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Article

Assessment of Different Machinery Packages for Identification of Climate Smart Wheat Cultivation in Central India

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Abstract: Wheat (*Triticum aestivum*) is a major food grain crop cultivated in India (31.4 million hectares in 2022-2023). In view of rising concerns of emissions from agriculture, it was considered to assess the global warming potential (GWP) of various wheat cultivation practices being followed in central India. Wheat sowing by five different machines along with associated cultivation practices were evaluated and compared with traditional wheat cultivation with seed cum fertilizer drill. The five wheat cultivation machinery packages evaluated were i) Zero till seed cum fertilizer drill; ii) Zero till drill with straw handler; iii) Happy seeder; iv) Broad bed former seeder; and v) Rotary tiller assisted broad bed former seeder–over a period of three years from 2021-2022 to 2023-2024. The GWP was found minimum with Happy seeder at 555.0 kg CO2eq./ha, followed by Zero till drill with straw handler (648.3 kg CO_2 eq./ha) and Zero till drill (651.8 kg CO_2 eq./ha). Wheat cultivation with conventional Seed cum fertilizer drill had highest GWP of 775.4 kg CO_2 eq./ha due to higher fuel usage in the whole cultivation process. The grain yield was highest on wheat cultivation with Rotary tiller assisted broad bed former seeder(5401.3 kg/ha)and this cultivation practice also had minimum Greenhouse Gas(GHG) intensity of 0.126 kg CO_2 eq./kg of grain output. Wheat cultivation with Rotary tiller assisted broad bed former seeder was considered climate resilient due to its higher yield, lower GHG intensity, and maximum economic return (Rs.23,530 per hectare) over conventional method.

Keywords: carbon footprint; climate resilient technologies; conservation tillage; global warming potential; greenhouse gas emission

1. Introduction

Agricultural sector contributes significantly to global GHG emissions, especially in the Indo-Gangetic plains of South Asia that have predominant rice-wheat cropping systems (Tesfaye et al., 2019). The farming practices alone account for approximately 25–30% of GHG emissions (Czyżewski et al., 2018). Various methods and adaption strategies are given by Intergovernmental Panel on Climate Change (IPCC)for risk management with effective adaptation options including cultivar improvements, agroforestry, community-based adaptation, farm and landscape diversification, and urban agriculture (IPCC, 2023; Suman et al., 2025).

Environment friendly cultivation involves a combination of technologies and practices that aims to simultaneously boost farm productivity and profitability, increase resilience to climate change, and reduce GHG emission (Hussan et al., 2022; Khatri-Chhetriet al.,2017;Verma et al.,2023). Such conservation agriculture practices adopt reduced tillage, novel methods of crop establishment, proper management of irrigation, nutrient, crop residue and utilization of bio energy from crop (Branca et al., 2011; Jat et al., 2014; Sapkota et al., 2014, 2015; Uchida, et al.,2012; Choudhary and Behera, 2020;

Sawant et al., 2019). When the tillage intensity was decreased using different combination of tillage implements, there was significant saving in fuel consumption (Miah et al., 2023). Also when the depth of operation was reduced in ploughing or harrowing or no tillage cultivation was done, environmental saving is done due to reduction in CO_2 emissions (Naujokiene et al., 2018). Suitable tillage and sowing implement selected according to soil texture, soil and climatic conditions and type of arable crop reduced emissions (Lovarelli et al., 2017). The amount of carbon lost as CO_2 from soil tillage was closely linked to the extent and depth of soil disturbance (Reinsch, 2018; Abdelhafez et al., 2018).

Wheat is one of the major cereal crops grown in India with an area of 31.4 million hectare and production of 110.54 million tonnes giving productivity of 3521 kg/ha in 2022-2023 (Anon., 2024). Various kinds of machinery packages and practices are adopted for wheat cultivation in India. Majority of carbon emissions come from the use of fossil fuels during machinery operation (Patel et al., 2018; Zhang et al., 2017). Improving fuel efficiency can lower fuel consumption and CO2 emissions, thereby contributing to more environment friendly production (Habaibeh et al., 2025; Prinz et al., 2018). It is important to explore climate-smart practices and machinery to potentially reduce GHG emission while sustaining or enhancing crop yields (Kumar et al., 2013; Jat et al., 2022;Izzah et al., 2025). There existed a need to find out carbon footprint of different types of wheat cultivation practices for bringing out the technology that is beneficial in terms of climatic effects and returns both.

Five different methods of wheat cultivation were evaluated for climate resilience and these were compared to the wheat cultivation with conventional Seed cum fertilizer drill. These five methods of wheat cultivation were i) Zero till seed cum fertilizer drill; ii) Zero till drill with straw handler ; iii) Happy seeder; iv) Broad bed former seeder ; and v) Rotary tiller assisted broad bed former seeder. Application of climate smart agriculture is a good approach to reduce GHG emission and boost crop output for food security and climate change adaption (Barua and Mitra, 2023). GWP index defined how much a greenhouse gas contributed to global warming compared to carbon dioxide (Zhang et al., 2016; Pratibha et al., 2016). A higher GWP index meant the gas had a greater warming effect over a specific time period (Linquist et al., 2012). Carbon footprint indices were used to measure GHG emissions from agricultural activities for analysing the differences in GHG emissions from various crops and technologies (Wang et al., 2019;Soltani et al., 2013; Yousefi et al., 2014). In view of this, a study was taken with an aim to bring out the climate resilient wheat cultivation practice among the different practices being followed in central India. This work was conducted with an objective to evaluate farmer's cultivation practice and improved cultivation practices in respect of climate resilience. The novelty of this work lies in finding and recommending resilient wheat cultivation practice. The outcome of this work can be used by planners and policy makers to promote climate smart wheat cultivation through different government programs.

