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Effect of climate-smart agriculture practices on energy, greenhouse gas mitigation and resource use efficiency of rice-wheat cropping system in North West IGP: A review

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Abstract

Rice–wheat 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 with sharp increase in number of districts under over-exploitation category, 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. Intensive tillage operations, indiscriminate use of irrigation water, chemical fertilizers, and pesticides and crop biomass burning have made the conventional rice–wheat (RW) system highly energy-intensive and inefficient. In the recent past, portfolios of climate-smart agricultural practices (CSAP) have been promoted as a potential alternative to improve the energy efficiency in conventional RW system. Therefore, to evaluate the energy input–output relation, energy flow and economic efficiency in various combinations of crop management options, a review study was conducted. The net energy, energy use efficiency and energy productivity were 11–18, 31–51 and 29–53% higher under CSAP in RW system than conventional tillage without residue, respectively. However, renewable and non-renewable energy inputs were 14 and 33% higher in conventional tillage without residue compared to CSAP, respectively, it showed that conventional tillage without residue practices mostly dependents on non-renewable energy sources whereas CSAP dependents on renewable energy sources. Similarly, the adoption of CSAP improved the biomass yield, net farm income and economic efficiency by 6–9, 18–23 and 42–58%, respectively compared to conventional tillage without residue. Greenhouse gas emissions were also ~63% higher in conventional practices compared to CSAP. The energy input of under traditional method was 85.4 GJ/ha, and the energy output was 59.7 GJ/ha. Among all energy input elements, mineral fertilizers accounted for the highest proportion of energy input, accounting for 48.31%. Under water-saving irrigation, the energy input and output are 72.3 GJ/ha and 62.3 GJ/ha; the highest energy input is also mineral fertilizer. The total input energy for rice-wheat cultivation as 63825 and 50799 $MJha^{-1}$ respectively. Main contributors are electricity, fertilizer and diesel for both crops; however irrigation water is also a significant contributor in rice. The yield per unit energy use is relatively low and warrants better crop management practices to reduce the environmental footprint of the rice-wheat cropping system. Overall, the adoption of CSAP could be a viable alternative for improving energy use efficiency, farm profitability and eco-efficiency in the RW system.

Keywords: Conservation tillage, greenhouse gases, soil quality, energy efficiency

Introduction

Agriculture is a major driver of climate change. According to 5^{th} FAR (IPCC fifth assessment report), Agriculture and its allied sciences contribute 20-24% of human induced GHGs emission and IPCC estimates that agricultural contributes about 13.5% of GHGs emission. These emissions are largely from the results of synthetic fertilizers use; methane from large scale animal operation and some methane are released from rice paddies. It is projected that climate change affects around 49 million people at risk of hunger by 2020. RW system of the IGP, the energy is expensed in several forms such as labour, farm machines, fertilizers, insecticides, fungicides and herbicides, electricity for pumping irrigation water, manual transplanting of rice seedlings into the well-puddled soils etc. But presently, RW system are showing energy insecurity in the IGP`s region due to intensive energy used in various crop production activities such as multiple tillage to get ready the field for rice and wheat planting (Kakraliya *et al*., 2018; Chaudhary *et al*., 2009) [15, 5]. Further, the use of more manual labour in transplanting of rice seedlings into well-puddled soil also consumes an enormous amount of energy. In PTR, puddling alone needs approximately 25–30% of the total irrigation water requirement of rice (Kakraliya *et al*., 2018) [15]. Higher water requirement in rice is also due to more water losses in the form of puddling, percolation and surface evaporation which ultimately leads to more consumption of electricity for groundwater pumping for puddling, nursery raising and frequent irrigation to keep the fields flooded throughout the growing season (Kakraliya *et al*., 2018) [15].

In upper and middle IGP, irrigation water is mostly driven by electricity pumps whereas in lower IGP diesel pumps are mainly used, and both consume a huge quantum of energy Kakraliya *et al*., 2018) [15]. Approximately 84% of wheat production costs incurred from these energy-intensive inputs (Saharawat *et al*., 2010; Naresh *et al*., 2018) [27, 20]. In South Asia and elsewhere, published outcomes from diverse research findings have highlighted that intensive tillage practices accounts~25% or more of the total production cost in RW system. This energy-intensive system has started suffering from other production fatigue owing to over mining of nutrients, declining factor productivity, increasing production cost, reducing farm profitability, deteriorating soil health and labour shortage causing concern about its sustainability (Kakraliya *et al*., 2018; Abbas *et al*., 2020) [15, 1]. Escalating the production and energy costs in the RW system is not only harmful to keeping productivity and farmers' farm incomes but are also a major challenge for global food and energy security (Abbas *et al*., 2020) [1].

Energy smart agriculture (ESA) practices namely laser land levelling, zero tillage (ZT), direct-seeded rice (DSR), site-specific nutrient management (SSNM) and precision irrigation management have been suggested as potentially sustainable alternatives to traditional energy-intensive practices. Non-requirement of intensive tillage operations in energy-smart agriculture translates into less diesel requirement, lesser working time and slower depreciation rates of equipments. These all are reducing energy inputs in various farm operations, particularly from land preparation, as well as from the agricultural machinery manufacturing processes. By adopting the ESA-based ZT system under the RW system, farmers could save 36 L diesel ha^{-1} which is equivalent to 2027 MJ ha^{-1}. In addition, energy-intensive agricultural practices have high carbon footprints especially; greenhouse gases (Yuan & Peng, 2017) [36] have enhanced the global energy budget by more than 10 times since the beginning of twentieth century (Pratibha *et al*., 2015) [16] and at the same time increased the cost of cultivation in crop production by approximately 4 times than ZT farming during the same period (Parihar *et al*., 2017; Naresh *et al*., 2021) [22, 21]. Therefore, energy requirements can be minimized by adopting of energy-efficient technologies. Furthermore, adequate availability of the accurate source of energy and its effective and proficient use are the prerequisites for the conventional RW system with the lowest energy inputs (Yuan & Peng, 2017) [36]. In energy budgeting, it is essential to identify or develop energy-efficient technologies, with less energy and environmental footprints. A number of climate smart agriculture (CSA) practices have been assessed in cereal systems as an alternative to energy-intensive traditional practices. So far, information on energy footprints of these practices together (as a portfolio) is scanty. Hence, there is an urgent need for a scientific assessment to use a holistic tactic of principles and procedures known to increase the energy-use efficiency (EUE) and decrease the input energy as well as associated carbon footprints in crop production.

