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# Ecological significance of tillage systems and precision nutrient management in cereal based systems for carbon-cum-energy efficient and energy-carbon footprint vis a vis system productivity and profitability: A sub-tropical Indian perspectives

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## Abstract

Identifying an energy-efficient system with low energy use, low global warming potential (GWP), and high profitability is essential for ensuring the sustainability of the agro-environment. The soil sustains most living organisms, being the ultimate source of their mineral nutrients. On croplands, tillage is the most important practice, which can have a major effect on the carbon pool, either negative with conventional plowing or positive, when No-tillage is applied. No-tillage practices claim to reverse historical carbon loss from soils, thereby reducing $CO_2$ in the atmosphere through storage in soil sinks-a process known as sequestration. Carbon sequestration and an increase in soil organic matter will have a direct positive impact on soil quality and fertility. There will also be major positive effects on the environment, and on the resilience and sustainability of agriculture. The total energy inputs for TPR and DSR were 31.5 and 22.8 GJ ha$^{-1}$ across two growing seasons, respectively. Higher energy input for TPR primarily resulted from extra energy use of the nursery beds and transplanting. Higher energy output of DSR (202.5GJ ha$^{-1}$) over that of TPR (187.7 GJ ha$^{-1}$) was due to a slightly higher yield from DSR. Therefore, DSR exhibited significantly higher energy use efficiency than that of TPR. Lower specific energy for DSR (2.78 MJ kg$^{-1}$) relative to TPR (4.02 MJ kg$^{-1}$) indicated that the energy used to produce per unit of rice grain could be reduced by 30.8% by adopting DSR. On average, GWP of DSR was reduced by 5.6% compared with TPR. Moreover, DSR had a 55.8% higher gross return and a 25.7%lower production cost than those of TPR. Overall, compared with TPR, DSR has the potential to increase gross economic return and energy output with reduced energy input and emissions.

The agricultural production systems are highly vulnerable in the region and are primarily dominated by small and marginal farmers with intensive farming practices that had favored the loss of carbon (C) from soil. This review discusses the potential of soil and crop management practices such as minimum/reduced/no-tillage, use of organic manure, balanced and integrated plant nutrient application, precision land levelling, precision water and pest management, residue management, and cropping system optimization to maintain the C-equilibrium between soil and atmosphere and to enhance the C-sequestration in the long run. Results of meta-analysis show a potential 36% increase in soil organic C stock in the top 0–15 cm layer in this region which amounts to ∼18 Mg C stocks ha$^{-1}$. Improved management practices across crops and environment may reduce methane emission by 12% resulting in an 8% reduction in global warming potential (GWP), while non-submerged condition led to a 51% GWP reduction in rice. Conservation agriculture and precision fertilization also reduced GWP by 11 and 14%, respectively. Adoption of soil test crop response (STCR) based integrated nutrient management (INM) module (FYM + 75% NPK of STCR) minimized the energy requirement by 14%, cost of cultivation by 6.5% and besides that CF on a spatial scale was 17% lower than general recommended dose (GRD). Thus, STCR based INM module enhanced the energy use efficiency (EUE), energy productivity (EP) and energy profitability (EPF) by 28.5%, 31.5% and 31.8% respectively, over GRD.

**Keywords:** Energy use efficiency, energy input, nutrient management alternatives

## Introduction

Energy is one of the most significant inputs for crop productivity and food security, especially in the current scenario of population boom (Parihar *et al*. 2018; Jat *et al*. 2019) [33, 17]. Modernizing agriculture by expanding the use of fossil fuels, as in the past, will be neither cheap nor sustainable due to climate change and the influence of high and fluctuating fossil fuel prices on production costs and food prices.

Energy efficiency improvement is regarded as the best means of minimizing carbon dioxide ($CO_2$) emissions, limiting energy reliance, and mitigating the effects of rising oil costs (Vourdoubas 2016) [18]. Therefore, carbon sequestration and low energy input farming should be prioritized owing to their critical significance in environmental sustainability in terms of decreasing carbon footprint values. The energy carbon footprint assessment of a particular crop rotation adopted is vital, especially for resource-limited situations. Crop rotations that are more energy efficient and have a low carbon footprint must be encouraged to make the present agricultural practice cheaper and cleaner with lower greenhouse gas (GHG) emissions (Parihar *et al.* 2018) [33]. Hence, a noteworthy crop rotation could considerably decrease the rate of global climate change.

The indiscriminate use of natural resources in the pursuit of meeting the demands of the current generation has jeopardized the needs of future generations. Considering the decreasing arable land resource base, water and energy resource use efficiency is critical for the adoption and sustainability of any crop rotations for a particular region (Sammauria *et al.* 2020) [41]. This is far more critical in arid and semi-arid regions of Rajasthan, where shrinking water resources; severe erosion, periodic drought, and low biological productivity are major limiting factors for crop productivity (Singh *et al.* 2007) [42]. The situation in these areas is exacerbated by the continuous adoption of pearl millet-wheat crop rotation, resulting in a significant reduction in soil fertility, leading to low factor productivity and profitability (Sammauria *et al.* 2020) [41]. The befitting solution to the above-listed problems is a shift towards diversification of crop rotation from traditionally followed pearl millet-wheat crop rotation. The literature is replete with studies of the positive effect of crop diversification on conserving natural resources, food and nutritional security, poverty alleviation, increasing farm income while maintaining and ensuring environmental health and agricultural sustainability (Beillouin *et al.* 2019; Sammauria *et al.* 2020) [2, 41].

The anthropogenic intensification has vehemently metamorphosed the earth's ecosystem and resulted in environmental pollution, land degradation, loss of biodiversity and put all life forms under jeopardy (Yadav *et al.*, 2018) [52]. Fertilizers and manures contributed to agriculture at 0.68 and 1.8 Gt $CO_2$-e emission per year, respectively. However, balanced use of chemical fertilizers is vital to fulfil the widening gross requirement for food, feed and bio-energy for the fastest growing population in the globe (Jat *et al.*, 2019) [17]. Overuse of chemical fertilizers has led to negative impacts on crop yields, soil health and environment quality, as it is an imperative cause of nitrous oxide ($N_2O$) emissions (Adegbeye *et al.*, 2020) [59]. About 80% of non-$CO_2$ emission ($N_2O$) from agriculture sector and comes largely from organic and inorganic sources of nutrients added to soils (Reay *et al.*, 2012) [60], and it is further exacerbating with additional supply of nitrogen and jeopardizing the soil and environment sustainability. Hence, flawed fertilizer management practices are the foremost constraints in maintaining high yield stability and economic viability, environmental sustainability and societal wellbeing (Saldarriaga-Hernandez *et al.*, 2020) [40]. Subsequent to nutrients, energy has always been essential inputs for the food grain production (Jat *et al.*, 2019) [17]. The food production is directly linked with fossil fuels in the form of fertilizers, petroleum-based agrochemicals and fuel consumption in maintenance farm machinery (Deike *et al.*, 2010) [57]. Fertilizer production and transportation are the contributors of the largest proportion of the total energy inputs, and hence it is a major source of GHGs emission (Amenumey and Capel, 2014) [58]. Moreover, the energy is used in different farm operations such as field preparation (tillage), irrigation, intercultural operations and other inputs including fertilizers/manures, pesticides, labour, transportation, and electricity escort to GHGs emission with strong effect on natural environment (Yadav *et al.*, 2018) [52]. Fertilizers are very important for the crop growth, yield, quality parameters, even for soil health only when applied in optimum recommended dose or when used judiciously. Fertilizer improves the nutrient status and quality of soil by enriching it with nutrients which it lacks. Crop plants require nitrogen, phosphorous and potassium to maintain the normal physiological function of the cell.

Growing environmental crises and resource degradation negatively impacted food and nutritional security across the Globe (Yadav *et al.*, 2019) [53]. The negative effect of faulty agricultural production practices on ecosystem integrity is the major constraint in achieving environmental sustainability and societal well-being (Saldarriaga-Hernandez *et al.*, 2020) [40]. Hence, achieving environmental sustainability concurrently with food, nutrition, and socioeconomic targets is a major challenge before the researchers and policymakers of every nation (Bilali *et al.*, 2018) [1]. Circular and green economies both are interconnected concepts (Toop *et al.*, 2017) [47] which can help in addressing these challenges without jeopardizing environmental sustainability. The circular economy in agriculture implies the sustainable production of food commodities with minimum resource use in closed nutrient loops while reducing adverse effects on the environment (Ward *et al.*, 2016) [50]. Food and nutritional security are integral parts of the green and circular economy (Fassio and Minotti, 2019) [11] that improve economic growth and help in poverty alleviation without escalating resource consumption (Chen *et al.*, 2020) [8]. Achieving them without deteriorating environmental quality with minimum wastage of natural resources like land and water, along with multiple cropping instead of single cropping becomes the foremost objective toward ensuring food and nutritional security all over the world. Therefore, efforts to intensify the prevailing production systems must be included in the evaluation the indicators of green and circular economies such as low carbon emission or carbon footprint (CF), resource and energy use efficiency, and social acceptability (D'Amato *et al.*, 2017) [10]. The enhancement of cropping intensity, minimum tillage, residue retention, mulching, etc. can be some of the plausible options for achieving food security, ecosystem services and employment targets while ensuring low carbon footprint and high energy use efficiency (Yadav *et al.*, 2019) [53].

India is the fourth largest producer as well as consumer of fertilizer in the world. With population growing at a fast rate, food production was given highest priority in India since the 1960s (New Agricultural Strategy). Although India’s soil is varied and rich, it is naturally deficient in major plant nutrients (nitrogen, phosphate and potassium). Growth in chemical fertilizer production and consumption therefore presents the single largest contributor to agricultural progress, its technological transformation and commercialization. Energy ratio of diverse tillage production systems depends on soil types, tillage practices, fertilizer, plant protection chemical, crop cutting, threshing, and total biomass (Mandal *et al.,* 2015) [25]. Nowadays, energy flow increases with the prologue of new farm machinery and other related inputs (Chaudhary *et al.*, 2017) [7]. The rice-wheat system is energy- and carbon-intensive, and the use of agricultural inputs *i.e.,* fertilizer and plant protection chemicals increase the crop yields but at the same time increase energy inputs (Jat *et al.*, 2019) [17]. Thus, identification of an energy/carbon-efficient production system is crucial, as the contribution of non-renewable sources of energy was absent except crop residue. Mechanization involves higher energy expenditures and optimizes cultivation cost. It ensures the appropriateness of agricultural operations by increasing crop yield per unit human or animal labour, mostly used in traditional tillage (Jat *et al.*, 2020) [16].