2. Materials and Methods

2.1. Different sowing machines and practices in wheat cultivation

Sowing machines and implements used in different practices in the farmers' field are shown in Table 1. Field preparation practices followed for sowing by a particular machine is shown in Table 2. It was observed in the farmer's field that all the field cultivation was done by the tractor operated machinery that uses fossil fuel for operation. Any other source of energy like solar pump, biofuel operated engines etc. were absent in the cultivation scenario of these farmers.

Table 1. Operational parameters of wheat sowing machines and implements used in farmer's field.

Machine/Implement	Working depth mm	Working width mm	Weight kg	Life h	Field capacity ha/h
Seed cum fertilizer drill (SFD)	30-50	2100	300	3000	0.47
Zero till drill (ZTD)	30-50	1980	300	3000	0.36
Zero till drill with straw handler (ZTD-SH)	30-50	1750	350	3000	0.35
Happy Seeder (HS)	35-50	2100	550	2400	0.35
Broad Bed Former(BBF) seeder	150-200	1600	300	3000	0.39
Rotary tiller assisted broad bed former(RTABBF) seeder	150-200	1600	550	3000	0.37
Mould board plough	300-400	750	350	3000	0.15
Cultivator	100-150	2000	220	3000	0.44
Rotavator	80-100	1650	500	4000	0.40
Power sprayer	--	3000	500	2000	0.63
Combined harvester	--	4850	7600	5000	0.86

Table 2. Tillage and irrigation practices associated with a sowing machine in wheat cultivation.

Sowing machine	Associated tillage practice			Irrigation height of water, mm x Number of times
	Mould board plough	Cultivator	Rotavator	
SFD	1 pass	2 pass	Nil	130 mm x 5
ZTD	Nil	Nil	Nil	120 mm x 4
ZTD-SH	Nil	Nil	Nil	120 mm x 4
HS	Nil	Nil	Nil	80 mm x 4
BBF	1 pass	1 pass	1 pass	100 mm, 4 (In furrows)
RTABBF	1 pass	1 pass	Nil	100 mm x 4 (In furrows)

Wheat sowing with SFD required field preparation of single pass of mould board plough+ two passes of cultivator. Sowing with BBF seeder required single pass of mould board plough+cultivator+rotavator. In sowing with RTABBF seeder, single pass of mould board plough+single pass of cultivator was required as this had an inbuilt rotavator in itself. No seed bed preparation was required in case of ZTD, ZTD-SH and HS, where seed was directly drilled in the field having straw load of previous crop. The seed rate for wheat was kept at 100 kg/ha and sowing was done at 40±10 mm depth. In case of BBF seeder, row to row spacing was 225 mm. The fertilizer application of N, P and K was done at the rate of 120:60:40 in case of SFD, BBF seeder and RTABBF seeder. The same was 150:60:40 in case of HS, ZTD and ZTD-SH. Additional rate of nitrogen fertilizer in the fields sown by these machines was taken due to straw load of previous crop in the field. Fertilizers were supplemented in the form of urea, di-ammonium phosphate and murate of potash, all through manual broadcasting. Five flood irrigations of 130 mm each were applied in crop sown with SFD. In ZTD and ZTD-SH, four flood irrigations were applied of 120 mm each. In case of HS, four flood irrigations of 80 mm each were applied. In case of BBF seeder and RTABBF seeder, four irrigations were applied in furrows, each of 100mm depth. Weed management was done by herbicide 2,4-D @ 1.25 litre/ha mixed in 500 litre of water and sprayed using tractor operated power sprayer. For plant protection, Dimethoate (0.75 litre/ha; 30%EC; mixed in 500 litre water) was sprayed using power sprayer. Harvesting was done with combine harvester in the month of March end. Crop after harvest was transported with tractor and trolley in each cultivation practice.

2.2. Experimental details

The experiment was conducted over three consecutive years (2021-2022 to 2023-2024) at two locations. Three machines i) SFD; ii) BBF seeder; and iii)RTABBF seeder were operated in a village (Kachibarkheda)in Bhopal district (Latitude: 23°25'05"N; Longitude: 77°23'13"E). These were operated in the farmers' fields of six farmers each in 0.1 ha area counted as six replications of each machine operation. Other three machines HS, ZTD, ZTDSH were operated in the experimental farm of ICAR-Central Institute of Agricultural Engineering, Bhopal (Latitude: 23°18'35"N; Longitude: 77°24'10"E). These locations had similar weather and climatic conditions. Variety of wheat sown for the assessment was HI-1544 with 135 days of duration.

2.3. Statistical analysis

The experimental design was Randomized Block Design in operation of these machines, both in village trials and research farm trials. Operational parameters *viz*. man-hour, operating time of machine and fuel consumption were measured. Analysis of Variance (ANOVA) was done with general linear model. Duncan's multiple-range tests (DMRT) was conducted at $p < 0.05$ to find the significant difference in means within dependent variables at $p < 0.05$.The data was analyzed in statistical software SAS 9.0.

