of wheat sowing and economics when compared with conventional tillage [59,76]. Zero tillage improves soil health and enhances nutrient concentrations at the soil surface Table 4 [77,78].

| Soil Property                  | Units         | Soil Type                                      | Value in ZT | Value in PT | Reference |
|-------------------------------|---------------|-----------------------------------------------|-------------|-------------|-----------|
| Bulk density                  | Mg m$^{-3}$   | Siltic soils (Haplic Solonetz)                | 1.63        | 1.67        | [2]       |
| Soil pH                       |               | Siltic soils (Haplic Solonetz)                | 7.84        | 8.06        |           |
| EC                            | dS m$^{-1}$   | Siltic soils (Haplic Solonetz)                | 0.25        | 0.21        |           |
| Total N                       | %             | Silty soils (Haplic Solonetz)                 | 0.19        | 0.14        |           |
| Bulk density                  | Mg m$^{-3}$   | Sandy loam                                    | 1.54        | 1.50        | [79]      |
| Infiltration rate             | mm h$^{-1}$   | Sandy loam                                    | 1.5         | 0.3         |           |
| MWD                           | mm            | Sandy loam                                    | 1.9         | 1.7         |           |
| WSA (>0.25 mm)                | %             | Sandy loam                                    | 73          | 57          |           |
| Bulk density                  | Mg m$^{-3}$   | Sandy loam                                    | 1.24        | 1.38        | [80]      |
| Soil temperature              | °C            | Sandy loam                                    | 33.15       | 35.29       |           |
| PAWC (0–15 cm)                | mm            | Sandy loam                                    | 16.70       | 14.7        |           |
| Infiltration rate             | mm h$^{-1}$   | Sandy loam                                    | 9.58        | 11.40       |           |
| Bulk density                  | Mg m$^{-3}$   | Sandy loam                                    | 1.52        | 1.48        | [81]      |
| Infiltration rate             | mm h$^{-1}$   | Sandy loam to loam                            | 18.0        | 42.0        | [66]      |
| β-Glucosidase (p-NP)          | µg g$^{-1}$ h$^{-1}$ | Loam                              | 51.24       | 36.23       | [82]      |
| Bulk density                  | Mg m$^{-3}$   | Sandy loam                                    | 1.44        | 1.46        | [83]      |
| Earthworm count               | ha$^{-1}$     | Sandy loam                                    | 380,000     | 60,000      | [84]      |
| Dehydrogenase activity        | µg g$^{-1}$ d$^{-1}$ | Sandy loam                          | 166.6       | 29.5        |           |
| SOC                           | g kg$^{-1}$   | Sandy loam                                    | 2.51        | 1.47        |           |
| Bulk density                  | Mg m$^{-3}$   | Sandy loam                                    | 1.60        | 1.56        | [68]      |
| SOC stock                     | kg m$^{-3}$   | Sandy loam                                    | 6.88        | 5.91        |           |
| Oxidizable organic C          | g kg$^{-1}$   | Fine loam (Typic Natrustalf)                  | 8.1         | 4.9         | [85]      |
| WSA (>0.25 mm)                | %             | Sandy loam                                    | 70          | 59          | [69]      |
| MWD                           | mm            | Sandy loam                                    | 2.68        | 1.62        |           |
| Infiltration rate             | mm h$^{-1}$   | Sandy loam                                    | 5.0         | 4.7         |           |
| Bulk density                  | Mg m$^{-3}$   | Sandy loam                                    | 1.52        | 1.57        |           |
| Crack width                   | cm            | Sandy loam (typic ustrochrept)                | 0.53        | 2.68        | [86]      |
| Least limiting water range    | %             | Sandy loam                                    | 6.2         | 3.3         | [72]      |
| WSA (>0.25 mm)                | %             | Sandy loam                                    | 67.24       | 52.66       |           |
| Bulk density                  | Mg m$^{-3}$   | Sandy loam                                    | 1.55        | 1.48        |           |
| Infiltration rate             | mm h$^{-1}$   | Sandy loam                                    | 3.3         | 1.8         |           |
| Penetration resistance        | MPa           | Sandy loam                                    | 1.4         | 1.0         |           |
| Volume of crack ($\times 10^{-4}$) | m$^3$ m$^{-2}$ | Clayey                                          | 77.21       | 55.57       | [87]      |
| Bulk density                  | Mg m$^{-3}$   | Clay                                          | 1.5         | 1.5         | [88]      |
Table 4. Cont.