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 (Naresh *et al*., 2018; Chauhan *et al*. 2012) [20, 6]. It is estimated that out of total energy input (52.4 ±1.3 GJ ha^{-1}) 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) [33]. This is also accompanied by increase in associated carbon dioxide (CO_2) 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_4) emission as a result of methanogenesis (Sapkota *et al*. 2015) [30]. Grace *et al*. (2003) [11] reported that rice–wheat system emitted greenhouse gases with global warming potential of 13–26 Mg CO_2 ha^{-1} yr^{-1} in Indo-Gangetic Plains. The environmental threats of intensive rice cultivation are also encouraged by dominating chemical-based weed control strategies. Thus, climate smart (CSA) improves the EUE, decreases the carbon footprints, cost of production and efficient use of production inputs in the RW system without jeopardizing the productivity of the crops relative to those for the conventional management practice of the RW production system, and offers a hygienic and environmentally sustainable energy use efficient production technology for this IGP region of India. This review mainly focuses on the importance of the assessment and insight into: (1) to find out the energy conservation and energy-efficient agricultural practices for the RW system in western IGP of India; (2) to assess the key energy indicators and inputs for the RW system; and (3) reducing and/or removing GHGs, in the RW system.

Climate smart agriculture strives to sustainably increase productivity and profitability build resilience and adaptive capacity; where possible reduce greenhouse gas emissions (GHGs). CSA is an approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security with changing climate. Development of appropriate adaptation, mitigation of GHGs and food security strategy under rice-wheat production condition is important to cope with the progressive climate change and variability.

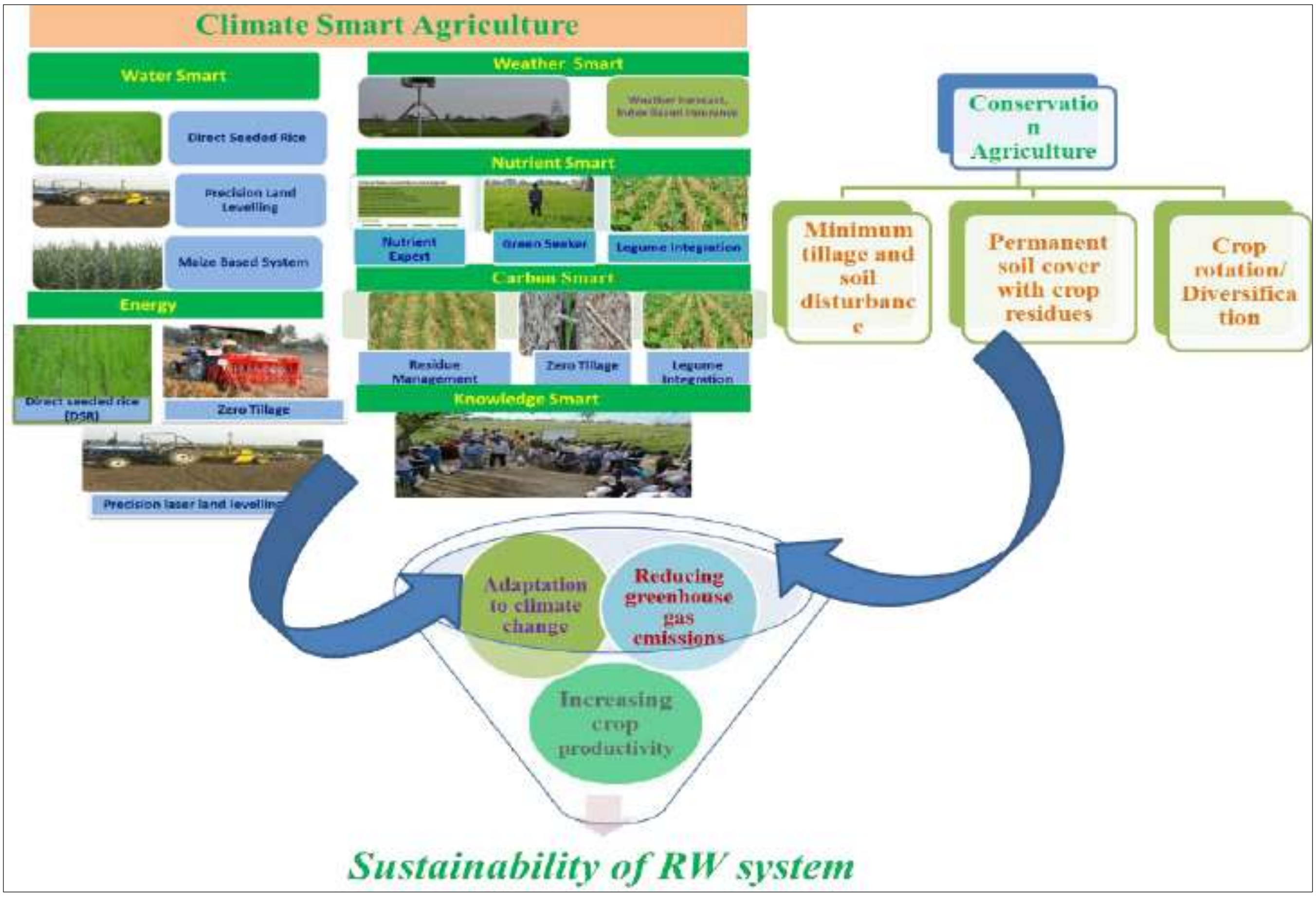

Fig 1: Climate smart agricultural and conservation agriculture based management practices for sustainability of RW system

Crop Establishments

The comparison of energy use pattern from different crop establishment methods of wheat revealed that the highest input energy consumption was(22164.8 MJ ha^{-1}) for CT and the lowest (18948.5 MJha^{-1}) was for PRB which was closely followed by ZT(19861.9 MJ ha^{-1}). The higher energy consumption under CT than ZT, attributed to more tillage operation. Residue retention proved 56% higher energy consuming than residue removal. The reason for higher energy use for R_R attributed to 40-cmresidues left in situ. Compared to zero N, the energy inputs were higher by 71% and 61% for 120 kg Nha^{-1} and 100 kg Nha^{-1}, respectively. The energy outputs for the TCE methods varied significantly. However, the highest energy output (75191 MJ ha^{-1}) was obtained from ZT followed by CT (66908 MJ ha^{-1}) and the lowest from PRB (64361 MJ ha^{-1}). Residue removal proved more energy output (7448 MJ ha^{-1}) than residue retention as residues added more to energy output. The abundant N (120 kg ha^{-1}) produced the highest energy output (88473 MJ ha^{-1}) followed by farmers' N (100kg ha^{-1}) of 83795 MJ ha^{-1} and the lowest (34192 MJha^{-1}) from zero N application. The energy use efficiency was 3.78, 3.4 and 3.02% for ZT, PRB, and CT, respectively. The higher energy use efficiency under ZT was mainly attributed to higher energy production with the use of relatively lesser energy utilization.