2.4. Climate and soil condition

The region where sowing operations and study was conducted with these machines has 1070 mm average annual rainfall with 56 rainy days every year. Average maximum and minimum annual temperature of the region varied from 46.5°C to 5.6°C respectively, during experimental period. This region comprised of vertisol with clay content of 47.3-54.7 % having drainable porosity between 6.2 – 7.0 %. The soil pH varied from 7.5 to 8.0 with soil depth of 0.0 –1.8 m. Bulk density of the soil in the region varied from 1.38-1.45 g/cm^3. The particle size distribution of one particular soil sample from village trail site had 16% sand, 30% silt, and 54% clay. This type of soil tends to have high water retention but may have poor drainage and aeration.

2.5. Energy analysis

The energy provided from indirect sources such as equipment, chemicals, fertilizers, and seeds, as well as from direct sources viz., human labour, fuel, and electricity was calculated as per coefficients shown in Table 5.Calculation of energy required for field activities such as supplied by human energy, fuel, machine's intrinsic energy and electric energy was calculated as shown in equations 1 to 4. The energy indices were evaluated from the equations 5 to 10 provided by Lohan et al. (2023).

$$\text{Human energy (MJ/ha)} \quad \text{He} = \frac{\text{no.of labour} \times \text{time consumed (h)}}{\text{Area covered (ha)}} \times \text{Energy Equivalent (EE) (MJ/h)} \tag{1}$$

$$\text{Fuel energy (MJ/ha)} \quad \text{Fe} = \frac{\text{Fuel consumption (l/h)}}{\text{Area covered (ha/h)}} \times \text{EE (MJ/l)} \tag{2}$$

Machine energy (MJ/ha)

$$\text{Me} = \frac{\text{weight of machine (kg)}}{\text{Useful life of machinery (h)} \times \text{Effective field capacity (ha/h)}} \times \text{EE (MJ/kg)} \tag{3}$$

$$\text{Electric energy (MJ/ha)Ee} = \frac{\text{electricity consumption (kWh)}}{\text{Capacity of pump (ha/h)}} \times \text{EE (MJ/kWh)} \tag{4}$$

$$\text{Energy input (MJ/ha)} = \text{sum of all direct and indirect energy source} \tag{5}$$

$$\text{Energy output (MJ/ha)} = \text{Total biomass (grain + straw) (kg/ha)} \times \text{EE(MJ/kg)} \tag{6}$$

$$\text{Energy use efficiency (EUE)} = \frac{\text{Useful Work}}{\text{Input Energy}} \tag{7}$$

$$\text{Energy productivity} = \frac{\text{Grain productivity, kg/ha}}{\text{Energy input in MJ/ha}} \tag{8}$$

$$\text{Specific energy} = \frac{\text{Energy input in MJ/ha}}{\text{Grain productivity, kg/ha}} \tag{9}$$

$$\text{Energy profitability} = \frac{\text{Energy output} - \text{Energy input}}{\text{Energy input}} \tag{10}$$

Diesel consumption of a 33.6 kW, two-wheel drive tractor was measured in different operations for calculating energy supplied by fuel. Intrinsic energy input for different machines was calculated based on its weight, useful life, time required to cover one hectare field, and its intrinsic energy coefficient (Table 3). Electrical energy for irrigation was calculated based on the amount of electricity consumed for irrigation and the energy coefficient of electricity. The energy contribution from other sources such as seed, fertilizer, and chemical was calculated based on the amount of input used for cultivation and its respective energy coefficient. The farm produce of grain yield and straw yield was also converted into energy in terms of energy output (MJ) by using three year's average yield. Source wise percentage distribution of input energy was calculated for all the experimented methods of wheat cultivation.

Table 3. Energy coefficients of various farm inputs and outputs.

Particulars	Unit	Energy coefficients (MJ per unit)	Reference
A. Inputs			
1. Labour			
(a) Adult man	h	1.96	Dhawan and Mittal (1992); Singh et al. (2008)
2. Diesel	L	56.31	Devsenapathy et al. (2009); Chaudhary et al. (2017)
3. Water	m^3	1.02	
4. Electricity	kWh	11.93	Ozkan et al. (2004); Chaudhary et al. (2017)
5. Prime mover/tractor	kg	68.4	Panesar and Bhatnagar, (1994); Lohan et al.(2023); Singh et al. (2008)
6. Machinery			
a) Farm machinery (Including self-propelled machines)	kg	68.4	Panesar and Bhatnagar, (1994); Lohan et al.(2023); Chaudhary et al. (2017)
b) Farm machinery (Excluding self-propelled machines)	kg	62.7	Canakci et al. (2006); Chaudhary et al. (2017)
7. Chemical fertilizers			
(i) Nitrogen	kg	60.6	Toader et al. (2014)
(ii) Phosphate (P_2O_5)	kg	11.1	Toader et al. (2014)
(iii) Potash (K_2O)	kg	6.7	Chaudhary et al. (2017)
8. Pesticides			
(i) Fungicides	kg	97	Singh et al. (1992)
(ii) Insecticides	kg	184.63	Singh et al. (1992)
(iii) Herbicides (2, 4-D)	kg	85	Nassri et al. (2009)
B. Output			
1. Wheat Seed	kg	14.7	Singh et al. (1992)
2. Wheat Straw	kg	13.4	Singh et al. (1992)

2.6. Evaluation of GHG emission

The quantities of farm inputs such as diesel, fertilizers, chemicals, biocides, and farmyard manure (FYM) were multiplied by their CO_2 eq. emission coefficients to get the equivalent carbon dioxide emissions as shown in Table 4. Thus total emissions were obtained in wheat cultivation using a particular set of machinery and cultivation practice. The carbon output was calculated by summing up the carbon equivalents of the grain and straw yield. Carbon sustainability index (CSI) was worked out for each sowing system. CSI indicates environmental efficiency of a production system where carbon inputs were converted into productive outputs while minimizing GHG emissions (Dubey and Lal, 2009). CSI was calculated by dividing the difference between the total CO_2 output and CO_2 input as given by Lal (2004). The carbon indices were calculated as indicated in equations 11 to 16.