| Soil Property                          | Units                  | Soil Type                      | Value in ZT | Value in PT | Reference |
|----------------------------------------|------------------------|--------------------------------|-------------|-------------|-----------|
| Infiltration rate                      | mm h⁻¹                 | Clay                           | 17.30       | 15.55       |           |
| PAWC (0–15 cm)                         | mm                     | Clay                           | 40          | 36          |           |
| Bulk density                           | Mg m⁻³                 | Clay                           | 1.24        | 1.28        | [89]      |
| WSA (>0.25 mm)                         | %                      | Clay                           | 60.47       | 51.36       |           |
| Alkaline phosphatase (p-nitrophenol)   | µg g⁻¹ h⁻¹             | Silty clay                     | 287.7       | 269.8       | [90]      |
| Carbon build up                        | %                      | Silty clay                     | 14.56       | 5.44        |           |
| Fluorescein diacetate activity         | mg kg⁻¹ h⁻¹            | Silty clay                     | 49.54       | 43.54       |           |
| Bulk density                           | Mg m⁻³                 | Illitic, Ustic Typic Calciorthent | 1.46       | 1.55        | [91]      |
| Carbon input addition                  | Mg h⁻¹                 | Illitic, Ustic Typic Calciorthent | 14.64      | 3.10        |           |
| Fluorescein diacetate activity         | µg g⁻¹ h⁻¹             | Mixed loamy sand              | 27.9        | 13.3        | [92]      |
| Total C                                | g kg⁻¹                 | Sandy clay loam               | 7.25        | 6.95        | [93]      |
| KMnO₄ C                                | g kg⁻¹                 | Sandy clay loam               | 0.43        | 0.39        |           |
| Soil water retention                   | mm                     | Sandy clay loam               | 4.6         | 4.2         | [94]      |
| WSA (>0.25 mm)                         | %                      | Sandy loam (Typic Ustochrept) | 77.3        | 68.4        | [95]      |
| MWD                                    | mm                     | Sandy loam                    | 0.74        | 0.71        | [96]      |
| Effective porosity                     | %                      | Sandy loam                    | 18.7        | 17.4        |           |
| Bulk density                           | Mg m⁻³                 | Sandy loam                    | 1.43        | 1.39        |           |
| Active C                               | g kg⁻¹                 | Sandy loam (Typic Ustochrept)  | 4.09        | 2.92        | [95]      |
| MWD                                    | mm                     | Sandy loam (Typic Ustochrept)  | 1.21        | 0.92        |           |
| Total organic carbon                   | g kg⁻¹                 | Fluvisol (silty clay)         | 7.25        | 6.38        | [64]      |
| Saturated hydraulic conductivity       | m s⁻¹                  | Clay                           | 7.32        | 2.13        | [97]      |
| MWD                                    | mm                     | Clay                           | 0.94        | 0.76        |           |
| MWD                                    | mm                     | Silty loam (Typic Ustochrept)  | 1.86        | 0.95        | [17]      |
| WSA (>0.25 mm)                         | %                      | Silty loam (Typic Ustochrept)  | 96          | 84          |           |
| SOC                                    | g kg⁻¹                 | Silty loam (Typic Ustochrept)  | 7.86        | 5.81        |           |
| Bulk density                           | Mg m⁻³                 | Sandy loam                    | 1.60        | 1.56        | [98]      |
| MWD                                    | mm                     | Sandy loam                    | 0.95        | 0.79        | [99]      |
| Porosity                               | %                      | Clay                           | 42.40       | 42.62       | [60]      |
| Bulk density                           | Mg m⁻³                 | Clay                           | 1.43        | 1.40        |           |
| Soil moisture (%)                      |                        | Non-calcareous brown sandy loam Haplaquept | 18.6        | 7.4         | [100]     |

EC, electrical conductivity; MWD, mean weight diameter; WSA, water stable aggregates; PAWC, plant available water capacity; BD, bulk density; SOC, soil organic carbon; ZT, zero tillage; PT, plow tillage.