Sah *et al*. (2014) reported that with 100 kg N ha^{-1} and residue removal, CT consumed the highest energy input (19642.5 MJ ha^{-1}) followed by ZT (18314.4 MJ ha^{-1}) and the lowest from permanent raised bed (16866.5 MJ ha^{-1}). The maximum energy utilization was through fertilizers application in all the TCE methods. Conventionally grown wheat consumed energy on irrigation (24.3%), threshing and cleaning (18%), seeding (9.5%), tillage and crop establishment (9.1%), harvesting (1.8%), and the least (1.6%) on chemical application, while, PRB wheat consumed energy on threshing and cleaning (22.1%), irrigation(17%), TCE (8.2%), seeding (7.2%), harvesting (2.1%), and the least (1.8%) on chemical application. Zero-till wheat utilized energy on threshing and cleaning (27%), irrigation (17.9%), seeding (10%), TCE (3.2%), harvesting (1.9%), and the least (1.7%) on chemical application. Thus, the minimum TCE cost was associated with ZT as seed sowing was accomplished in one tractor-pass. About one-fourth of the total energy consumption was spent on irrigation applications in CT, while, they were 17.9 and 17% in ZT and PRB, respectively, as more water was required for CT than others.

Fig 2: Different management practices under direct seeded and mechanically transplanted rice

Source and operation wise energy utilization pattern

Kakraliya *et al*. (2022) [17] revealed that an energy used in different field operations under various crop management activities was significantly affected by the rice establishment methods and was ranged from 422 to 436 MJ ha^{-1} (Fig. 1). Business as usual (Sc1) with high energy intensive practices consumed the highest (4336 MJ ha^{-1}) energy in seed bed preparation, whereas in Sc5 and Sc6 no energy was required for seed bed preparation (Fig. 1). CSAP (mean of Sc4, Sc5and Sc6) consumed 57% less energy in crop establishment (transplanting/ sowing) operations compared Sc1 (978 MJ ha^{-1}). Irrespective of field operations, tillage consumed highest input energy in conventional management practice of RW system. This was due to repeated (5–6 passes) dry and wet tillage to prepare a seedbed for nursery raising and puddling consumed more diesel in machinery in Sc1. In addition to this, Sc1 and Sc2required 15–20 additional manual labour for transplanting rice seedlings.

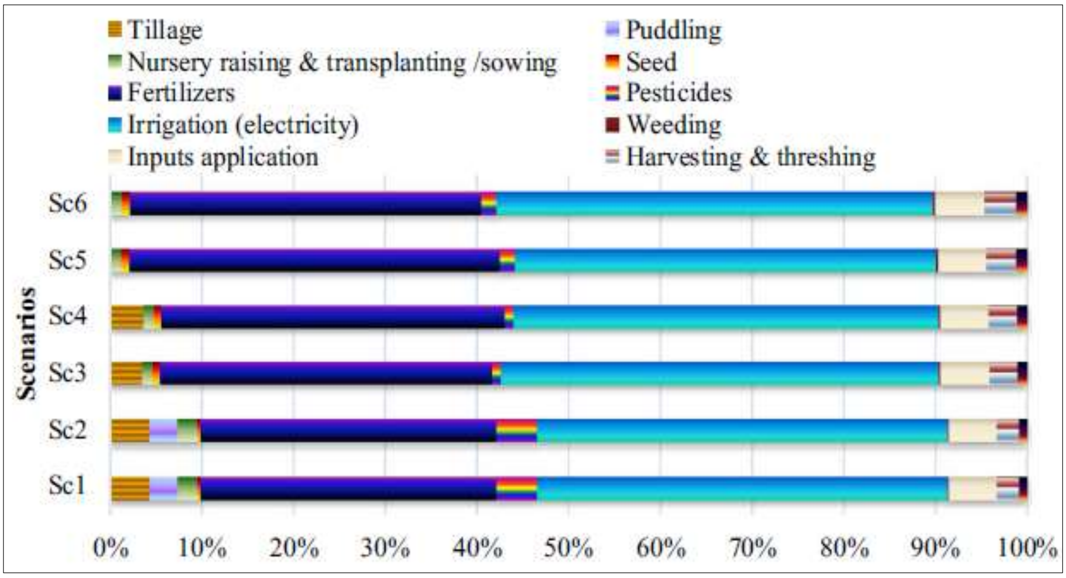

Fig 1: Operation-wise input energy-use pattern (%) under different management practices in rice. Where; Sc1, business as usual-conventional tillage (CT) without residue; Sc2, CT with residue; Sc3, reduce tillage (RT) with residue + recommended dose of fertilizer (RDF); Sc4, RT/Zero tillage (ZT) with residue + RDF; Sc5, ZT with residue + RDF + Green Seeker + Tensiometer; Sc6, Sc5 + Nutrient expert.

Zhang *et al*. (2023) reported that the total energy input under the surface irrigation method is 85.4 GJha^{-1}, of which the largest energy input is inorganic fertilizer, accounting for 48.31%, followed by electricity and labor, accounting for 13.74% and 12.19%, respectively. The smallest proportion of energy input is organic fertilizer, accounting for 2.58%. The total energy input under the water-saving irrigation method is 72.3 GJha^{-1}, showing a decrease of 15.42% compared with the total energy input of the surface irrigation method (Fig.2). The largest proportion of the energy input is still inorganic fertilizer, accounting for 35.7%, followed by the materials of the water-saving irrigation system and electricity. The proportion of the energy input is 16.06% and 13.73% respectively. The smallest proportion of the energy input is organic fertilizer, which accounts for 1.25%.