The average fertilizer application per hectare of about 145 kg in India during 2019-20 was much below than that in the SAARC countries of about 174 kg ha$^{-1}$. There are huge interstate and inter-regional variations in fertilizer use. The changes in government policies pertaining to fertilizer distribution and use have impacted significantly the nutrient use ratio. Overuse or misuse or imbalanced application of fertilizer nutrients and sheer negligence in the application of secondary and micronutrients have been responsible for the lower utilization of applied nutrients, leading to the accumulation of fertilizer nutrients in the soil and/or leakage to the environment, and thus causing environmental degradation and climate change. The compounded harmful effects of imbalanced fertilizer use are not only intensifying soil and atmospheric pollution but also impacting water bodies (eutrophication) and causing threat to biodiversity.

Cereal stubble has low concentrations of nutrients including nitrogen (N), phosphorus (P), and sulphur (S), although some nutrients may be released from existing SOM during the decay of stubble after its incorporation in the soil (Sarker *et al.* 2019). The addition of extra nutrients from fertilizers, along with the return of nutrient poor stubble in soil, may stimulate microbial activity and decrease nutrient mining by microorganisms while preserving existing SOM. Hence, integrated stubble–nutrient management may enhance the decay of stubble and increase microbial biomass and carbon-use efficiency (Fang *et al.*, 2018a) [61], with potential to convert a greater quantity of stubble-derived carbon (C) into stable SOM fractions (Kirkby *et al.*, 2016) [62].

Few studies had been conducted in the Indian sub-continent as to assess the energy performance of different crops and cropping systems, e.g., upper Indo-Gangetic Plains (Nassiri and Singh, 2009) [32], middle Indo- Gangetic plains (Chaudhary *et al.*, 2009) [6], Western Himalayan region (Singh *et al.*, 2016b) [39] and, coastal region of India (Manjunath *et al.*, 2017) [26]. But these studies are mostly confined to rice (*Oryza sativa* L.) based cropping systems. Some studies have also quantified CF of various crops (Yang *et al.*, 2014) [50], energy use pattern and $CO_2$ emissions from diverse cropping scenarios and soil management practices (Jat *et al.*, 2019) [17] in different regions of the world. But a comparative assessment of cropping systems in terms of CF, energy input-output relationship and profitability are lacking. Though energy saving and CF reduction are the environmental necessities, most often they may lead to low net income (Li *et al.*, 2018) [22]. Hence, simultaneous assessment of CF, energy and economic audit of the cropping systems would help in designing sustainable intensification planning for clean technologies to meet the food demand and to improve ecosystem services. Thus, the review study was undertaken to assess the energy carbon footprints and the economic feasibility of cereal-based cropping systems that will contribute to the development of sustainable and low GHG production existing cereal-based crop rotation through an appropriate combination of different tillage and precision nutrient management, which also helps to reduce input costs of production thus, boosting farm income.

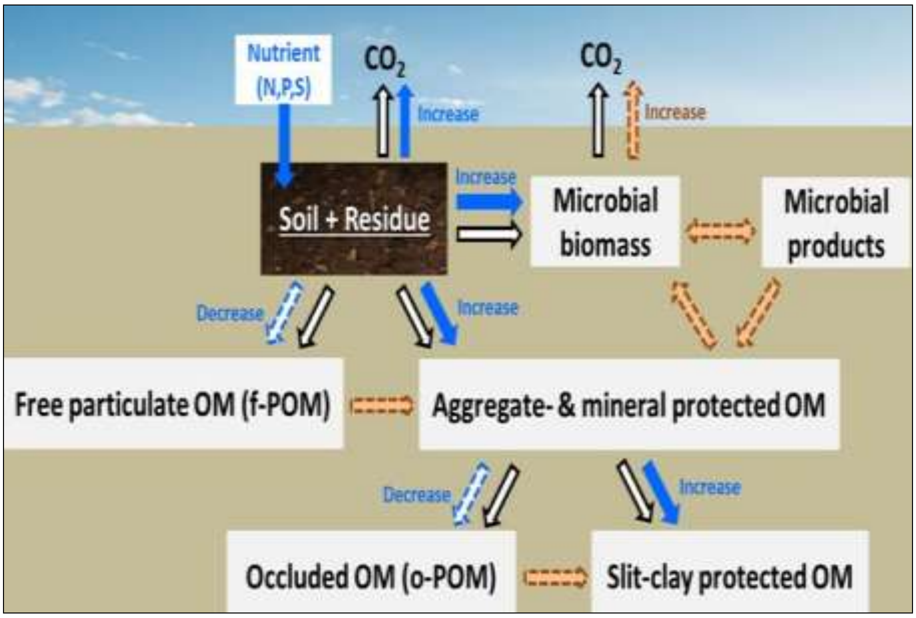

**Fig 1a:** A conceptual model showing the allocation of wheat stubble carbon in physically-defined soil organic matter fractions in two contrasting soils at high stubble rate (12t/ha), influenced by nutrient input [Source: Singh *et al.*, 2020] [63]

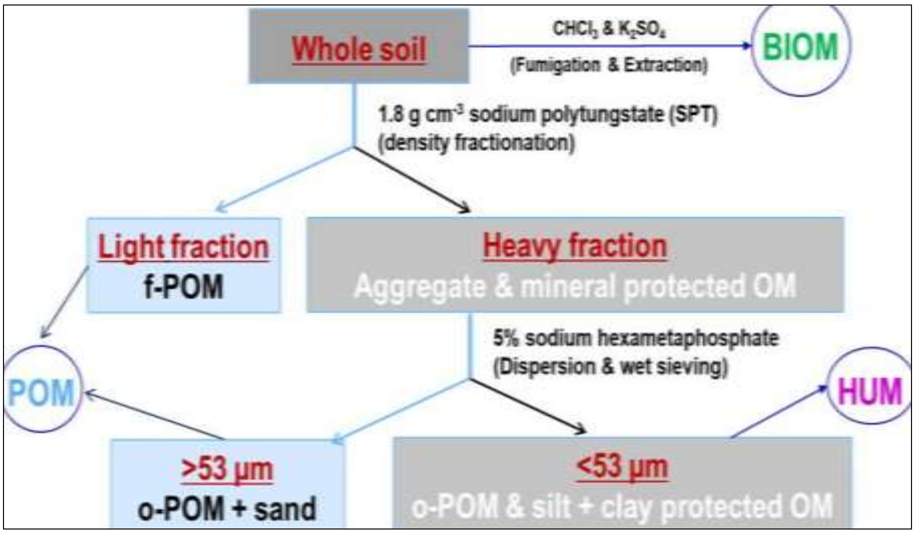

**Fig 1b:** The density-size fractionation process used to separate five soil carbon pools; light fraction (free particulate organic matter, f-POM), heavy fraction (aggregate and mineral protected OM), >53µm fraction (occluded particulate organic matter, o-POM), and <53µm fraction (silt-clay mineral associated OM). POM = particulate organic matter, HUM = humified organic matter and BIOM = microbial biomass [Source: Singh *et al.*, 2020] [63]

Kumar *et al.* (2021) [64] observed that different sources of total input energy, chemical fertilizer accounted for the highest energy used in partly mechanized tillage (44%) and mechanized tillage (38%) followed by diesel, irrigation water, plant protection chemical, seed and electricity. Seed, human, animal energy and farmyard manure accounted for 21, 20, 16 and 16%, respectively, of the total energy input in traditional tillage. Maximum energy input (52161 MJ ha$^{-1}$) was noted in mechanized tillage and minimum with traditional tillage (16879 MJ ha$^{-1}$). On an average, the total energy output in mechanized tillage (395245 MJ ha$^{-1}$) was 0.3 and 2.4 times higher over partly mechanized and traditional tillage, respectively. Mechanized tillage had higher carbon efficiency (3.75), carbon-sustainability index (2.75), carbon-footprint in spatial scales (4342 kg $CO_2$eq. ha$^{-1}$), but had 34% less carbon-footprint in yield scales compared to traditional tillage. Mechanized tillage showed 22 and 73% higher system productivity compared to partly mechanized and traditional tillage, respectively.

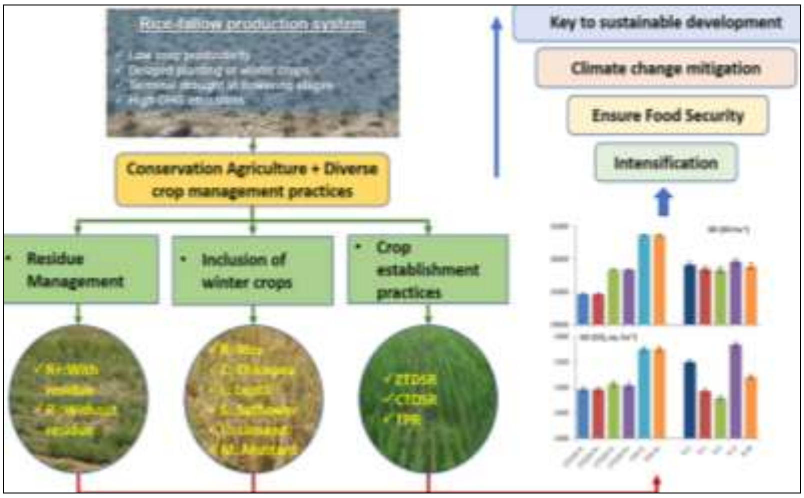

**Image 1:** Agricultural conservation and crop management practices

Lenka *et al.* (2020) [21] reported significantly higher SOC in reduced tillage (0.87%) than no-tillage (0.71%) under100% NPK fertilization in the bulk soil for 0-15 cm depth. However, 100% NPK + FYM showed a significant increase in the bulk soil organic carbon in the no-tillage treatment only. Available nitrogen content in the bulk soil and aggregate fractions were significantly lower under no-tillage than the corresponding reduced tillage treatments.