$$\text{Carbon input (kg CO}_2\text{eq./ha)} = \text{sum of all the carbon inputs from various sources} \quad (11)$$

$$\text{Carbon output (kg CO}_2\text{eq./ha)} = \text{Total biomass (grain + straw)} \times \text{GHG coefficient} \quad (12)$$

$$\text{Carbon efficiency (kg CO}_2\text{eq./ha)} = \frac{\text{CO}_2\text{ output (kg CO}_2\text{ eq./ha)}}{\text{CO}_2\text{ input (kg CO}_2\text{eq./ha)}} \quad (13)$$

$$\text{Carbon productivity} = \frac{\text{Grain productivity, kg/ha}}{\text{CO}_2\text{ input in kg CO}_2\text{eq./ha}} \quad (14)$$

$$\text{Carbon sustainability index} = \frac{\text{CO}_2\text{ output} - \text{CO}_2\text{ input}}{\text{CO}_2\text{ input}} \quad (15)$$

$$\text{Greenhouse gas intensity} = \frac{CO_2 \text{ input in kg } CO_2 \text{eq./ha}}{\text{Grain productivity, kg/ha}} \tag{15}$$

GWP was worked out for each wheat cultivation practice taking into account the carbon equivalent input from different sources by multiplying their quantity with respective emission factor and then adding them together (Magar et al. 2022).

Table 4. Greenhouse gas emission coefficients of different farm inputs and outputs.

Energy source	Unit	GHG coefficient (kg CO_2 eq. per unit)	Reference
Diesel,	L	2.68	Dyer and Desjardins (2003); Pratibha et al. (2019)
Electricity,	kWh	0.523	Tabatabaie et al. (2012)
Chemical fertilizer			
i. Nitrogen	kg	1.35	Tabatabaie et al. (2012)
ii. Phosphorous (P_2O_5)	kg	0.2	Tabatabaie et al. (2012)
iii. Potassium (K_2O)	kg	0.58	Tabatabaie et al. (2012)
Biocide			
i. Herbicide	kg	1.7	Tabatabaie et al. (2012)
ii. Insecticide	kg	4.65	Tabatabaie et al. (2012)
Farm machinery	kg	3.32	Jat et al. (2019)
Biomass			
i. Grain	kg	0.4	Pratibha et al.(2019); Chaudhary et al. (2017)
ii. Straw	kg	0.4	Pratibha et al.(2019); Chaudhary et al. (2017)

3. Results and Discussion

3.1. Energy involvement in wheat cultivation with different sowing machinery packages

3.1.1. Energy inputs

Energy input in wheat cultivation using different machinery packages are shown in Table 5. Each parameter depicts a mean value. Total energy input in wheat cultivation on sowing with different machines was significantly different at a 5% significance level ($p < 0.05$). Total energy requirement in wheat cultivation was minimum with HS (22610.3 MJ/ha) and maximum with SFD (29883.9 MJ/ha).Minimum total energy requirement was observed in wheat sowing with HS due to direct sowing of seed in the standing crop residue. Whereas, in sowing with SFD, it was maximum due to seed bed preparation with one pass of mould board plough and two pass of cultivator. However, cultivation with ZTD, ZTD-SH and HS did not require any field preparation thus consuming lesser energy in the whole process of wheat cultivation. Cultivation with these machines required higher energy input from fuel consumption during sowing but overall energy input was less in sowing (Singh et al., 2007; Singh et al., 2014; Kumar et al., 2013; Waghmode and Patel, 2019). Reduced soil tillage decreased the tractor and machines' working time thus minimizing fuel consumption and emissions.

3.1.2. Grain yield

The grain and straw yield (Table 5) was found maximum in case of wheat cultivation with RTABBF seeder at 5401.3 and 6810.6 kg/ha, respectively. As a result energy output was highest with RTABBF seeder at 170,663 MJ/ha. RTABBF seeder did one pass of rotary tilling, made broad beds and completed sowing on the beds in a single pass of operation that resulted in good crop stand, proper irrigation in furrows, better drainage from furrows and better root zone aeration due to elevated beds. Crop sown on broad beds not only saved water but provided proper space for seed germination which in turn increased the grain yield (Singh et al., 2022). Hence, this machine proved to be good in respect of production and productivity, mitigating the climatic effects of waterlogging and crop lodging. Ghani et al. (2007) also reported 6% increase in wheat grain yield when sowing was done on broad beds. Sowing on broad bed improved yield as it increased soil aeration, improved water management and reduced soil compaction (Mandal et al., 2013; Rao et al., 2015). The energy output was also significantly different for sowing machines at 5% significance level ($p < 0.05$) except for HS and ZTD. Dunkan's Mean Range Test(DMRT) results showed that grain yield was similar in HS and ZTD-SH and ZTD, in the range of

4594 to 4760.3 kg/ha.