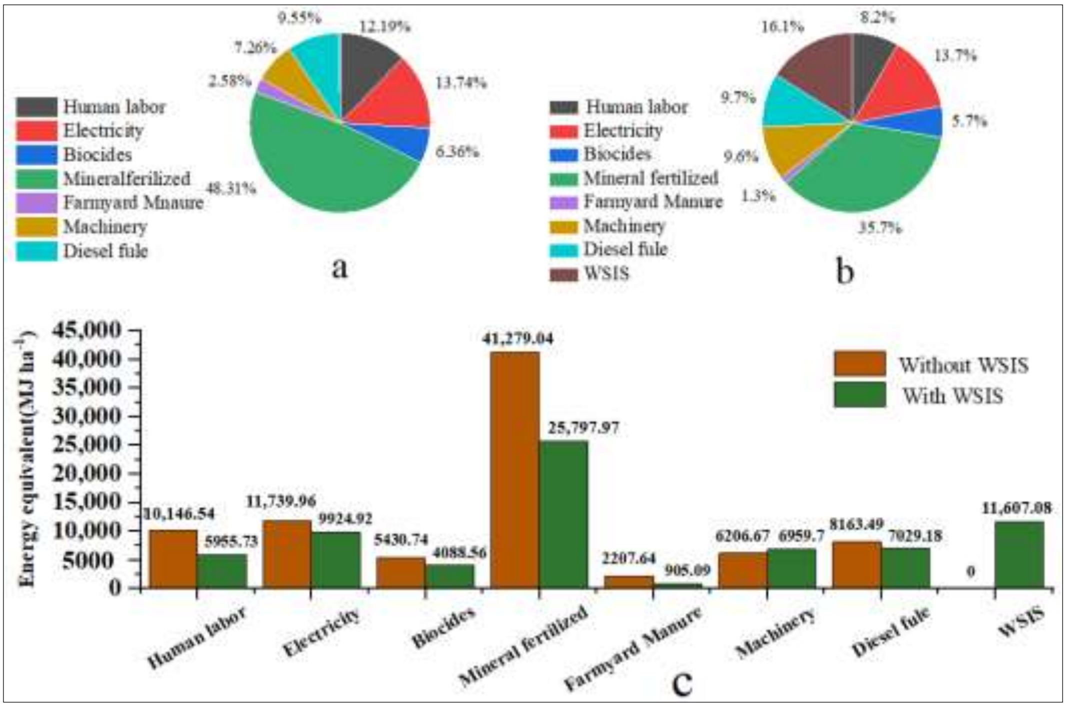

Fig 3: Composition of energy input under different irrigation methods

Kakraliya *et al*. (2022) [17] also found that in wheat, energy used under different management practices for seedbed preparations ranged from 892 to3078 MJ ha^{-1} and were significantly affected by crop establishment method. In seedbed preparation, Sc1 and Sc2 consumed highest energy (2228 MJ ha^{-1}) followed by Sc3 (1382 MJ ha^{-1}), whereas in Sc5 and Sc6no energy was required for seed bed preparation. Sc3-Sc6 consumed ~ 53% less energy in seedbed preparation and in sowing compared to Sc1 (Fig. 3).

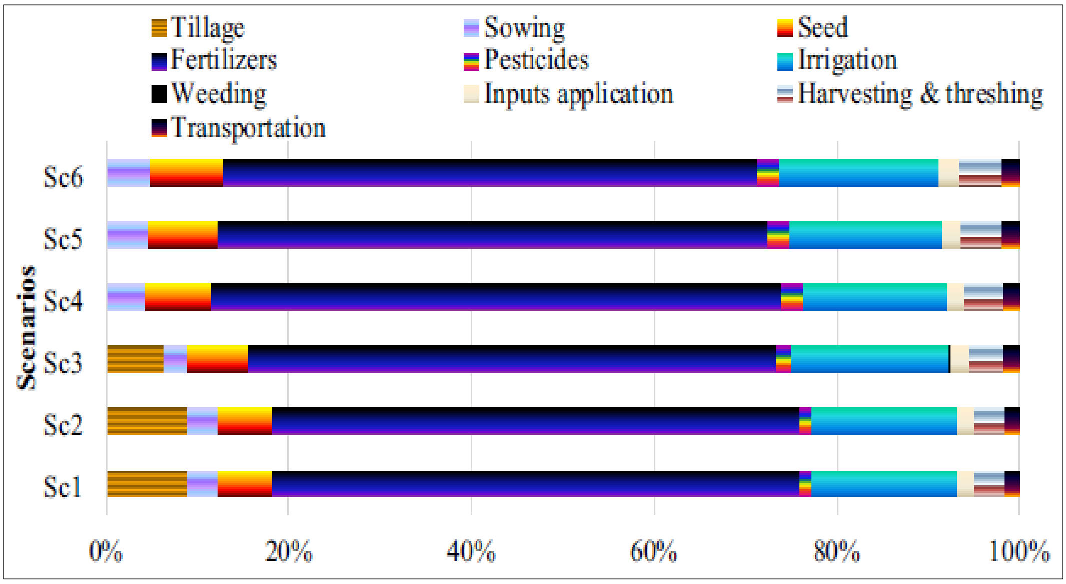

Fig 4: Operation-wise input energy-use pattern (%) under different management practices in wheat. Where; Sc1, business as usual or conventional tillage (CT) without residue; Sc2, CT with residue; Sc3, reduce tillage (RT) with residue + recommended dose of fertilizer (RDF); Sc4, RT/Zero tillage (ZT) with residue + RDF; Sc5, ZT with residue + RDF + Green Seeker + Tensiometer; Sc6, Sc5 + Nutrient expert

Diljun *et al*. (2023) observed that direct energy constituted 70% of total input energy in rice with a share of 44,613.28 MJha^{-1}. Direct energy made up 59% of input energy in wheat production with a share at 30,047.85 MJha^{-1}. The residual is indirect energy (30% and 41% for rice and wheat respectively). The renewable energy has a minor share and non-renewable energy accounted for 75% and 76% share in rice and wheat respectively. However, Energy use efficiency was estimated at 2.53 for rice and 2.15 for wheat. If energy use-efficiency is above 1, then the production system is generating energy and specific energy is estimated at 10.98 and 12.77 MJkg^{-1} for rice and wheat respectively (Fig.4a & 4b).

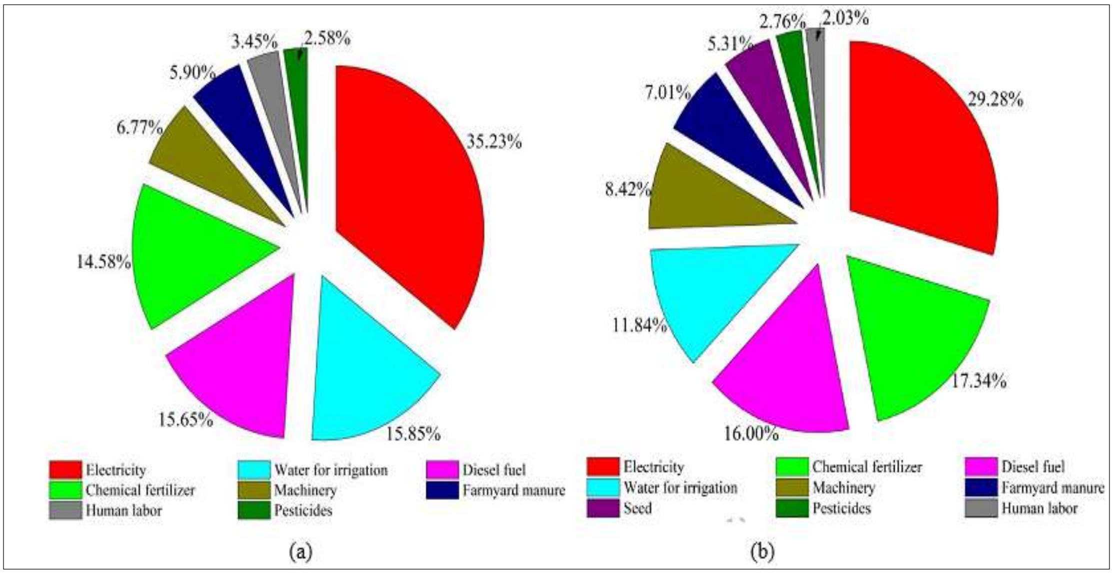

Fig 5: Percentage share of various constituents in total energy input in (a) rice production and (b) wheat production

Kakraliya *et al*. (2022) [17] observed that business as usual (Sc1) consumed more energy because of it required more tillage operations in seedbed preparation. However, in CSAP, tillage is not required for seeded preparation and energy is used only for seed sowing. On the system basis, CSAP consumed 76% less energy in seed bed preparation compared to Sc1 (7416 MJ ha^{-1}) (Fig. 5). The higher energy consumption in tillage could be due to fewer usages of modern agricultural machineries and higher use of human & animal power in conventional RW production (Fig. 3).