## Energy-use efficiency and energy productivity

Energy-use efficiency (EUE) and energy productivity (EP) are commonly used in evaluating crop production systems considering the energy input and output. Higher EUE indicates higher energy output through grain plus straw compared to energy input through various production inputs while higher EP indicates lower energy use per unit of grain productivity.

Ghosh *et al.* (2022) [65] reported that zero till dry direct seeded rice – zero till wheat (~double zero till)system incurred highest total input energy (157.4 × $10^3$ MJ ha$^{-1}$), having ~64% of this energy shared from renewable crop residue, but had highest (11.3) energy use efficiency from non-renewable resources (fuel, fertilizers, machinery). In contrast, the zero till direct seeded rice – zero till wheat – zero till mung bean system without residue resulted in highest net energy returns, energy ratio, energy productivity and energy intensity. The ZTR WMb+R system led to 64% lower yield scale C footprint (304 kg $CO_2$-eq. $t^{-1}$) compared to CTRW (848 kg $CO_2$-eq. $t^{-1}$) and had highest C efficiency, C sustainability index and C efficiency ratio.

Timsina *et al*. (2022) [45] observed that the highest GHGI was found in rice followed by wheat and maize. Higher GHGI in rice was mostly attributed to puddling and flood water adopted as the predominant water management practice in rice (IPCC, 2019). $CO_2$-eq. emissions from fertilizers were higher in maize than in rice or wheat due to higher fertilizer rates and other agrochemicals, and irrigation water, which was mostly attributed to higher fertilizer application in NE than in FP (Fig.2b). However, variability of $CO_2$ eq. emission was higher in FP compared to NE. the treatments, GHGI in rice ranged from 754 to 2201 kg $CO_2$ eq. emission $t^{-1}$ of grain produced, with 870 to 1822, 754 to 1475, and 916 to 2201 respectively for GR, NE, and FP.

Gathala *et al.* (2020) [14] reported mean $CO_2$-eq. emissions (t $CO_2$ eq-emissions $ha^{-1}$) of 0.65, 0.76 and 1.06 in rice, wheat, and maize in eight districts of the EIGP varying in soil, climate and farmers' management practices. In the current study, $CO_2$-eq. emissions (kg $CO_2$ eq. emissions $t^{-1}$ grain produced) in rice ranged from 754 to 2201, in wheat from 129 to 1172, and in maize from 43 to 396. Differences between these studies are due to differences in soil, climate, and management practices.

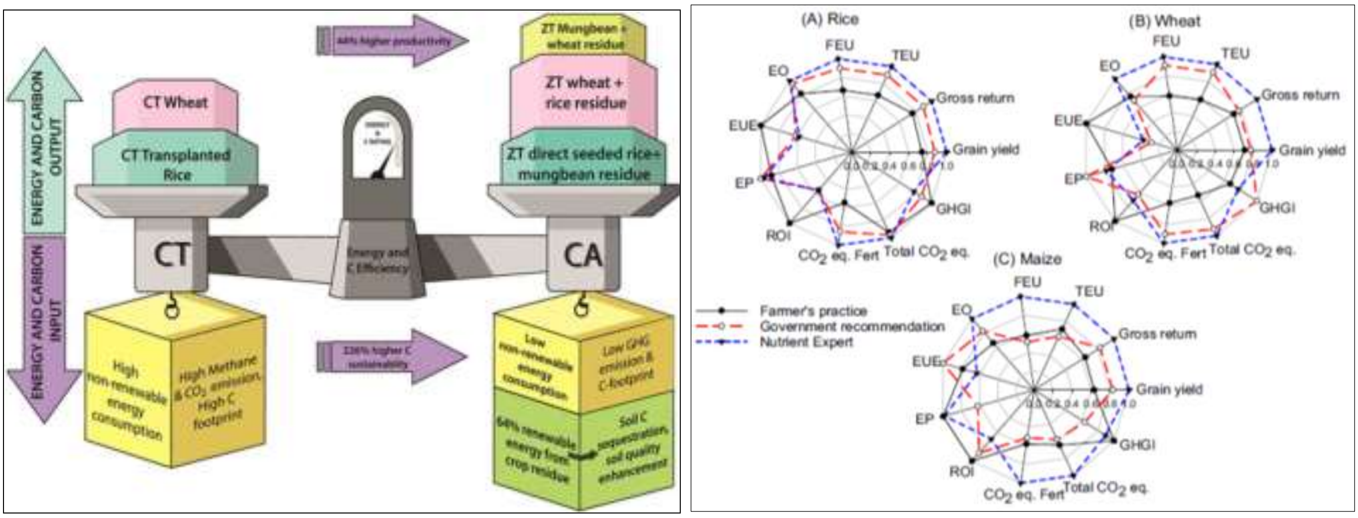

**Fig 2 a, b:** Multi-criteria assessment with various economic, energy, and environmental indicators across three nutrient management practices for the smallholders in the EIGP of Nepal. TEU = Total energy use (MJ $ha^{-1}$); EU = Fertilizer energy use (MJ $ha^{-1}$); EO = Energy output (MJ $ha^{-1}$); EUE = Energy-use efficiency; EP = Energy productivity (kg $MJ^{-1}$); $CO_2$ eq. Fert. = $CO_2$ equivalent emission from fertilizer applied (kg $ha^{-1}$); Total $CO_2$ eq. = Total $CO_2$ equivalent emission (kg $ha^{-1}$); GHGI = Greenhouse gas emission intensity [Source: Timsina *et al.*, 2022] [45]

Meena *et al*. (2022) [27] also found that the mean total energy requirement or energy footprint ($E_I$) was the highest for the conventional$R_0$ rotation (65,470 MJ $ha^{-1}$) and the lowest for the $R_2$ (40,327 MJ $ha^{-1}$) (Fig.3a). The $E_I$ of most productive and profitable diversified crop rotations $R_4$ and $R_1$ were 5.2% and 16.8% lower than the conventional cereal-based $R_0$ rotation, respectively. The $R_1$ rotation (54,499 MJ $ha^{-1}$) required lower energy than that of the $R_4$ rotation (62,080 MJ $ha^{-1}$). Among different energy sources, indirect non-renewable energy contributed maximum to the total energy requirements of all crop rotations, ranging from 48.6% in the diversified$R_4$ rotation to 59.3% in the conventional $R_0$ rotation.

The input-wise energy requirement analysis showed that fertilizer and irrigation water (data spread over a range of 15,936 MJ $ha^{-1}$ and 5967 MJ $ha^{-1}$, respectively) were the top two factors responsible for creating variability in total energy requirements across crop rotations (Fig.3b). The share of fertilizer, diesel, labor, irrigation, machinery, seed, herbicide, and insecticides in total energy requirements was 28.4–42.7%, 19–26%, 9.7–13.9%, 10.2–16.3%, 7–10%,1.9–7.5%, 3–5.4%, and 0.7–1.4%, respectively. Among, input-wise energy requirements, the energy requirement for fertilizer was the highest, ranging from 12,050 MJ $ha^{-1}$in $R_8$ to 27,986 MJ $ha^{-1}$ in $R_0$ across crop rotations. The diversified crop rotations $R_4$ and $R_1$ required 29.6% and30.7% lower fertilizer energy than that of the conventional $R_0$ rotation. The energy requirement for irrigation water ranged from 4131 MJ $ha^{-1}$ in $R_2$ to 10,098 MJ $ha^{-1}$ in$R_4$ rotation. The diversified $R_4$ rotation required a 37.5%higher irrigation water energy requirement than that of the cereal-based $R_0$rotation. Thetotalenergy requirement of $R_1$ was 12.2% lower than that of the $R_4$ rotation, mainly due to 36.3% lower irrigation energy requirement in the former than the latter. The variability in energy relations of studied crop rotations was due to the variability in energy utilization patterns and system productivity.

Yadav *et al.* (2017) [51] also reported that among various inputs, fertilizer consumed the highest energy input (44–54%) indifferent rice-based cropping systems. As all the diversified crop rotations included legumes in the cropping sequence, the fertilizer requirements in these rotations were lower than the cereal-based $R_0$ rotation. The fertilizer energy requirement of traditional cereal-based crop rotation $R_0$ was 2.32 times higher than that of the triple legume-based crop rotation $R_8$.

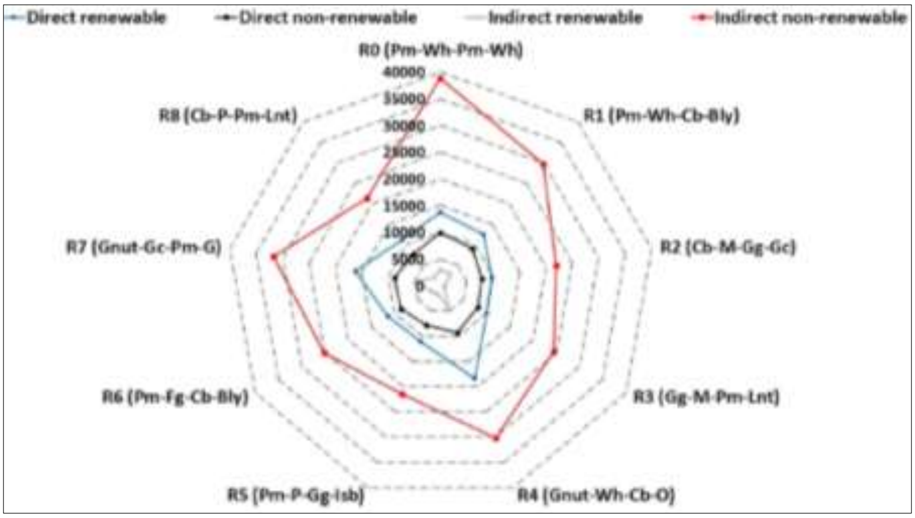

**Fig 3a:** Source-wise energy requirements (MJ ha$^{-1}$) under different crop rotations [Source: Meena *et al.*, 2022] [27]