Sowing wheat with ZT ensures early sowing and suppresses the obnoxious weed e.g., littleseed canarygrass (68–80% reduction in population) when compared with conventional farmers’ practices [101]. Moreover, ZT facilitates the timeliness of wheat sowing [3], improves soil structure, fertility, soil biological activities [102], and water-stable aggregates [103], and reduces the costs of land preparation [73,104]. In ZT wheat, the activities of soil microbial biomass carbon [73,105], soil enzymes [106], soil respiration [66], and soil quality index [107] are higher than plow tillage. In no-till with permanent soil cover, water infiltration is usually higher than plow tillage [108].

The Happy Seeder is a zero-tillage seeder that sows wheat into large amounts of crop residue and saves $136 ha⁻¹. Moreover, it facilitates timely wheat sowing, saves water, reduces air pollution, and enhances the sustainability of agriculture [24]. The use of Happy Seeder reduces the labor requirement for crop establishment by 80%, herbicide use by 50%, and irrigation by 20–25% [109]. Use of zero-tillage drill and Happy Seeder made it easy to plant wheat 2.7 days earlier (with earlier stand establishment) than that in CT wheat [24]. Many farmers in RWCS in South Asia are quickly shifting towards Happy Seeder wheat sowing due to the short turnover time between rice harvest and wheat sowing and imposition of huge penalties on the burning of rice residues. In conclusion, switching wheat sowing from conventional tillage to ZT ensures timely wheat sowing, saves production costs and improves soil health, yields, and yield sustainability.
4.3. Promotion of Precision Agriculture Practices for Nutrient Management

In the IGP, fertilizer recommendations are based on crop response data without considering the inherent nutrient supply capacity of the soil, causing over- or under-fertilization [68]. Improved nutrient management under CA improves yields and nutrient and water use efficiencies [110]. For RWCS in the IGP, a combination of macro- and micro-fertilizers with green manure, crop residues, and organic manures is a practical option for better nutrient management [111].

In maize–wheat–mungbean rotations, the adoption of ZT with site-specific nutrient management improved the soil physical, chemical, and biological properties, i.e., water-stable aggregates, saturated hydraulic conductivity, soil organic C, available N, P, and K, microbial biomass C, and enzyme activities (dehydrogenase, alkaline phosphatase, and β-glucosidase), relative to conventional and unfertilized treatments [112].

A recent study on N application rates in RWCS recommended N application rates of 120–200 kg ha\(^{-1}\) for rice and 50–185 kg ha\(^{-1}\) for wheat [26]. Zinc (Zn) application at 25 kg ha\(^{-1}\) as ZnSO\(_4\) improved rice and wheat yields [113]. In another study, the application of Zn improved the grain yields in both DSR and PTR systems [114]. Likewise, the boron (B) application to soils deficient in B improved growth and grain yield of rice [115,116].

Leaf color charts and SPAD chlorophyll meters are good options for managing N application, with a strong correlation (0.84–0.91) reported between these and various rice and wheat genotypes. Moreover, net returns increased by 19–31% using a leaf color chart for N management rather than a fixed N application rate [68].

In conclusion, integrated nutrient management, crop rotations incorporating legumes, site-specific optimization of nutrients rates, and the use of SPAD chlorophyll meters and leaf color charts are the best options for nutrient management and enhanced nutrient use efficiencies in rice and wheat.

4.4. Planning Wise Crop Rotations

Continuous monocultures have caused nutrient imbalances and increased the risk of pest and disease occurrence [59]. Diversifying the area sown to rice to incorporate other remunerative crops sustains soil fertility and improves crop productivity and farmer income [66]. Rotating cereals and pulses help to maintain soil quality and soil microflora and fauna [66,107]. It has been reported that the inclusion of leguminous crops in the cereal system increased system productivity by 18% and net returns by 15% [117]. In another study, the CA-based rice–wheat–mungbean cropping system improved system productivity by 11% and profitability by 24%, and reduced energy inputs by 25%, relative to a conventional rice–wheat system [62].