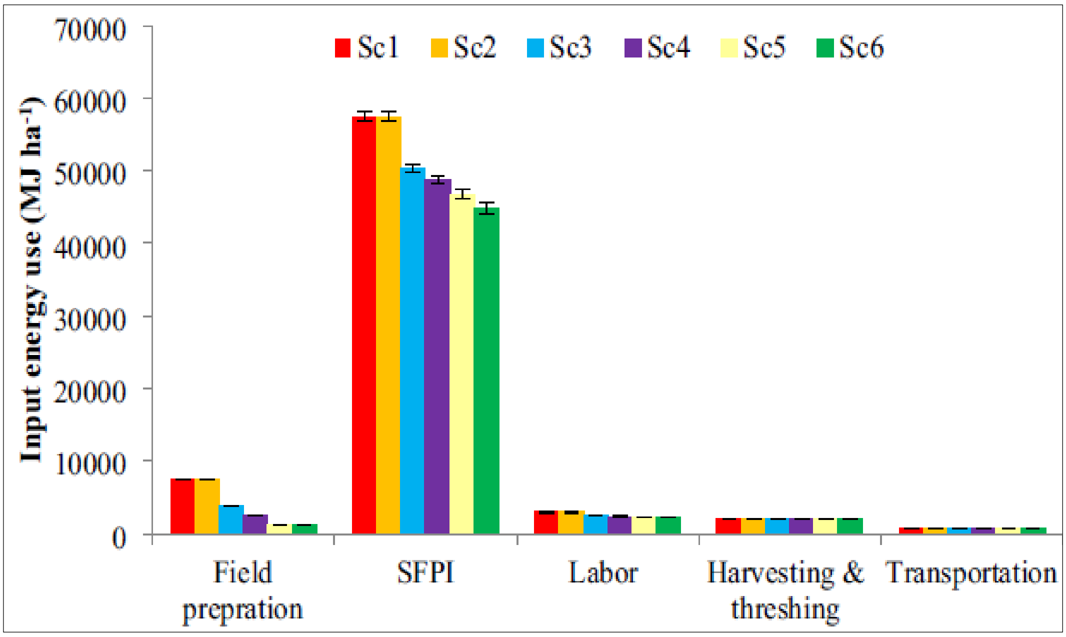

Fig 6: Operation-wise input energy-use (%) of RW system under different management practices. Where; SFPI are seed, fertilizer, pesticides and irrigation. Sc1, business as usual-conventional tillage (CT) without residue; Sc2, CT with residue; Sc3, REDUCE tillage (RT) with residue + recommended dose of fertilizer (RDF);Sc4, RT/Zero tillage (ZT) with residue + RDF; Sc5, ZT with residue + RDF + Green Seeker + Tensiometer; Sc6,Sc5 + Nutrient expert

Diljun *et al.* (2023) reported that the net energy gain is estimated at 97487.82 and 58476.09 $MJha^{-1}$ for rice and wheat respectively. Per kilogram net energy gain for rice is 16.70 which is significantly higher than wheat (14.70) thereby implying that the production of rice leads to higher energy gain for every unit of production. The combined net energy gain of the rice-wheat cropping system is estimated at 155963.91 $MJha^{-1}$ which is well within the range estimated by (Soni *et al.*, 2018) [35] for fertile Indo-Gangetic Plains (1537900 to 2685100 $MJha^{-1}$). The agrochemical energy ratio for rice is 17% and for wheat its 20%. A high ratio implies large agrochemical footprint and negative environmental effects as nitrogen leaching, pollution in air and water and greenhouse gas emission (Pishgar *et al*., 2013) [24]. The higher consumption of nitrogen in the total input energy is the reason for the higher ratio in wheat. However, the ratio for both rice and wheat is lower than comparable studies in Iran which estimated the ratio in the production of corn as 40% which illustrates a chemical-intensive production system. The energy productivity for rice and wheat is estimated at 0.09 and 0.08 $kgMJ^{-1}$ respectively.