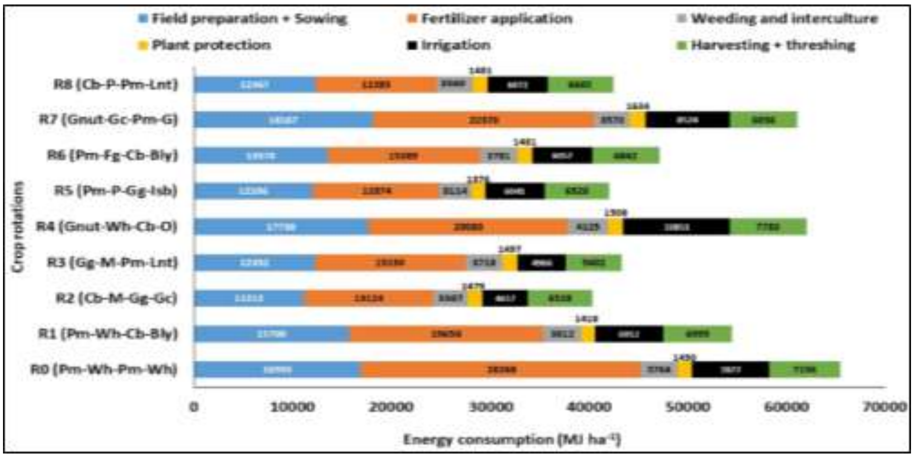

**Fig 3b:** Input-wise energy requirement (MJ ha$^{-1}$) under different crop rotations [Source: Meena *et al.*, 2022] [27]

## Source and operation-wise energy utilization pattern

The direct energy inputs to agriculture are in the form of gasoline, diesel fuel, electricity, and space heating fuels, including natural gas where available and are used in the production of crops and animals. Direct fuel use in farm production can be as high as 50 percent of total farm energy use. Keeping in view current energy crisis, studies on energy dynamics and energy use efficiency in agricultural production systems also assume great importance to identify promising production systems which have less dependency on non-renewable energy sources. Naresh *et al.* (2018) [23] revealed that the energy use in different tillage crop residue practices revealed that $T_7$ CT utilized highest energy (28.9 GJ ha$^{-1}$) followed by $T_4$ FIRB without residue retention (26.4 GJ ha$^{-1}$), $T_5$ FIRB with 4 tha$^{-1}$ residues retained and $T_6$ FIRB with 6 tha$^{-1}$residue retained, respectively. $T_7$ CT practices used highest energy input because rice consumes higher energy with respect to puddling, nursery rising as well as human labour for transplanting and thrashing operations in rice; besides more energy input in tillage operations in wheat. $T_4$ also consumed more energy owing to regular spraying of weedicides in rice crop being prone to weed infestation besides relatively frequent irrigation requirements in rice and wheat (Naresh *et al.*, 2015) [28] $T_1$ ZT without residue retained and $T_2$ ZT with 4 tha$^{-1}$residueretained tillage practices also produced higher energy equivalents which resulted in greater net energy returns quite close to $T_3$ ZT with 6 tha$^{-1}$ residue retained practice was primarily due to higher yield of this system. The energy use efficiency was highest in $T_3$ (7.42) followed by $T_2$ (7.12), $T_1$ (7.08), $T_6$ (7.04) and least in $T_7$ (6.15). Due to lesser energy input and higher output T3 had 20% and 5% higher energy use efficiency than $T_7$ and $T_6$. Based upon the energy output and energy input use under different tillage methods in rice-wheat cropping system, $T_3$ had energy gains of 8%, 7%, 4% and 2% than $T_7$, $T_4$, $T_5$and $T_6$, respectively.

Jat *et al.* (2019) [17] observed that irrespective of residue retention the mean total energy of 82,988 and 79,551 MJ/ha was used in the MMuMb and MWMb rotations, respectively. Largely, crop residues contributed highest energy input 68.4 and 61.5% in MMuMb and MWMb cropping system, respectively. Next to it, the major energy demanding operation is fertilizer application, it accounts for about 17.2% of total energy in MMuMb and 20.0% in MWMb.

Parihar *et al.*, (2018) [33] reported that tillage practices residue plus fertilizer application consumed major (76-81%) input energy, of which residue application consumed about 43.7-49.8% and fertilizer application consumed about 31.2-32.4%. CA based (ZT and PB) planted cereal crop consumed 3-5% less energy, compare to conventionally tilled. However, fertilizer use was the second most important energy contributor with 29-36% share in total input energy, and rest all other operations consumed about 17- 22% of input energy.

Yuan *et al.* (2022) [54] indirect and nonrenewable energy was higher than direct and renewable energy, respectively. On average, the share of indirect energy to total energy consumption was 63.2% and 69.7% in TPR and DSR, respectively. The 17.9% of total energy input in rice production was renewable, while the contribution of nonrenewable energy was 82.1%. Aghaalikhani *et al.* (2013) [66] further indicated that rice production was heavily based on nonrenewable energy. It has to be noted that renewable and nonrenewable energy forms in DSR declined by 19.9% and 29.2% compared with TPR, respectively. It's clearly suggested that DSR can effectively reduce energy consumption, especially for energy from nonrenewable form. However, differences in grain and straw yields were observed between the two cultivation systems and, thus, resulted in different energy outputs (Fig.4a). Total energy outputs for TPR vs. DSR were 181.3 vs. 201.6 GJ ha$^{-1}$ during early-growing season and 194.0 vs. 203.4 GJ ha$^{-1}$ during late-growing season, respectively (Fig.4b). More importantly, this further indicated that DSR is an alternative system to reduce energy consumption while meeting food demand amid energy crisis worldwide. Average EPB was 7.87 in DSR, which was 58.0%higher than TPR. By contrast, average SE exhibited the reverse trend, with TPR showing 44.6% higher SE than DSR. This finding indicated that 1 Mg of rice grain produced by DSR could save 1.2GJ of energy expenditure as compared with TPR.

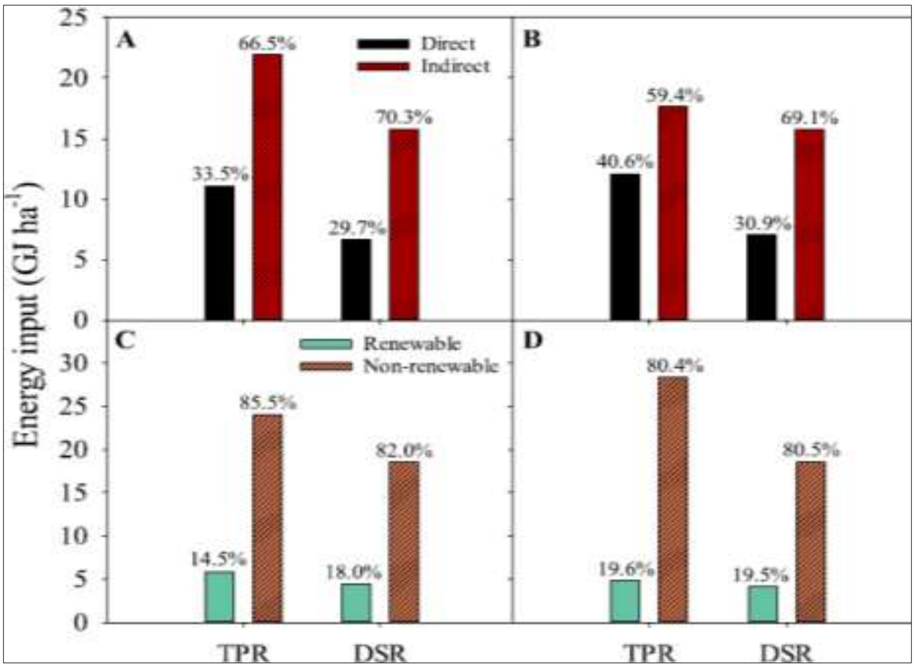

**Fig 4a:** Direct and indirect energy input (A and B, GJ ha$^{-1}$) and renewable and non-renewable energy input (C and D, GJ ha$^{-1}$) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- (A and C) and late-growing seasons (B and D) [Source: Yuan *et al.*, 2022] [54]

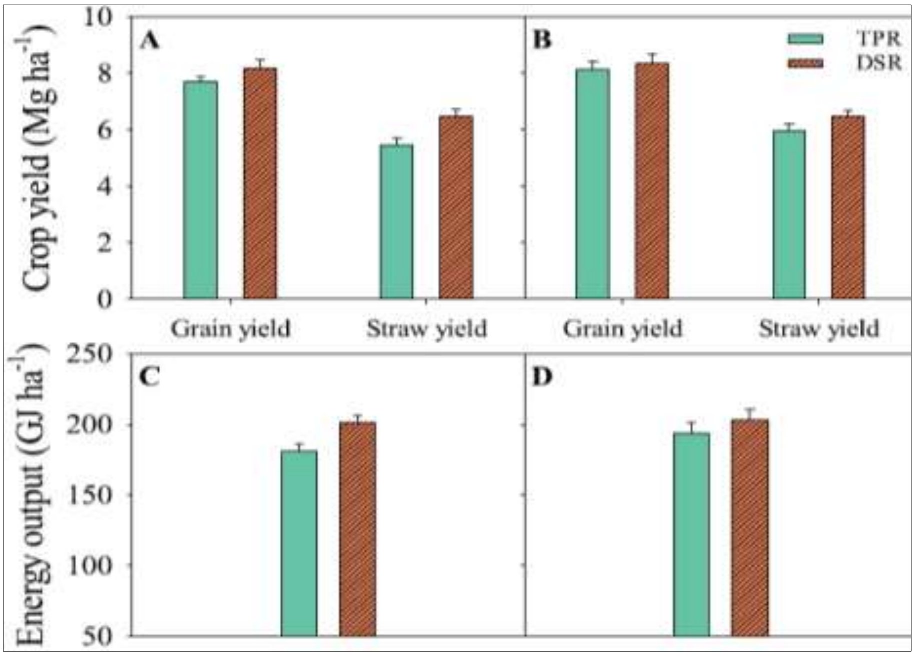

**Fig 4b:** Rice grain and straw yield (A and B, Mg ha$^{-1}$) and energy output (C and D, GJ ha$^{-1}$) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- (A and C) and late-growing seasons (B and D) [Source: Yuan *et al.*, 2022] [54]

Soni *et al.* (2018) [43] observed that the PW system was more energy efficient with Energy Use Efficiency (EUE) of 6.87}1.7 compared to 3.61}0.58 for the PP system. Higher Energy Efficiency Ratio (EERM) (3.94}1.30) and Specific Energy (4.39} 2.06) (SE) were reported for the PW system, compared to 2.62} 0.47 and 2.15} 0.35 respectively for the PP system. Fertilizer use accounted for the highest input energy consumption in both systems, accounting for 58% and 51% of the energy consumed in PW and PP systems respectively, followed by fuel, seeds and electricity. The output energy in the PP system (236.95} 22.66 GJ. ha$^{-1}$) was lower than that of the PW system (250.89} 40.13 GJ. ha$^{-1}$). For the input energy, the trend was reversed, with the PW system consuming less input energy than the PP system. The higher output energy in the case of the PW system can be attributed to the different forms of the yield compared to the PP system. The PW system contributed same amount of energy from straw and grains on average, which was not the case in the PP system.