3.1.3. Energy use efficiency

Energy use efficiency (EUE) representing sustainability and productivity was highest (6.96) with RTABBF seeder followed by HS (6.73) and BBF (6.58). Lower EUE (4.8) in case of wheat cultivation with SFD was due to more energy intensive cultivation practice and giving comparatively lower yields. With RTABBF seeder, energy losses were reduced by integrating operations. Sowing with RTABBF seeder also ensured better moisture conservation and root zone aeration that translated into higher grain yield and biomass yield per unit of energy invested. HS and BBF seeder also showed high EUE values 6.73 and 6.58 % respectively due to improved seed placement, better soil-seed contact, and reduced number of field passes compared to SFD.

3.1.4. Specific energy and energy profitability

Specific energy was highest in wheat cultivation with SFD being as 6.84 MJ/kg followed by that with ZTD (5.94) and ZTD-SH (5.67). The lowest specific energy was for wheat cultivation with RTABBF seeder at 4.53 MJ/kg. This showed that total energy input required to produce 1 kg of grain was lowest with RTABBF seeder. Rawat et al. (2007) also reported that specific energy of ZTD was 13.3 % less than sowing with SFD. Energy profitability was highest ($p < 0.05$) in RTABBF being as 5.96 followed by HS (5.73) and BBF (5.58). This indicated that cultivation with RTABBF seeder was also beneficial in terms of energy profitability.

Table 5. Energy involvement in wheat cultivation by different sowing machines and their associated practices.

Wheat sowing machine	**Energy from Input source, MJ/ha**							**Energy input, MJ/ha**	**Energy output, MJ/ha**	**Energy use efficiency (EUE)**	**Energy productivity, kg/MJ**	**Specific energy, MJ/kg**	**Energy profitability**	**Grain yield, kg/ha**	**Straw yield, kg/ha**
	Man	Diesel	Water + Electricity	Seed + treatment	Fertilizer	Pesticide	Machinery								
SFD	288.6	4235.6	14261.0	1567.0	8206.0	563.6	761.7	29883.9 ^{f}	143699.3 ^{a}	4.80 ^{a}	0.145 ^{a}	6.84 ^{e}	3.80 ^{a}	4367.0 ^{a}	5933.1 ^{a}
ZTD	2115.4	2345.3	11650.4	2155.0	10024.0	563.6	266.5	27220.2 ^{e}	149754.2 ^{b}	5.50 ^{b}	0.168 ^{b}	5.94 ^{d}	4.50 ^{b}	4594.0 ^{b}	6136.0 ^{b}
ZTD-SH	2221.5	2401.6	11386.8	2155.0	10024.0	563.6	268.9	27021.6 ^{d}	154651.5 ^{c}	5.72 ^{c}	0.176 ^{c}	5.67 ^{c}	4.72 ^{c}	4760.3 ^{c}	6319.0 ^{b}
HS	1777.2	2739.5	6668.1	2155.0	10024.0	563.6	283.2	22610.3 ^{a}	152134.9 ^{b,c}	6.73 ^{e}	0.206 ^{d}	4.85 ^{b}	5.73 ^{e}	4654.1 ^{b,c}	6247.6 ^{b}
BBF	2334.5	4607.3	9765.1	1273.0	8206.0	563.6	501.1	25150.8 ^{c}	165676.6 ^{d}	6.58 ^{d}	0.213 ^{e}	4.71 ^{a,b}	5.58 ^{d}	5338.6 ^{d}	6507.3 ^{c}
RTABBF	2224.2	4067.3	9683.2	1273.0	8206.0	563.6	482.1	24499.2 ^{b}	170662.5 ^{e}	6.96 ^{f}	0.221 ^{f}	4.53 ^{a}	5.96 ^{f}	5401.3 ^{d}	6810.6 ^{d}

* *Values followed by the same letters at the tail (a, b, c, d, e, f) in a column do not differ between the treatment for the specified energy parameters*

3.2. Energy quantum by different inputs

The quantum of energy inputs by various inputs for different sowing machines (Figure 1) show that highest amount of energy input was given by chemical fertilizers in the range of 33.5 to 44.3%, followed by electricity in the range of 15.7 to 23 %. Next energy input was from water in the range of 13.7 to 19.8%. Energy input from water was least in case of HS (13.7%) as the water requirement reduced in this practice of sowing. This happened because wheat was sown on the residue of previous crop that gave the effect of mulching and reduced the water requirement. Earlier also it was reported that water requirement reduced by 3-11% on mulching (Chakraborty et al. 2008, Singh et al., 2021; Singh et al., 2020). Contribution of energy input from water was 19.8% in case of ZTD as here the seed was drilled directly in residue of previous crop that saved one irrigation. Wani et al. (2005) observed the performance of BBF seeder was consistently superior to the traditional system in conserving the moisture. Energy input from electricity was proportional to the amount of irrigation given to crop. It was significantly less in case of HS (15.7%) and highest in wheat cultivation with SFD (25.4%). Also, the electricity used for irrigating the crop was lower in case of RTABBF seeder (14.6 %) compared to that with ZTD.

The contribution of fossil fuel energy in total energy input was 14.3% on wheat sowing with SFD. The consumption of diesel on sowing with SFD was 75.2 L/ha including field preparation operations and harvesting. On sowing with RTABBF seeder, total diesel consumed was 72.2 L/ha. However, significant reduction in diesel consumption was observed on using HS by 35.3% as compared to SFD. On sowing with ZTD, the diesel consumption was 51.5% lesser compared to SFD. Lesser diesel consumption meant lesser emission making machinery package more environment friendly. Consumption of fossil fuel was least on sowing with ZTD at 41.7 L/ha including that consumed in sowing, weed management, spraying, harvesting and transport. Total fuel consumption was less in wheat sowing by ZTD and HS as the crop was sown in single pass of operation in the residue condition of previous crop. This saved the energy expenditure in tillage operation. Hence, these machinery packages are more climate friendly.