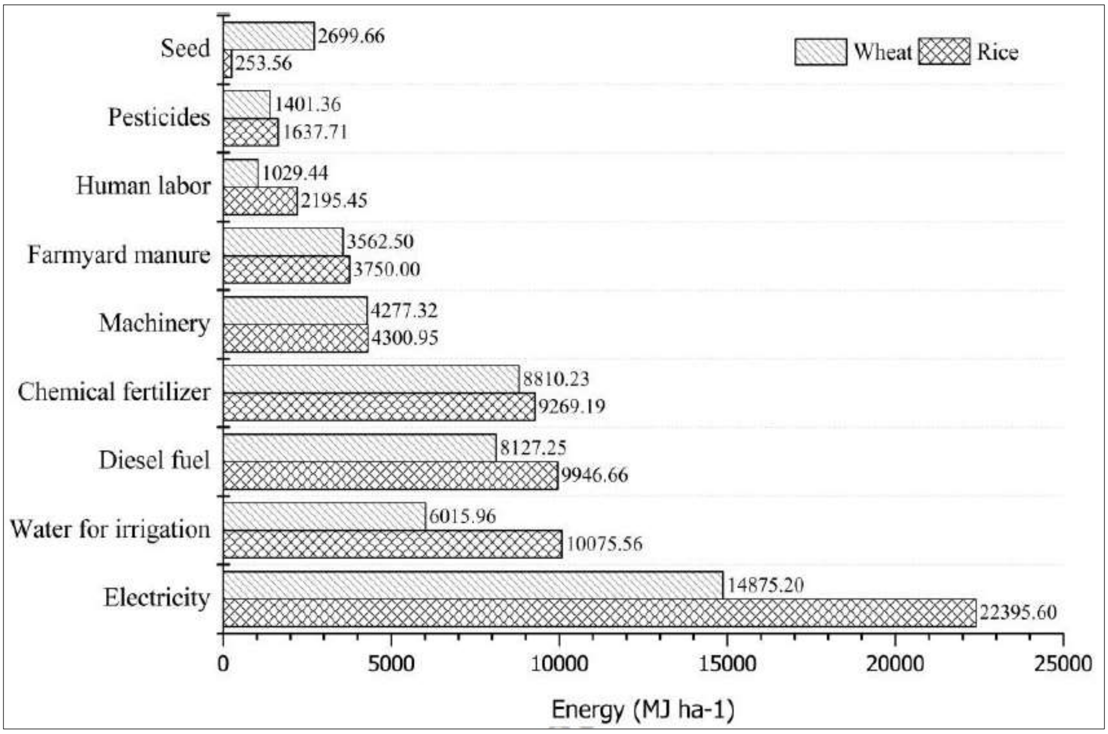

Fig 7: Input wise energy consumption for rice and wheat

Global Warming Potential

Agricultural activities contributes to the emission of three important greenhouse gases leading to the global warming– carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The share of agriculture to the emission of N_2O, CH_4, and CO_2 are 60%, 39%, and 1%, respectively (OECD, 2001). Rice based cropping system plays the major role to the emission of greenhouse gases (Fig. 5). Conventional flooded rice culture with puddling and transplanting is the major source of CH_4 emissions as prolonged flooding creates an anaerobic soil conditions accounting for 10–20% (50–100 Tg yr^{-1}) emission. Methane formation depends on the metabolic activity of a group of bacteria and activity of methanogen bacteria increases in anaerobic condition. The major pathways of CH_4 production in flooded soils are the reduction of C compounds to CH_4 due to restricted oxygen supply. Anaerobic condition is the pre-requisite for the activities of methanogenic bacteria and CH_4 production. Thus, CH_4 is low under aerobic condition. In the conventional transplanted rice field standing water is kept throughout the crop growing season and thus the methane emission is higher in this case while DDSR field is not continuously submerged and therefore, CH_4 is less in the DDSR field (Joshi *et al*., 2013) [38].

Atmospheric carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) had been accepted as the potential source of greenhouse gases (GHGs) that had significantly contributed to global warming due to their great radiative forcing (IPCC, 2007). Global agriculture contributed 10-12% to the net anthropogenic greenhouse gases (GHG) emissions estimated as 5.1-6.1 Pg CO_2-eq yr^{-1} in 2005 (IPCC, 2007). However, there could be a great potential to reduce total GHGs emission in agriculture by improving soil organic carbon (SOC) storage and/or decreasing CH_4, N_2O and CO_2 emissions through improving crop production techniques (Smith *et al.*, 2008) [34]. The emission of methane from the soil in puddled transplanted rice ranged from 0.8 to 1.9 t CO_2 equivalent ha^{-1} in various districts of Punjab compared to only 0.1–0.3 t CO_2 equivalent ha^{-1} in DDSR (Gartaula *et al*., 2020) [10]. The average global warming potential due to all the three greenhouse gases (carbon dioxide, methane, and nitrous oxide) in transplanted rice was 2.91 t ha^{-1} compared to 1.94 t ha^{-1} in DDSR (Gartaula *et al*., 2020) [10]. Gupta *et al*. (2016) [12] reported significantly low methane emission (82–87.2%) in the DDSR as compared to the puddled transplanted rice. DDSR leveraged with short or medium duration rice varieties/hybrids with early maturity and faster field vacation helps in conserving residual soil moisture useful for crops in rotation, widening the time window for effective residue management, and also facilitates in early or timely sowing of long-duration wheat varieties ultimately leading to enhanced system productivity, profitability, and sustainability.

The crop establishment method, cropping system followed and management of nutrient, water and pests are the key agronomical components responsible for remittance of greenhouse gases from agricultural fields. Methane is the second most important greenhouse gas after carbon dioxide (CO_2) and a single molecule of methane (CH_4) traps nearly 28 times as much heat, as does the CO_2. The studies on methane emission measurement indicated that CH_4 emission is primarily dependent on parameters such as frequency of water drainage, soil types, soil temperature (Parashar *et al*., 1991) [40] 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_4 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) [28, 32]. For instance, the production of 1 kg of rice returns 2.6 times more CO_2 equivalent emission to the environment than other cereals. Singh and Benbi (2020) [32] reported emission of 0.2 kg CO_2 equivalent per kg grain in rice–wheat system as compared to 0.1 kg CO_2 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) [32]. The conventional rice cultivation showed higher CH_4 emission (50–250 mg m^{-2} d^{-1}) than direct seeded rice (<50 mg m^{-2} day^{-1}). The total cumulative soil flux of CO_2, nitrous oxide (N_2O) and CH_4 emissions in terms of CO_2 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) [29]. 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; Naresh *et al*., 2021) [29, 20]. Rice residue burning is largely practiced in northern India and burning of 1 Mg rice straw releases about 280 kg CO_2–C, 3 kg CH_4 and 0.07 kg N_2O-N with a global warming potential of 1118 kg CO_2 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 that rice crop poses extreme high global warming potential (0.50–5.65 kg CO_2-eq kg^{-1}) over others, *viz*. maize (0.18–0.45 kg CO_2-eq kg^{-1}).