PW and PP systems had comparable contributions in terms of direct and non-renewable energy, but the PP system used more renewable and indirect energy. Direct energy contributed 30.81% and 24.84%of the total energy input in the PW and PP cropping systems, respectively. Renewable energy use was higher in PP systems, with a contribution of 21.66% compared to 9.59% in the PW system. The higher renewable energy input in the PP system can be explained by the higher human and animal energy input in the system. Figs. 5a and 5billustrate the share of direct and indirect energy inputs and the output energy in the two systems.

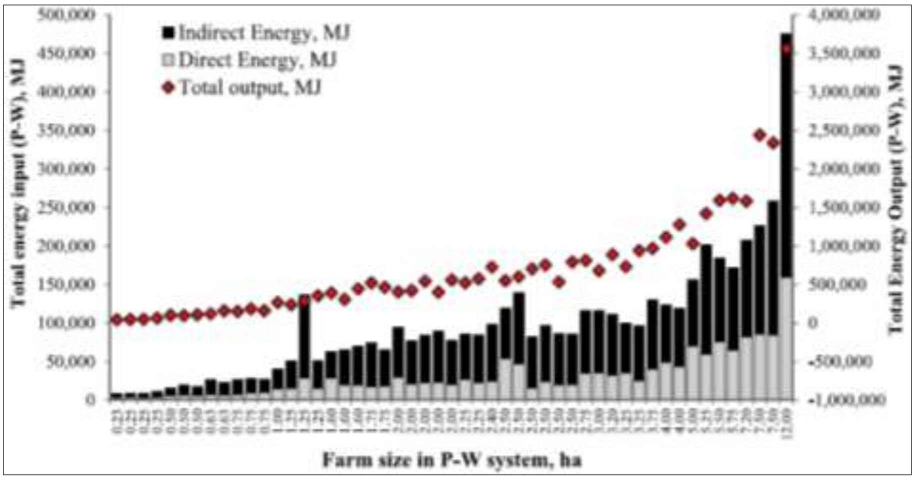

**Fig 5a:** Share of direct and indirect energy sources to total input energy, and output energy of Paddy–Wheat system [Source: Soni *et al.*, 2018] [43]

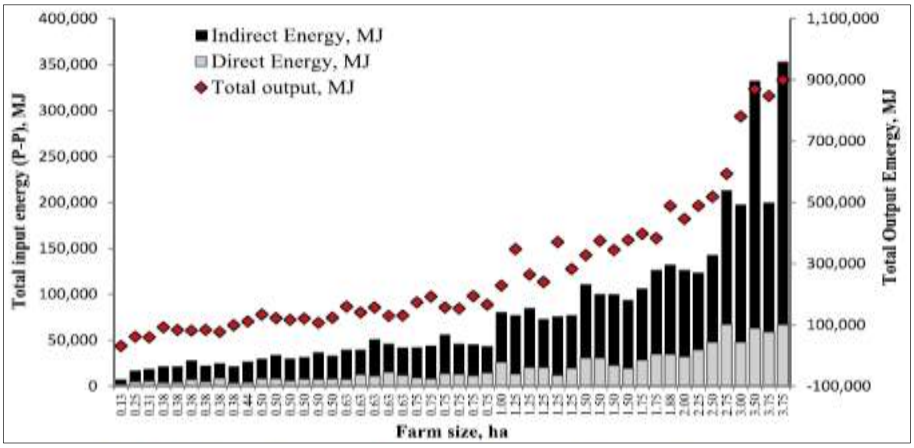

**Fig 5b:** Share of direct and indirect energy sources to total input energy, and output energy of Paddy–potato system [Source: Soni *et al.*, 2018] [43]

Jat *et al.* (2020) also found that CA systems, crop residues contributed the maximum (~76%) in total energy input (167,995 MJ ha$^{-1}$); however, fertilizer application (nonrenewable energy source) contributed the maximum (43%) in total energy input (47,760 MJ ha$^{-1}$) in CT-based systems. CA-based cereal (rice/maize) systems recorded higher net energy and energy-intensiveness (EI) levels of 251% and 300%, respectively, compared with those of the CT-based rice–wheat system (RW/CT) (295,217 MJ ha$^{-1}$ and 46.05 MJ USD$^{-1}$), irrespective of mung bean integration. MWMb/ZT+R utilized 204% more input energy, which resulted in 14% higher net energy and 229% higher EI compared with RW/CT. CA-based RW and MW systems enhanced the crop productivity by 10 and 16%, water productivity by 56 and 33%, and profitability by 34 and 36%, while saving in irrigation water by 38 and 32%, compared with their respective CT-based systems, respectively.

Kakraliya *et al.* (2022) [19] revealed that 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. 6a). 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. 6a). 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.

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 (Fig 6b). 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. 6b). Business as usual (Sc1) consumed more energy because of it required more tillage operations in seedbed preparation (Chaudhary *et al*., 2009) [6]. 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. 7). 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. These findings are in support of many other researchers they revealed that diesel consumption (15–20 L ha$^{-1}$) can be reduced by minimizing numbers of tillage operations (Chaudhary *et al*., 2017; Naresh *et al*., 2021) [7, 31]. Gathala *et al.* (2016) [13] and Laik *et al.* (2015) [20] have also described that more tillage operations are the biggest energy consumer (~ 40% of the total energy) compared to best agronomic management practices.

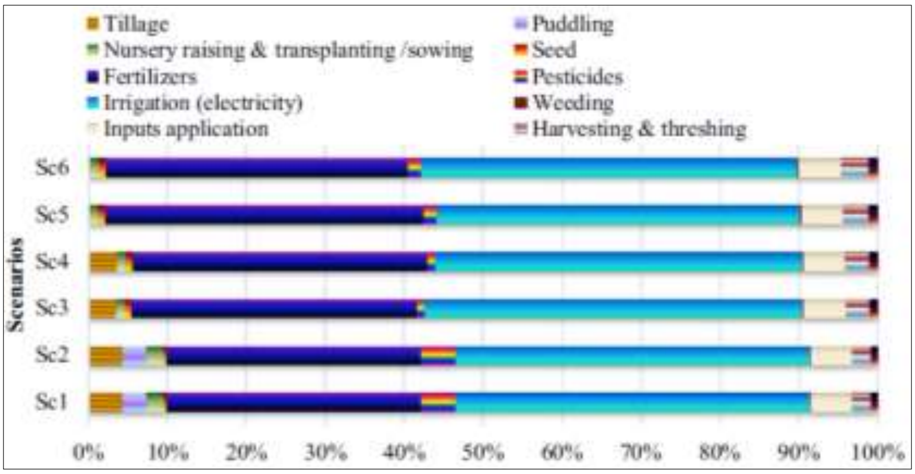

**Fig 6a:** Operation-wise input energy-use pattern (%) under different management practices in rice. Where; Sc1, business as usual-conventional tillage (CT) without residue; Sc2, CT with residue; Sc3, reduce tillage (RT)with residue + recommended dose of fertilizer (RDF); Sc4, RT/Zero tillage (ZT) with residue + RDF; Sc5, ZT with residue + RDF + Green Seeker + Tensiometer; Sc6, Sc5 + Nutrient expert [Source: Kakraliya *et al.*, 2022] [19]

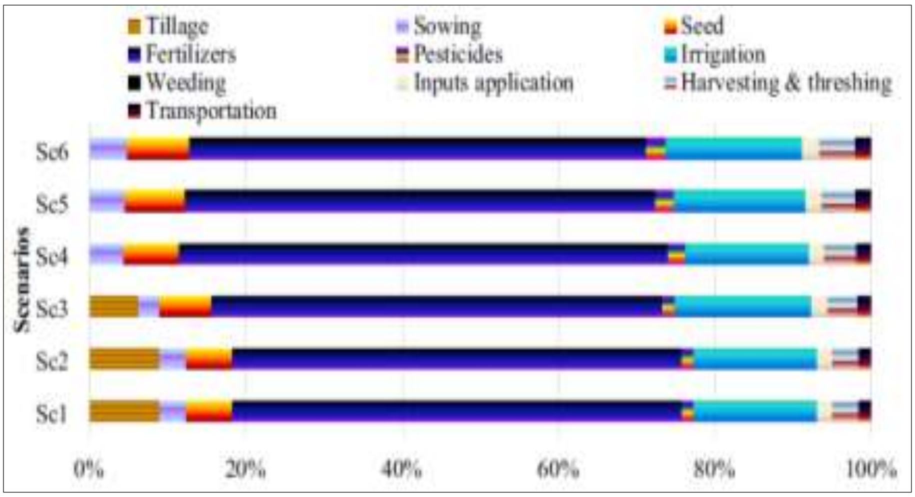

**Fig 6b:** Operation-wise input energy-use pattern (%) under different management practices in wheat [Source: Kakraliya *et al.*, 2022] [19]

## Carbon Footprint and Use Efficiency

The ecological sustainability of agricultural production systems mainly depends on their CF. The CO$_2$e emission varied significantly among the cropping system. In a study, it was observed that more than 50% of the total CF from crop production resulted from Ninputs (Hillier *et al*., 2009) [15]. It can be inferred that the cropping system intensification increased the CF in spatial scale (GWPs/CFs) over the M–F system as the intensified systems needed more production inputs and energy consumption. The strong correlation between energy input and GWP was reported by (Yadav *et al*., 2018) [52]. This was due to differences in input and management practices adopted, as CF and energy input were positively related to each other (Zhang *et al.*, 2016) [55]. An increase in the number of crops in crop rotation significantly increased the CF over M-F rotation (Plaza-Bonilla *et al.*, 2018) [34]. Prechsl *et al.* (2017) [36] also reported slightly higher GWP due to higher energy demand in intensified cropping systems compared to crop fallow systems. Intensified systems had 31.8 to 69.1% higher CF in spatial scale, but, up to 80% less CF in yield scale.