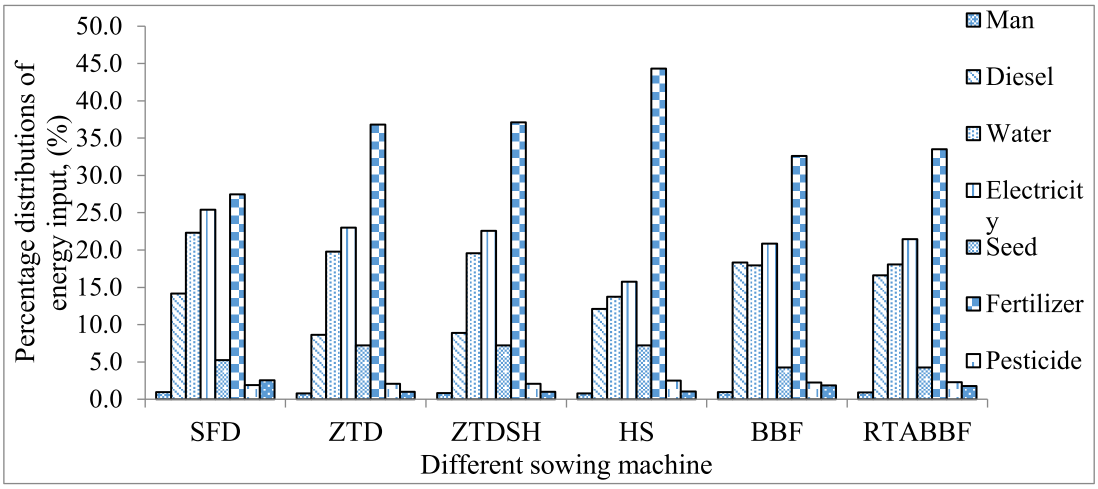

Figure 1. Percentage distribution of energy inputs from different inputs in wheat cultivation with different sowing machines and their associated practices

3.3. Carbon footprint with different sowing machinery

3.3.1. Carbon footprints of various farm inputs by different sowing machinery

Table 6 shows carbon footprint of wheat cultivation with different sowing machinery practices. Total carbon input was significantly different in different machinery practices. It was highest in case of SFD (812.3 kg CO_2 eq./ha) followed by BBF seeder (717.9 kg CO_2 eq./ha), ZTD (706.5 kg CO_2 eq./ha), ZTD-SH (702.5 kg CO_2eq./ha), RTABBF seeder (685.4 5 kg CO_2eq./ha and HS (608.1 5 kg CO_2eq./ha). Low carbon input here directly means low fuel consumption as the other components of the crop *viz.* fertilizer and chemicals (insecticide and pesticides) were almost same in all the cases. Direct sowing was also reported to have 87-88% reduction in CO_2 emissions (Filipovic et al., 2006).

3.3.2. Carbon Output and Sustainability Index

Carbon output in the form of grain and straw yield also varied in different wheat cultivation practices. The highest carbon output (Table 6) was from RTABBF seeder (4884.8 kg CO_2 eq./ha) followed by BBF seeder (4738.4 kg CO_2 eq./ha). The carbon output was similar on sowing with ZTD-SH, HS and ZTD in the range of 4292.0 to 4431.7 kgCO_2 eq./ha. Carbon Sustainability Index (CSI) of various sowing machinery package showed significant difference as p value was less than 5% significance level (Table 7). In case of SFD the CSI was lowest at 4.07, indicating less efficient use of inputs. Sowing with HS and RTABBF seeder showed higher CSI of 6.17 and 6.12 respectively, signifying better carbon efficiency and a more sustainable balance between carbon input and output. Higher CSI values reflected improved practice that enhanced productivity while reducing the carbon footprint. Carbon output was highest on cultivation with RTABBF seeder because yield was highest (5401.3 kg/ha) in this system of cultivation, which is of prime importance to a crop grower. RTABBF seeder method also exhibited lowest GHG intensity (0.126 kg CO_2 eq./kg) compared to other methods.

Table 6. Carbon footprint of wheat cultivation with different experimented sowing machinery practices.

Sowing machine	**Carbon input, kg CO_2eq./ha**	**Carbon output, kg CO_2eq./ha**	**Carbon use efficiency**	**Carbon Productivity, kg/kg CO_2eq.**	**GHG intensity, kg CO_2eq./kg**	**Carbon Sustainability Index (CSI)**
SFD	812.3 ^{f}	4120.1 ^{a}	5.07 ^{a}	5.37 ^{a}	0.186 ^{e}	4.07 ^{a}
ZTD	706.5 ^{d}	4292.0 ^{b}	6.07 ^{b}	6.50 ^{b}	0.154 ^{d}	5.07 ^{b}
ZTD-SH	702.5 ^{c}	4431.7 ^{c}	6.30 ^{c}	6.77 ^{c}	0.147^{c}	5.30 ^{c}
HS	608.1 ^{a}	4360.7 ^{b,c}	7.17 ^{e}	7.65 ^{d}	0.130 ^{a,b}	6.17 ^{e}
BBF	717.9 ^{e}	4738.4 ^{d}	6.60 ^{d}	7.43 ^{d}	0.134 ^{b}	5.60 ^{d}
RTABBF	685.4 ^{b}	4884.8 ^{e}	7.12 ^{e}	7.88 ^{e}	0.126 ^{a}	6.12 ^{e}

a, b, c, d, e, f next to the values in the table indicate the results of statistical significance testing of DMRT

Table 7. ANOVA of CSI of different sowing machine.