Datta *et al*. (2022) also found that lower GHGs emission ($F_{CA\text{-}High\ Fertilizer}$: 1474 kg CO_2-eq ha^{-1}) -compared to conventional practices ($F_{CP\text{-}High\ Fertilizer}$: 2400 kg CO_2-eq ha^{-1}). The intensity of GHG emissions was higher in FCP-High Fertilizer (0.37 kg CO2-eq kg^{-1}) over $F_{CA\text{-}High\ Fertilizer}$ (0.10 kg CO_2-eq kg^{-1}). Crop residue burning in conventional practices resulted higher CH_4 (788 kg CO_2 eq ha^{-1}) and N_2O emission (179 kg CO_2-eq ha^{-1}); whereas in CA, there were no GHG emissions as no burning took place. Higher N_2O emissions were estimated in $F_{CA\text{-}High\ Fertilizer}$ (559 kg CO_2-eq ha^{-1}) over $F_{CP\text{-}High\ Fertilizer}$ (518 kg CO_2-eq ha^{-1}) from fertilizer-induced field emission. A large amount of C was sequestered in soil under $F_{CA\text{-}High\ Fertilizer}$ (899 kg CO_2-eq ha^{-1}) compared to $F_{CP\text{-}High\ Fertilizer}$ (172 kg CO_2-eq ha^{-1}) wheat. In FCA-Medium Fertilizer, lower GHG emissions (1296 kg CO_2-eq ha^{-1}) were observed over $F_{CP\text{-}Medium\ Fertilizer}$ (2062 kg CO_2-eq ha^{-1}). The GHG emission intensity was also lower in the former (0.06 kg CO_2-eq kg^{-1}) than in $F_{CP\text{-}Medium\ Fertilizer}$ (0.41 kg CO_2-eq kg^{-1}), although the fertilizer dose was same. Also N_2O emissions were higher in $F_{CA\text{-}Medium\ Fertilizer}$ (501 kg CO_2-eq ha^{-1}) than $F_{CP\text{-}Medium\ Fertilizer}$ (452 kg CO_2eq ha^{-1}) practices. Due to burning crop residues in $F_{CP\text{-}Medium\ Fertilizer,}$ 665 and 151 kg CO_2-eq ha^{-1} CH_4 and N_2O were emitted, respectively. Significantly higher quantities of SOC were sequestered under FCA-Medium Fertilizer (929 kg CO_2-eq ha^{-1}) than FCP-Medium Fertilizer (122 kg CO_2 eq ha^{-1}) wheat. Conventional practices with application of 250 kg urea and 125 kg DAP ha^{-1} ($F_{CP\text{-}Low\ Fertilizer}$) caused additional GHG emissions of 1827 kg CO_2-eq ha^{-1} with an intensity of 0.37 kg CO_2-eq kg^{-1}. Similar quantities of CH_4 and N_2O were emitted due to crop residue burning as in $F_{CP\text{-}Medium\ Fertilizer}$ with conventional practices. Field induced emissions of CH_4 and N_2O were 151 and 375 kg CO_2 eq ha^{-1}, respectively, under $F_{CP\text{-}Low\ Fertilizer}$. The main source of variation in GHG emissions between CA and conventional agricultural practices was the management practices. Conventional practices in $F_{CP\text{-}High\ Fertilizer}$ registered about 63% higher total GHG emissions than $F_{CA\text{-}High\ Fertilizer}$, which were due to less soil disturbance (zero tillage), residue retention instead of burning, green seeker and Nutrient Expert-based N applications to soil in later stages, leading to lower emissions (Kakraliya *et al*. 2018) [15]. In CA-based practices, higher N_2O emissions might occur due to denitrification from soil under residue retention conditions developing anaerobic micro-pockets in the presence of high soil moisture content at soil surface where microbes use nitrate and nitrite as terminal electron acceptor and produce N_2O (Brady and Weil 2007) [4]. Bhatia *et al*. (2010) [3] and Gupta *et al*. (2016) [12] also observed higher N_2O emissions under CA-based agricultural practices in northern India. Sapkota *et al*. (2017) [31] pointed out that the source and amount of N fertilizer also influences GHG emissions from soil. Lower GHG emissions were observed upon application of lower doses of N fertilizer to soil. In conventional wheat, about 12% less N_2O emissions were observed than in zero tilled wheat in northern India (Bhatia *et al*. 2010) [3]. Higher N_2O emissions from zero tilled wheat than conventional were also observed by Sapkota *et al*. (2015) [30] in rice–wheat cropping systems of north-western Indo-Gangetic plains.

Datta *et al*. (2022) [7] also found that dry direct seeded rice culture reduced 24 to 79% and 43 to 75% CH_4 emission under continuous flooded and intermittent irrigated system compared with the puddle transplanted continuous flood irrigated rice field (Kumar and Ladha, 2011) [18]. Pathak *et al*. (2013) [23] reported that CH_4 emission in dry seeded field was 0.6–4.9 kg ha^{-1} and puddled trans-planted field was 42.4–57.8 kg ha^{-1} in different areas of Punjab, India. Although dry direct seeding can re-duce CH_4 emission under aerobic soil condition, the relatively more soil aerobic state may increase N_2O emission. N_2O is produced as by-product during soil microbial nitrification and de-nitrification processes. N_2O emission in DDSR and PTR–CI field was0.95 kg N^2O N ha^{-1} and 0.65 kg N_2O N ha^{-1}, respectively (Liu *et al*., 2014). In India, the N_2O emission was 0.31–0.39 kg N ha^{-1} under PTR–CI which increased to 0.90–1.1 kg N ha^{-1} and1.3–2.2 kg N ha^{-1}, in conventional tillage dry direct seeded rice and zero till dry direct seeded rice, respectively (Kumar and Ladha, 2011) [18]. Pathak *et al*. (2013) [23] estimated that N_2O emission in 2009 in DDSR was 0.9–1.2 kg ha^{-1} and 0.8 to 1.1 kg ha^{-1} in PTR field's in Punjab, India while that was 2.0–2.2 kg ha^{-1} in DSR and 1.6–1.8 kg ha^{-1} in TPR in 2010. Methane emission starts at redox potential of soil below −150 mV and is stimulated at less than −200 mV (Wang *et al*., 1993) [39].

Fuller *et al*. (2011) [9] also found that rice based cropping system plays the major role to the emission of greenhouse gases (Fig.8). Methane formation depends on the metabolic activity of a group of bacteria and activity of methanogen bacteria increases in anaerobic condition. The major pathways of CH_4 production in flooded soils are the reduction of C compounds to CH_4 due to restricted oxygen supply. Anaerobic condition is the pre-requisite for the activities of methanogenic bacteria and CH_4 production. Thus, CH_4 is low under aerobic condition.

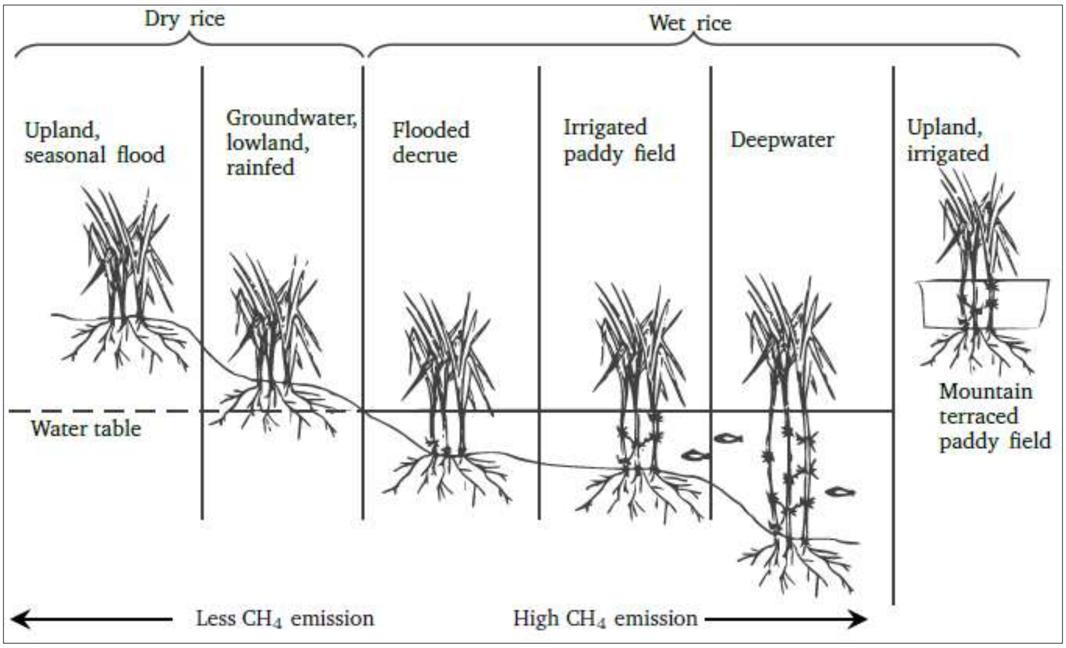

Fig 8: Methane gas emission from rice field as a function of water management in the field