A carbon footprint is the total amount of greenhouse gases (including carbon dioxide and methane) that are generated by our actions. The average carbon footprint for a person in the United States is 16 tons, one of the highest rates in the world. Globally, the average carbon footprint is closer to 4 tons. To have the best chance of avoiding a 2 ℃ rise in global temperatures, the average global carbon footprint per year needs to drop to under 2 tons by 2050. A carbon footprint corresponds to the whole amount of greenhouse gases (GHG) produced to, directly and indirectly; support a person's lifestyle and activities. Carbon footprints are usually measured in equivalent tons of $CO_2$, during the period of a year, and they can be associated with an individual, an organization, a product or an event, among others.

The GHGs whose sum results in a carbon footprint can come from the production and consumption of fossil fuels, food, manufactured goods, materials, roads or transportation. And despite its importance, carbon footprints are difficult to calculate exactly due to poor knowledge and short data regarding the complex interactions between contributing processes – including the influence of natural processes that store or release carbon dioxide.

Gan *et al.* (2014) [12] observed that carbon footprint value represents the balance between carbon emissions and carbon sequestration. Averaged over the 25-year study period, the annual greenhouse gas emissions averaged 357 kg $CO_2$ eq ha$^{-1}$ in dry years, 577 in normal years and 687 in wet years. The emissions included those from crop residue decomposition, applied inorganic N and phosphorus fertilizers, N leaching losses, application of pesticides, fuel used in various farming operations and fossil energy used during the manufacture, transportation, storage and delivery of these crop inputs to the farm gate. However, these emissions were more than offset by the greater carbon conversion of wheat plants from atmospheric $CO_2$ into plant biomass and ultimately sequestered into the soil. On average, annual soil carbon gain was 877±15 kg $CO_2$ eq ha$^{-1}$ in normal years and 961±14 in wet years, which were 69% and 85% more, respectively, than the soil carbon gain obtained in dry years.

Liu *et al.* (2016) [23, 24] also found that the wheat in the continuous wheat system produced the highest grain yield and gained highest soil organic carbon over the years, leading to the smallest footprint value at−0.441 kg $CO_2$eq kg$^{-1}$ of grain, significantly lower than the footprint for the other three systems which ranged between−0.102 to −0.116 kg $CO_2$eq kg$^{-1}$of grain.

Zhang *et al.* (2017) [56] observed that the carbon footprint (emission minus soil carbon sequestration), we found that the three crops emitted more carbon than they sequestered. Of the three main crops in 2013, maize had the lowest carbon footprint, i.e., 4052 kg ce/ha of carbon per unit area or 0.48 kg ce/kg per unit yield. The carbon footprint of wheat was 5455 kg ce/ha per unit area or 0.75 kg ce/kg per unit yield, while rice had the highest carbon footprint, i.e., 11881 kg ce/ha per unit area or 1.60 kg ce/kg per unit yield. The factors contributing to these emissions varied markedly between crops. Rice yielded the greatest emissions (maximum: 15679 kg ce/ha) with 45% consisting of $CH_4$ derived from paddy fields, 21% from straw burning, 14% from nitrogen fertilizer, 13% from fossil fuels for agricultural machinery and 4% from electricity consumption for irrigation. Wheat exhibited a high carbon emission value of 9119 kg ce/ha, of which 37% came from electricity consumption for irrigation, 28% from nitrogen fertilizers, 25% from fuel consumption by agricultural machinery and 6% from straw burning. Maize emitted 7900 kg ce/ha with 39% coming from nitrogen fertilizer, 20% from fuel consumption by agricultural machinery, 18% from electricity consumption for irrigation and 18% from straw burning. However, the carbon footprint of maize production varied substantially among the eight regions in China, ranging from 1192 kg ce/ha to 9282 kg ce/ha (the carbon footprint per unit yield ranged from 0.25 kg ce/kg to 0.73 kg ce/kg so that the regions could be divided into four groups.

Mandal *et al.* (2021) [25] observed that he carbon footprint (CF) for the rice-rice system was higher than that for rice-cotton system. Without considering soil C sequestration, the CF under ZT, RT and CT were 0.96, 0.99 and 1.37 kg $CO_2$-eq kg$^{-1}$ yr$^{-1}$, respectively in rice-rice and 0.89, 0.80 and 1.27 kg $CO_2$-eq kg$^{-1}$ yr$^{-1}$, respectively in rice-cotton system. When SOC sequestration was included, the CF under ZT, RT and CT were 0.80, 0.81 and 1.19 kg $CO_2$-eq kg$^{-1}$ yr$^{-1}$ respectively for rice-rice system compared with 0.84, 0.67 and 1.15 kg $CO_2$-eq kg$^{-1}$ yr$^{-1}$for rice-cotton system. Overall RT had the lowest CF in rice-based cropping system. The contribution to CF for both rice-rice and rice-cotton were in the following order: $N_2O$ and $CH_4$ emission >agricultural inputs >SOC sequestration for all treatments. Irrespective of the cropping system, the CF was in the order: RT >ZT >CT.

Tiwari *et al.* (2022) [46] reported that the GHGs emission from chemical fertilizers and irrigation accounted for >80% of that from agricultural inputs during the entire growing season. Integrating improved farming practices lowers wheat carbon footprint effectively, averaging 256 kg $CO_2$ eq ha$^{-1}$ yr$^{-1}$. For each kg of wheat grain produced, a net 0.027–0.377 kg $CO_2$ eq is sequestered into the soil. With the suite of improved farming practices, wheat takes up more $CO_2$ from the atmosphere than is actually emitted during its production. Global warming potential (GWP), GHG emission due to consumption energy and greenhouse gas intensity were recorded lower by 43%, 56% and 59% in Climate Smart Agriculture (CSA) with high adaptive measures than farmers practices (3652.7 kg $CO_2$ eq. ha$^{-1}$ yr$^{-1}$, 722.2 kg $CO_2$ eq. ha$^{-1}$ yr$^{-1}$ and 718.7 Mg kg$^{-1}$ $CO_2$ eq. ha$^{-1}$ yr$^{-1}$).

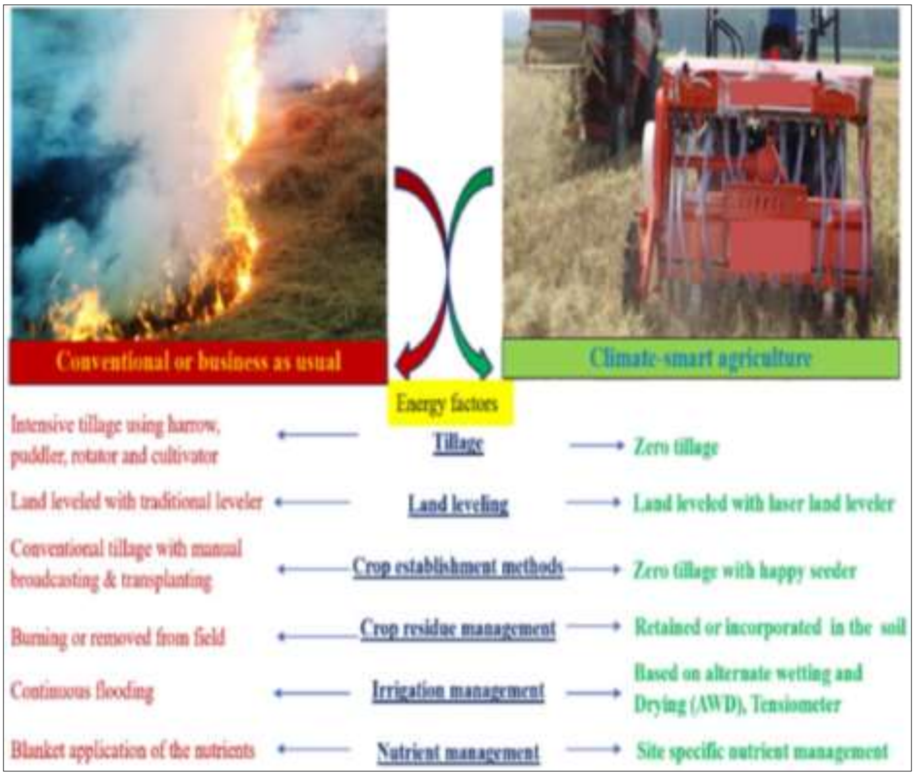

**Fig 7:** Energy sources of RW production under conventional management practice and climate-smar t agricultural practices [Source: Kakraliya *et al.*, 2022] [19]

## Global Warming Potential (GWP)

Global warming potentials (GWPs) are values that allow direct comparison of the impact of different greenhouse gases in the atmosphere by comparing how much energy one tons of a gas will absorb compared to one tons of carbon dioxide. For example, if methane has a global warming potential of 21, it means that 1 kg of methane has the same impact on climate change as 21 kg of carbon dioxide and thus 1 kg of methane would count as 21 kg of carbon dioxide equivalent. A positive GHGI indicates a net source while a negative GHGI indicates a net sink of GHGs in the soil. In this study, the highest GHGI was found in rice followed by wheat and maize. Higher GHGI in rice was mostly attributed to puddling and flood water adopted as the predominant water management practice in rice. $CO_2$-eq. emissions from fertilizers were higher in maize than in rice or wheat due to higher fertilizer rates and other agrochemicals, and irrigation water, which was mostly attributed to higher fertilizer application in NE than in FP. However, variability of $CO_2$ eq. emission was higher in FP compared to NE.