Long-term crop rotations (2000–2004) in India revealed that the rice–potato–green gram rotation had the highest net returns, system productivity, production efficiency, benefit: cost ratio, and profitability. Moreover, the inclusion of summer grain/fodder legumes improved soil organic matter [118]. The addition of short-duration summer legumes (mungbean and cowpea) in RWCS enhanced system productivity and profitability and nutritional security [119]. A rice–fallow cropping system with the intensification of five winter crop rotations (chickpea, lentil, safflower, linseed, and mustard) resulted in higher productivity for grain legumes (chickpea and lentil) than oilseed crops (safflower, mustard, and linseed) [120].

The inclusion of legumes in the cereal system fixes atmospheric N and improves soil fertility through nutrient recycling from deeper soil layers and mycorrhizal colonization [86]. Legume residues contain 20–80 kg N ha\(^{-1}\) (70% derived from N fixation), depending on the crop type [121,122]. A long-term study (2001–2004) showed that rice–legume rotations improved rice yields more than a rice–fallow rotation. In conclusion, the inclusion of short-duration grain or forage legumes in rotation in RWCS improves soil fertility and the yield of succeeding crops.
4.5. Rice Harvesting with Advanced Rice Harvesters

Rice harvesting is the most expensive rice production field activity, as the timing, duration, and mode of conduct of the harvesting directly affect rice quality, efficiencies, and farmer incomes [123]. In developing countries, rice is manually harvested with hand tools (as sickles) and threshed by beating on a hard matter or durum. The harvesting of rice with modern rice harvesters saves time, costs, and labor and reduces grain losses when compared with conventional manual harvesting [124]. Modern crop-specific mechanical harvesters, such as combine and mini-combine harvesters and reapers, can save time and labor, reduce harvesting losses, and increase profit margins and rice quality [125]. A reaper saved 37% and mini-combine harvesters saved 52% of harvesting costs over manual harvesting [126]. On average, a mini-combine harvester saves 95.5% of the time, 61.5% of costs, and 4.9% of grain losses compared with manual harvesting [127].

Combine harvesters (mini, medium, and large) are a time-saving technology, saving 20–30% of operation time than ordinary machines [128]. The use of a mini-combine harvester or reaper saved 65% and 52% of the labor costs over manual harvesting [129]. A combine harvester increased the net benefit by 30.3%, relative to manual harvesting and threshing [130]. Likewise, a vertical conveyor reaper saved 44% of harvesting costs [131]. Mechanical harvesting can also save grain losses, which were 2.88–3.60% for a tractor-mounted combine harvester [125], compared with 6.36% for manual harvesting [132].

However, in Pakistan and many other countries of South Asia, rice crop is harvested through wheat combine harvesters through some modification in machines. The use of wheat combine harvester in rice cause substantial grain losses which affect farmer profitability. In a study, the use of rice specific harvester reduces harvest losses by 14% and an extra premium of 5% on the paddy harvested from rice harvesters which increased farmer profitability [133]. In conclusion, rice harvesting with specific rice harvesters improves grain quality, reduces grain losses, and increases profit. However, the price of advanced rice harvesters is not affordable for all farmers. But this problem can be solved through the subsidy by the governments or and through cooperative investment, where a group of farmers pool their resources to purchase such machinery. Provision of such machinery by the service providers, on rental basis, can be another option. However, the rental charges for rice harvesters are double than the old model combine wheat harvesters. Therefore, private investors are interested to invest in the purchase and provision of on-farm services to farmers in South Asia.

5. Conclusions

The RWCS is the major cereal-based cropping system in South Asia, providing food to millions of people. However, the sustainability and productivity of this system are at high risk due to climate change, deteriorating natural resources, yield stagnation, and the negative impacts of this system on the environment. Major issues with this system include GHG emissions, declining soil quality and health, and reduced profit margins. However, the adoption of alternative innovative and sustainable approaches, including smart seeding/DSR, ZT wheat, crop rotation, precision agriculture, and rice and wheat harvesting using advanced harvesters such as the reaper, mini, and combine harvesters are the best options for improving yield, grain quality, and soil health, reducing environmental pollution, and preserving the ecosystem and natural resources (i.e., water, air, and soil).

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