Bijarniya *et al*. (2020) [2] reported that the crop management scenarios, S1 recorded the highest GWP and CO_2 emission intensity followed by S2 and the lowest was in S6 and following overall trend of S6 > S5 > S4 > S3 > S2 > S1 (Fig.9). The higher GWP and CO_2 emission intensity in farmer practices scenarios (S1 and S2) reflects the more contributed in carbon footprints. The mean CSAPs recorded lower GWP by 1598, 1749 and 1876.3 kg CO_2 eq. ha^{-1} yr^{-1} compared to S1 (3652.7 kg CO_2 eq. ha^{-1} yr^{-1}), respectively. Input like diesel fuel (for land preparation, seeding and irrigation water application), fertilizers constitute and puddling in rice, the major share of the total emissions of

GHGs (N_2O and CH_4) estimated for the system (Fig. 9). The CSA based scenarios (S4 S5 and S6) related to low inputs and no puddling in rice contributed to low emissions of GHGs compared to farmers practice (S1), whereas higher input used and followed repeated tillage in wheat and puddling in rice.

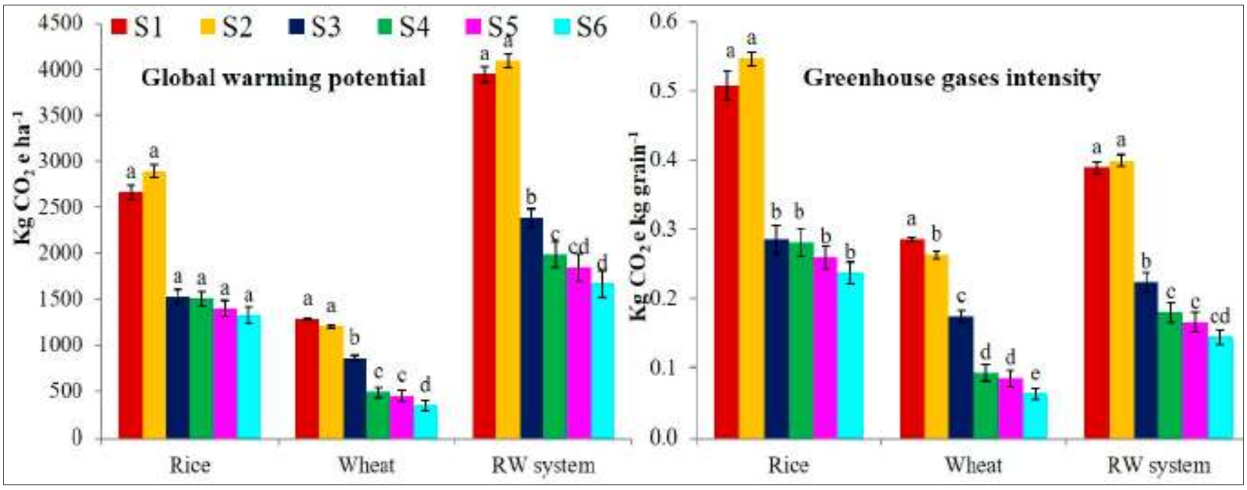

Fig 9: Mean annual global warming potential (GWP) and greenhouse gases intensity of rice-wheat system under divergent crop management scenarios. S1- Conventional tillage (CT) without residue; S2- CT with residue, S3- Reduced tillage (RT) with residue + Recommended dose of fertilizer (RDF); S4- RT/zero tillage (ZT) with residue + RDF, S5-ZT with residue + RDF + green seeker + tensiometer +Information & communication technology +crop insurance and S6- S5 + site specific nutrient management

Conclusions

Climate Smart agricultural practices such as CA with zero tillage, residue retention with diversified crop rotation resulted in a decrease in soil pH in wheat compared to conventional agriculture practices. Lower GHG emissions were estimated from CSA than from conventional practices. These CSA practices provide an excellent alternative to conventional agriculture practices in north-west IGP for adaptation to climate change irrespective of farm type and size. Rice–wheat cropping system in north-west IGP has contributed immensely to fill the increasing empty stomachs but has consequently led to many sustainability issues *viz*. declining water resources, degrading soil health and environment degradation which is further responsible for stagnating/decreased land and water productivity. There is need to refine the agronomical practices for direct seeded rice along with genetic tailoring for anaerobic 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.

The total energy input for rice and wheat was valued at 63825 and 50799 $MJha^{-1}$ respectively. Combine energy input and output for combine crop rotation 114624 and 270588 $MJha^{-1}$ respectively. Primary contributors in the input energy are electricity for water pumps and water for irrigation followed by nitrogen fertilizer and diesel fuel. The input-wise energy estimates can be used to estimate GHG emissions and the global warming potential (GWP) of the rice-wheat cropping cycle in north India for larger policy-relevant interventions. Energy use efficiency in rice-wheat system is low (2.53 for rice and 2.15 for wheat) and the specific energy ratio is high 10.98 $MJkg^{-1}$ for rice and 12.77 $MJkg^{-1}$ for wheat). This implies that there is a need to optimize energy use, implement energy efficiency measures and improve productivity per unit of energy consumed in the system. There is a close association between and GHG emissions, global warming potential (GWP) and non-renewable energy input. Our estimated share of non-renewable sources was 75% for rice and 74% for wheat. Therefore, there is a need to curtail the use of non-renewable energy resources. There is considerable scope in energy savings through improvement in energy efficiency in agriculture water pumps, minimum tillage and harmonizing sowing season with the monsoon season. Optimizing fertilizer management by reducing synthetic fertilizer inputs and increasing organic compost and improving water management is vital. The state departments should converge to introduce energy-efficient practices which will go a long way in ensuring the sustainability of production system in the country.

Hence, alternate tillage and establishment methods must be invented and recommended for the sustainable establishment of rice–wheat cropping system as a whole including the intervening period so that soil health and environment must be improved for overall lifting of the livelihoods of the farmers of north-west IGP. Performance of these technologies is, however, site-specific and changed depending upon the soil textural classes and agro-climatic conditions. This suggests that farmers must pick them up from the many as per their soil texture and agro-climatic conditions. Conventional indigenous age-old practices are responsible for all the earlier discussed un-sustainability issues which must be replaced with more advanced and sustainable climate smart agriculture practices (CSA). Therefore, the role of these CSA to achieve sustainable food production with minimal impact on the soil, underground water and the atmosphere and in improving the declining land and water productivity become more important now than ever. Apart from cropping system perspective, adoption of soil/water conserving technologies like conservation 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.

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