Robertson *et al.* (2000) [37] compared the net global warming potential (GWP) of conventional tillage, no-till, low input and organic management of a corn soybean-wheat system over 8 yrs. After converting the combined effects of measured $N_2O$ production, $CH_4$ oxidation and C sequestration, plus the $CO_2$ costs of agronomic inputs to $CO_2$ equivalents (g $CO_2$ $m^{-2}$ $yr^{-1}$) none of the systems provided net mitigation, and $N_2O$ production was the single greatest source of GWP. The no-till system had the lowest GWP (14), followed by organic (41), low input (63) and conventional (114).

Cavigelli *et al.* (2009) [4] also calculated was the greenhouse gas intensity (GHGI = GWP per unit of grain yield). The contribution of energy use to GWP was 807, 862, and 344 in NT, CT, and Org3, respectively. The contribution of $N_2O$ flux to GWP was 303, 406, and 540 kg $CO_2$e $ha^{-1}$ $yr^{-1}$ in NT, CT and Org3, respectively. The contribution of change in soil C to GWP was 0, 1080, and −1953 kg $CO_2$e $ha^{-1}$ $yr^{-1}$ in NT, CT and Org3, respectively. GWP (kg $CO_2$e $ha^{-1}$ $yr^{-1}$) was positive in NT (1110) and CT (2348) and negative in Org3 (−1069), primarily due to differences in soil C and secondarily to differences in energy use among systems. Despite relatively low crop yields in Org3, GHGI (kg $CO_2$e Mg $grain^{-1}$) for Org3 was also negative (−207) and significantly lower than for NT (330) and CT (153). Org3 was thus a net sink, while NT and CT were net sources of $CO_2$e.

Lenka *et al.* (2022) [21] also found that tillage, integrated nutrient management ($T_2$ and $T_3$) lowered NGWP and GHGI compared to NPK ($T_1$). The GHGI of NT system was less by 33% compared to RT. The results suggest that GHGs mitigation and sustained food production in the soybean-wheat system can be achieved in NT and RT with integrated use of organic and inorganic fertilizer as the major component of nutrient management.

Naresh *et al.* (2021) [31] reported that over six years, the $T_9$ cropping system (spring-sown sugarcane with PLL) had the lowest greenhouse gas emissions (0.24 kg CO2 eq $ha^{-1}yr^{-1}$), while the $T_{12}$ cropping system (late sown spring sugarcane under TLL) had the highest greenhouse gas emissions (0.97 kg $CO_2$ eq $ha^{-1}yr^{-1}$). The total $CO_2$-equivalent emissions were lower in cropping systems which included potato, as relatively more potassium fertilizer than nitrogen fertilizer was applied in these systems: excess or poorly timed nitrogen fertilizer is a key source of agricultural greenhouse gas emissions (Chai *et al*., 2019) [5]. Crop residues increased SOC, soil health and thereby reduce the green-house emissions in the top 20-cm soil layer. Further higher SOC stocks offset the input-induced greenhouse gas emissions. Under TLL, farmers till the field at least thrice and plank it once, which results in approximately 4.5 h' per hectare tractor usage to sow two crops each year. Under PLL, the tractor time required to sow each crop is reduced by 2.25 h’ per hectare, which saves approximately 19,536 MT $CO_2$ emissions per annum across western Uttar Pradesh.

Timsina *et al.* (2022) [45] observed that the $CO_2$ eq. emissions were variable across the nutrient management options in each crop. Comparing across the treatments, GHGI in rice ranged from 754 to 2201 kg $CO_2$ eq. emission $t^{-1}$ of grain produced, with 870 to 1822, 754 to 1475, and 916 to 2201 respectively for GR, NE, and FP. At all probability levels, FP had consistently the highest while NE had the lowest GHGI. The patterns were different for wheat and maize than for rice. GHGI in wheat ranged from 199 to 1172 kg $CO_2$ eq. emission $t^{-1}$of grain produced in GR, from 191 to 839 in NE, and from 129 to 1085 in FP. GR had consistently the highest while FP (80% cases) had the lowest GHGI. In maize, GHGI ranged from 62 to 166 kg $CO_2$ eq. emission $t^{-1}$ of grain produced in GR, 75 to 232 in NE, and 43 to 396 in FP. In about 80% cases, FP had higher GHGI than NE and in most cases; GR had lower GHGI than the other two treatments. These results indicate that NE-based management in rice can clearly result in lower GHGs $t^{-1}$of grain produced compared to GR or FP. Gathala *et al.* (2020) [13] reported mean $CO_2$-eq. emissions (t $CO_2$ eq-emissions $ha^{-1}$) of 0.65, 0.76 and 1.06 in rice, wheat, and maize in eight districts of the EIGP varying in soil, climate and farmers’ management practices. The $CO_2$-eq. emissions (kg $CO_2$ eq. emissions $t^{-1}$ grain produced) in rice ranged from 754 to 2201, in wheat from 129 to 1172, and in maize from 43 to 396.

Jat *et al.* (2021) [18] reported that the total GHG emission in terms of GWP along with GHG intensity of maize, wheat, and MW system considerably varied between the different methods of tillage and also with the diverse nutrient management approaches in both the years (Fig.8). In maize, the highest total GHG emission (758.54 kg $CO_2$ eq. $ha^{-1}$) was recorded under the farmer’s fertilizer management practices {FFP-broadcast (CT)} and lowest (-911.24 kg $CO_2$ eq. $ha^{-1}$) under Nutrient Expert with drilling {NE-drilling (PB)}) of fertilizer application. Similarly, the highest emission intensity was also recorded under FFP-broadcast (CT) (180.29 kg $CO_2$-eq $Mg^{-1}$ maize) and lowest with NE-broadcast (PB) (−159.35 kg $CO_2$-eq $Mg^{-1}$ maize) and NE-drilling (PB) (−153.98 kg $CO_2$-eq $Mg^{-1}$ maize). In wheat, highest total GHG emission ($CO_2$ eq. $ha^{-1}$) and emission intensity (kg $CO_2$-eq $Mg^{-1}$ wheat) was recorded under FFP-broadcast (CT)(908.63 kg $CO_2$ eq. $ha^{-1}$ and 197.65 kg $CO_2$-eq $Mg^{-1}$ wheat) and lowest under NE-drilling(PB) (127.02 kg $CO_2$ eq. $ha^{-1}$ and 22.51 kg $CO_2$-eq $Mg^{-1}$ wheat). Similar trends were observed in total GHG emission as well as emission intensity at the MW system level (Fig.8). The linear contrast (Broadcast vs. Drilling, FFP vs. SSNM, FFP-broadcast (B) vs.SR-broadcast, FFP-B vs. SR-drilling, FFP-B vs. SR+GS-drilling, FFP-B vs. NE-broad cast, FFP-B vs. NE-drilling, FFP-B vs. NE+GS-drilling) showed significant influence of GWP by various management practices. Fertilizer-induced field emission, emission from fertilizer production, transportation, and other management-related emissions were not different among the treatments. The negative GWP under PB systems was mainly due to carbon sequestration resulting from residue retention in the PB system whereas that was not the case in the CT system. Lower GWP was seen under NT with NE and SR nutrient management strategies with drilling method fertilizer application caused in maximum sequestration of $CO_2$ compared to the CT farmer’s fertilizer method. CT system with the broadcasting of fertilizer (FP) application methods contributed the highest $CO_2$ emission per Mg of maize and wheat yield coupled with lower yield as compared to other nutrient management strategies. Lower total GWP combined with higher yield in PB systems than in CT systems resulted in lower emission intensity in the PB system than in the CT system.

In PB planting technology, the emission of $CO_2$ per Mg of maize and wheat yield is found lower compared to NE and SR-based drilling, which might be due to increased yield with these nutrient application methods compared to broadcast application of N which is prone to more losses. Drilling of fertilizer N confirmed improved use and uptake of nutrients by the crops and thereby reducing the losses. Highest GWP was recorded in farmers’ fertilizer application methods than other nutrient application methods showing the importance of efficient management of nutrients not only to increase crops yield but also to shrink in the global warming potential of the maize-wheat system. The higher quantity of K fertilizer used in NE-based system probably helps to increase the uptake of other nutrients by crops, thereby producing more yields which are results in lower emission intensity compared to other nutrient management strategy. Sapkota *et al.* (2014) [38] also reported that precision application of nutrients based on Nutrient Expert tools increased crop productivity, profitability, and fertilizer-use and nutrient-use efficacy, while reducing GHG emission as compared to state recommendation and farmers’ fertilization practice in NW India.

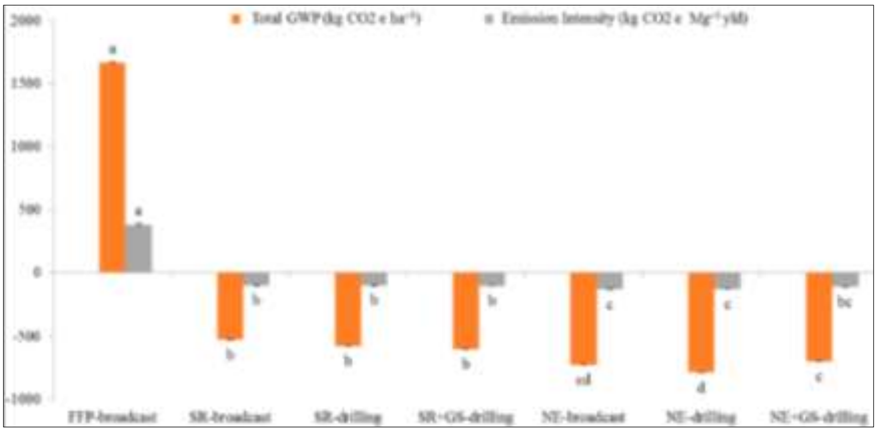

**Fig 8:** Global warming potential (GWP) and greenhouse gases intensity (GHGI) of maize-wheat system under different fertilizer management strategies [Source: Jat *et al.*, 2021] [18]

Bijarniya *et al.* (2020) [3] indicated that global warming potential (GWP) and $CO_2$ emission intensity of RW system was significantly influenced by divergent crop management practices. Among 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. On 3-years mean basis, 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.