	Sum of Squares	df	Mean Square	F	P value
Between Groups (sowing machine)	18.22	5	3.64	340.55	.000
Within Groups	0.32	30	.011		
Total	18.54	35			

3.4. GHG intensity with different sowing machinery

The grouping of statistically similar GHG intensity producing machinery is shown in Figure 2. GHG intensity was highest with SFD (0.186 kg CO_2 eq./kg). It was medium with ZTD (0.154 kg CO_2 eq./kg) followed by ZTD-SH (0.147 kg CO_2 eq./kg). Further, the GHG intensity was low with HS, BBF and RTABBF (average 0.13 kg CO_2 eq./kg). The GHG intensity values of HS, BBF and RTABBF were averaged as their values were significantly similar. These cultivation practices can be categorised in four groups having high, medium, low and very low GHG intensity. Very low GHG intensity group machines need to be promoted to mitigate GHG emission. The ANOVA (Table 8) indicated that the minimal within-group variation and the very high F-value are not due to random chance but they are directly influenced by the type of sowing machinery packages. Pratibha et al. (2016) showed that GHG intensity of conventional tillage was more than the conservation tillage method. Dubey and Lal (2009) stated that conservation tillage reduced GHG emission which in turn reduced the GHG intensity compared to conventional tillage. Tillage was proven to be the major contributor of the GHG emission that added 30-50% carbon in the atmosphere (Sorensen et al. 2014). In this study, sowing with normal field preparation and seed cum fertilizer drill has come out to be the highest GHG intensity practice that suggests going for the use of low GHG intensity machinery in wheat cultivation being as HS, BBF seeder and RTABBF seeder.

Table 8. ANOVA of GHG intensity of different sowing machine.

	Sum of Squares	df	Mean Square	F	P value
Between Groups (sowing machine)	.014	5	.003	141.69	.000
Within Groups	.001	30	.000		
Total	.015	35			

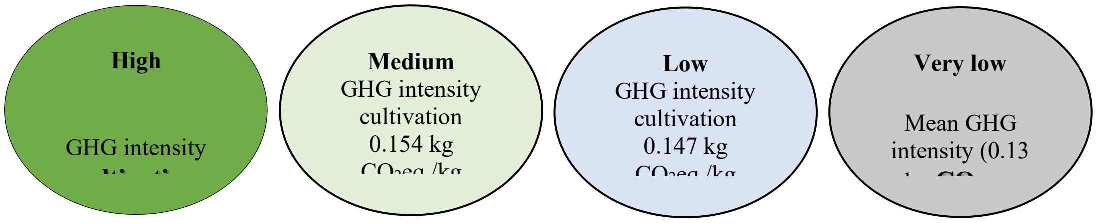

Figure 2. Categorization of sowing machines based on greenhouse gas (GHG) emission intensity (kg CO_2 eq./kg grain) grouped as high to very low GHG intensity according to DMRT test

3.5. GWP of different sowing machinery packages

GWP from different sources of energy in sowing with different practices are shown in Table 9. Highest fuel-related emissions were with BBF (221.35 kg CO_2 eq./ha), while lowest was with ZTD (112.48 kg CO_2 eq./ha). In terms of electricity consumption in irrigation, SFD had highest emissions (338.4 kg CO_2 eq./ha) and HS had lowest (156.93 kg CO_2 eq./ha). This was due to lesser amount of water required in case of HS cultivation as the evaporation losses were reduced due to mulching (Balwinder et al., 2011). Emission due to fertilizer was significantly similar across all the packages of sowing machinery, with ZTD showing highest (238.38 kg CO_2 eq./ha) and BBF seeder having lowest (197.83 kg CO_2 eq./ha).On sowing with HS, ZTD and ZTD-SH the residue of the previous crop was standing in the field that required extra fertilizer for decomposition of crop residue. Previous studies showed that extra 25-30 kg N/ha were required for enhancing decomposition of the crop residue (Gangwar et al., 2006; Verma and Shrivastava, 1994). Emissions from chemicals were relatively stable, with minor differences. Machinery emissions were highest for SFD (23.65 kg CO_2 eq./ha) and lowest for ZTD (11.78 kg CO_2 eq./ha). The statistical validation of these differences is provided in Table 10. The analysis revealed a highly significant difference in GWP among the six sowing machines ($F = 5031.049$, $p < 0.001$).

Table 9. Sources of carbon emissions and GWP with different wheat cultivation practices.

Improved sowing machinery package	Sources of Carbon emission, kg CO_2eq./ha					
	Fuel	Electricity	Fertilizer	Chemicals	Machine	Total GWP kg CO_2eq./ha
SFD	201.61 ^{e}	338.41 ^{e}	197.93 ^{a}	13.9 ^{a,b}	23.65 ^{d}	775.4 ^{f}
ZTD	112.48 ^{a}	275.28 ^{d}	238.38 ^{b}	13.8 ^{a,b}	11.78 ^{a}	651.8 ^{c}
ZTD-SH	114.80 ^{b}	268.40 ^{c}	238.33 ^{b}	14.3 ^{b}	12.46 ^{b,c}	648.3 ^{b}
HS	131.76 ^{c}	156.93 ^{a}	239.16 ^{b}	13.9 ^{a,b}	13.21 ^{b}	555.0 ^{a}
BBF	221.35 ^{f}	231.38 ^{b}	197.83 ^{a}	13.5 ^{a}	23.61 ^{d}	687.7 ^{e}
RTABBF	194.26 ^{d}	231.45 ^{b}	198.80 ^{a}	13.9 ^{a,b}	22.16 ^{c}	660.5 ^{d}

Table 10. ANOVAof GWP of different sowing machine.