Yuan *et al*. (2022) [54] reported that on average, GWPi was 618 kg $CO_2$-eq$Mg^{-1}$ grain in DSR, which was slightly lower than that of 684 kg $CO_2$-eq$Mg^{-1}$grain in TPR (Fig. 10a). Lower GWPi in DSR was mainly due to decreased GWP as compared with TPR. They note that US$ 329 and 381 were obtained from 1 Mg of $CO_2$-eq emissions in early- and late-growing season under DSR, respectively, which was 81% and 52% higher than those observed under TPR (Fig. 10a). This finding implied that an average of around US$ 140 more was obtained from one Mg of $CO_2$-eq emissions in DSR than TPR. Clearly, DSR was an eco-efficient cultivation system. Eco-efficiency estimated in the study was higher than US$ 82-134 per Mg of $CO_2$-eq reported in northeastern Thailand due to lower yield and higher GWP in that study (Thanawong *et al.*, 2014) [44], but lower than an average of 720 US$ per ton of CO2-eq across various rice-based cropping systems in Ne pal (Pokhrel and Soni, 2017) [35]. Thus, reducing fertilizer and diesel consumptions through increasing N use efficiency and mechanical efficiency are critical for both transplanting and direct seeding rice. Overall, the results of environmental analysis indicated that DSR could be an important approach for reducing GWP from rice farming. Total energy outputs for TPR vs. DSR were 181.3 vs. 201.6 GJ $ha^{-1}$ during early-growing season and 194.0 vs. 203.4 GJ $ha^{-1}$ during late-growing season, respectively (Fig. 10b). Averaged over growing seasons, EP was362.1 kg $GJ^{-1}$ in DSR and 251.8 kg $GJ^{-1}$ in TPR, which suggested that substantially lower energy expenditure would be required to produce equal amounts of rice grain in DSR compared with TPR. More importantly, this further indicated that DSR is an alternative system to reduce energy consumption while meeting food demand amid energy crisis worldwide.

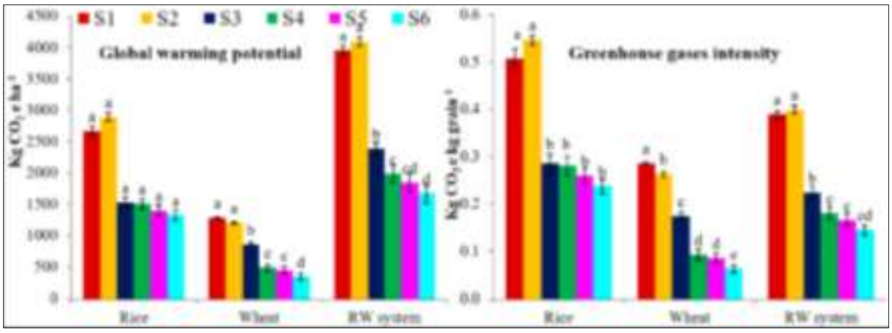

**Fig 9:** Mean annual global warming potential (GWP) and greenhouse gases intensity of rice-wheat system under divergent crop management scenarios. S1- Conventional tillage (CT) without residue; S2- CT with residue, S3- Reduced tillage (RT) with residue + Recommended dose of fertilizer (RDF); S4- RT/zero 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 [Source: Bijarniya *et al*., 2020] [3]

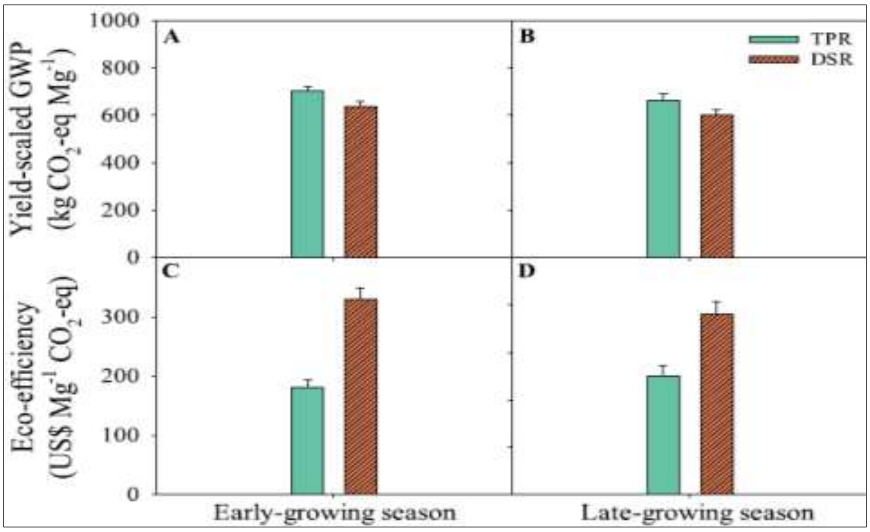

**Fig 10a:** Yield-scaled global warming potential (A and B, kg $CO_2$-eq$Mg^{-1}$ grain) and eco-efficiency (C and D, US$$Mg^{-1}$ $CO_2$-eq) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- (A and C) and late-growing seasons (B and D) [Source: Yuan *et al*., 2022] [54]

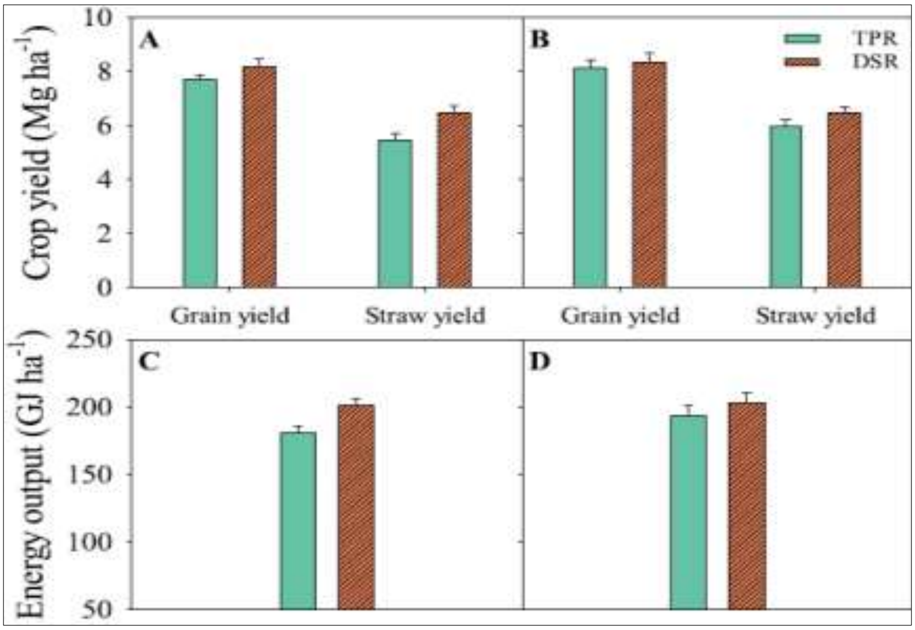

**Fig 10b:** Rice grain and straw yield (A and B, Mg ha$^{-1}$) and energy output (C and D, GJ ha$^{-1}$) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- (A and C) and late-growing seasons (B and D) [Source: Yuan *et al*., 2022] [54]

## Conclusions

The intensive agricultural production systems rely on fossil fuel burning for energy management and having a lion share in the energy input and GHGs emissions. The fossil fuel based $CO_2$ emissions are major contributors to energy input and GWP in agro-ecosystems. Hence, high water and fertilizer inputs as well as the operation of machinery for agricultural purposes not only induced soil $N_2O$ and $CH_4$ emissions but resulted in considerable consumption of energy from fossil fuels. Straw burning further increased the carbon emissions of these grain crops. The carbon balance can be an indicator of agricultural production efficiency, soil fertility and environmental pollution. So identifying the carbon footprint of a crop is an important component of sustainable agriculture. In aspects of carbon and energy efficiency the scope of diverse organic has immense importance, as it has the potential to replace a part of chemical fertilizer and then farming will be more dependent on renewable sources.

The PW system was more energy efficient with higher values of energy indicators in the system compared to the ones in the PP system. The EUE value for the PW system (6.87) was higher than that of the PP system (3.6). Similarly, the EERM and SE values were higher in the PW system. The total input energy for the PW and PP systems were 39.74 ± 17.23 GJ/ha and 65.82 ± 9.11 GJ. ha$^{-1}$, respectively. The net return for the PW and PP systems was 876.54 ± 273.17 USD ha$^{-1}$ yr$^{-1}$ and 1957.30 ± 240.84 USD ha$^{-1}$yr$^{-1}$, respectively. The total output energy was also higher in PW system (250.89GJ/ha) compared to the PP system (236.95 GJ ha$^{-1}$). The use of fuel as a source of energy was higher in the PW system (22.02%) compared to the PP system (15.37%), which was due to the higher use of renewable energy, which accounted for 9.59% and 21.66%, respectively, in the two systems. Fertilizer use accounted for the highest energy consumption with a total contribution of 58.13% and 51.06%, respectively, in the PW and PP systems. There was no use of animal power reported in the PW system.

The lowest input energy was reported in marginal farms and the highest in medium farms. It was also observed that smaller farms were more energy efficient compared to larger farms in terms of various energy indicators. The use of fertilizer was highest in the small farm category in the PW system while it was highest in the medium farm category for the PP system. The use of human power tended to decrease with the increase in farm size in the PW system, exhibiting increasing dependence on mechanized means of farming as farm size increased.

CA systems, crop residues contributed the maximum (~76%) in total energy input (167,995 MJ ha$^{-1}$); however, fertilizer application (nonrenewable energy source) contributed the maximum (43%) in total energy input (47,760 MJ ha$^{-1}$) in CT-based systems. CA-based cereal (rice/maize) systems recorded higher net energy and energy-intensiveness (EI) levels of 251% and 300%, respectively, compared with those of the CT-based rice–wheat system (RW/CT). There are huge gaps between the development of new cropping technologies and the implementation of the technologies in farming operations.

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