	Sum of Squares	df	Mean Square	F	P value
Between Groups	151674.93	5	30334.98	5031.04	.000
Within Groups	180.88	30	6.03		
Total	151855.82	35			

The GWP of different wheat sowing machinery packages is shown in Figure 3. GWP was minimum with HS at 555.0 kg CO_2 eq./ha as it required no tillage operation prior to sowing. The next least GWP was with ZTD-SH at 648.3 kg CO_2 eq./ha. The GWP of ZTD (651.8 kg CO_2 eq./ha) and ZTD-SH (648.3kg CO_2 eq./ha) were comparable. All these three machines required no field preparation and hence the emissions were less. BBF seeder and RTABBF seeder had higher emissions of 687.7 and 660.5 kg CO_2 eq./ha. These sowing technologies emitted higher CO_2 but higher grain yield was also obtained i.e. 5401.3 kg/ha with RTABBF seeder. The results indicated that wheat cultivation with HS had least overall

GWP followed by ZTD and ZTD-SH. Therefore, wheat cultivation with these machinery packages is considered as climate resilient production. Wheat yield was highest on cultivation with RTABBF seeder.

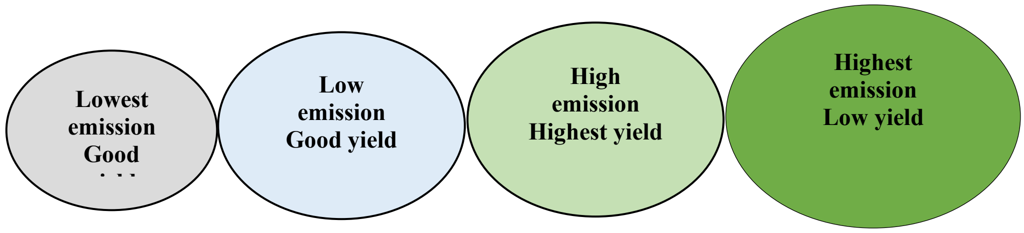

Figure 3. Categorization of wheat sowing machinery packages in increasing order of GWP.

3.6. Economic Benefits with different machinery practices

The higher yield was also beneficial in terms of costs. Table 11 shows the costs return from different sowing machinery packages of wheat. The grain yield was converted into the cost taking the base price as Minimum Support Price declared by government of India for the year 2023-2024. i.e. Rs.22.75 per kg. The additional grain yield was converted in to cost benefit and it was compared with that of SFD. The additional benefits were in the range of Rs.22,104 to Rs.23,530 per hectare. In case of ZTD, it was Rs.5,164 over SFD. The additional benefit of Rs.6,529 was with HS compared to SFD. In RTABBF seeder, the additional cost benefits was ofRs.23,530 over SFD. Sowing with RTABBF seeder gave maximum economic returns in wheat cultivation.

Table 11. Economic return on wheat sowing with different machinery packages.

Sowing machine	Carbon output, $kgCO_2eq./ha$	Total grain yield, kg/ha	Total cost, Rs.	Cost Benefits over SFD
SFD	4120.1 [a]	4367.0	99349	-
ZTD	4292.0 [b]	4594.0	104514	5164
ZTD-SH	4431.7 [c]	4760.0	108290	8940
HS	4360.7 [b,c]	4654.1	105879	6530
BBF	4738.4 [d]	5338.6	121453	22104
RTABBF	4884.8 [e]	5401.3	122880	23530

4. Conclusion

GWP of different wheat cultivation practices were studied in the Vertisols of central India. Traditional cultivation practices in farmers field were assessed along with improved cultivation practices experimented in the field. The GHG intensity was highest(0.186 $kgCO_2$ eq./kg) with SFD, medium with ZTD (0.154 $kgCO_2$ eq./kg) and lowest (0.13 kg CO_2 eq./kg) with RTABBF seeder. The GHG intensity was 30.1% lower in RTABBF seeder than that of SFD, indicating it to be a climate resilient technology. In terms of GWP, HS had minimum GWP at 555.0 kg CO_2 eq./ha and cultivation with SFD had highest GWP of 775.4 kg CO_2 eq./ha. The economic benefit was maximum with RTABBF seeder, generating an additional income of Rs.23,530 per hectare that was 23.6% higher than cultivation with SFD. The results clearly revealed that wheat cultivation with HS had least overall GWP followed by ZTD. The GHG intensity was lowest with RTABBF seeder (0.126kg CO_2 eq./kg). Therefore, wheat cultivation with these machinery packages was considered as climate resilient production. These findings provide a scientific basis for planners and policymakers to promote climate resilient wheat cultivation machinery packages that balance productivity and environmental benefits.

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Author Contributions

In this study, Chandrashekhar Sahay conducted investigation and conceptualized writing, Niveta Jain gave concepts of model and calculations, Uday R Badegaonkar supported operation of zero till drill with straw handler, Krishna Pratap Singh planned and conducted operations of machines, Manoj kumra di data curation Satish K Singh and Purvi Tiwari contributed in analysis and review, Ved Prakash Chaudhary supported in writing and Chetan Sawant helped in writing and editing this article.

Conflict of Interest Statement

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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