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Research Article

Carbon footprints of rice-wheat cultivation across farm size categories: Evidence from Punjab in India

Sangeet Ranguwal[1*], BaljinderKaur Sidana[2] and Sunny Kumar[3]

[1] *Department of Economics and Sociology, Punjab Agricultural University, Ludhiana, Punjab*

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***Corresponding author:**
E-mail: sangeet@pau.edu

Abstract

Carbon footprint (CF) can be a powerful tool to guide sustainable food production systems. The present study quantified the CF and analyzed the variability in CF across farm categories along with share of different contributing inputs for rice and wheat production in the Punjab state. The carbon footprint of rice was found to be much higher (6.34 tons CO_2eqha^{-1} and 0.91 tons CO_2 eq ton^{-1}) than wheat (1.41 tons CO_2eqha^{-1} and 0.28 tons CO_2eqton^{-1}). For rice, among different sources of emission, methane formed major share (60.7 %) followed by free electricity for irrigation (17.9 %), N_2O (10.8 %), plant protection chemicals (7.5 %), diesel (6.1 %) and fertilizers (3 %) while for wheat the major share of emissions were from N_2O (41.3 %) followed by diesel fuel (28.1 %), fertilizers (11.8 %), electricity (10.6 %) and chemicals (5.1 %). Across farm categories, the share of fertilizers (in terms of on-farm (11.2 %) and off emissions (3.1)) remained the maximum for marginal farmers while large farmers contributed the most to the GHG emissions (18.5 %) by using free electricity. The share of on-farm emissions was higher for rice (95.5 %) than for wheat (80.1 %) because of cultivation of rice under flooded conditions leading to methane emissions. The major contributors to the higher off-farm wheat emissions were fertilizers especially P_2O_5, followed by the use of diesel fuel and chemicals. The study stresses the need for sustainable management of agro-inputs which will not only offset the associated GHG emissions but also will improve the soil health. In addition, awareness of climate-smart agricultural practices and access to technologies like DSR, laser leveling, and Happy seeder are key factors in determining the utilization of farm and land management practices that may simultaneously decrease these emissions and increase the adaptive capacity of farmers, and thus improve food security.

Keywords: Carbon footprint, Methane, Fertilizers, Farm category

1. Introduction

Agriculture is both a victim of and a contributor to climate change. On the one hand, agricultural activities contribute to greenhouse gas (GHGs) emissions, mainly due to chemical fertilizers, pesticides, and animal waste. This rate is bound to rise further because of the increasing demand for food by the growing global population, a more robust market for dairy and meat products, and the intensification of agricultural practices. On the other hand, these GHGs include nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) which contribute to climate change and global warming and thereby have a profound impact on the sustainability of agricultural production systems. Globally, agriculture and its related sectors contributed 24 percent of the world's GHGs emissions in 2010 (Smith *et al.,* 2014). These GHG emissions from agricultural production systems have increased more than two–folds in the last 55 years (FAOSTATS, 2019). During the last four decades, the emission of GHGs from agriculture and its related sector increased by 35 percent from 4.2 Gt CO_2eq per year to 5.7 Gt CO_2eq per year and the highest increase was observed during the most recent decade (Tubiello *et al.*, 2013). Asian countries contributed about 44 percent of the total agriculture-related GHG emissions in 2011. As per FAO reports, India ranks second (contributing about 21 %) for paddy based CO_2 (equivalent) emission, followed by China at world level (FAO STAT, 2019). The situation will become more stressed as the world population is increasing rapidly, and food demand is anticipated to double by the year 2050 (Khan and Hanjra, 2009; Imran *et al.,* 2020). At the same time, increasing GHG emissions with more requirements for food production is another key challenge. This scenario requires production systems to maintain high yields without compromising environmental integrity.

Rice-wheat as a dominant cropping system in major agricultural states of India including Punjab has depleted soil health and water resources despite its many benefits (Bhatt *et al.*, 2021; Singh *et al.*, 2021). The estimated annual global warming potential is about ~89 Teragram (Tg) CO_2–C for rice and 45 Tg CO_2–C for wheat (Sapkota *et al.*, 2017), and it showed an increasing trend (Smith et al., 2014). In Punjab, where more than 80 percent of gross cropped area is under rice and wheat crops (PAU, 2022), there has been a 173 percent increase in GHG emissions due to crop burning (mainly rice) between 1980 and 2013, primarily due to farm mechanization, (combined harvesters) that generates enormous amounts of unused stubble, which is burnt to save cost and time (Benbi, 2018). The carbon footprint analysis is beneficial for policymakers, administrators and researchers and is imperative for production planning (Basavalingaiah *et al.,* 2020; Kashyap and Agarwal, 2021). The present study quantifies carbon footprints for rice and wheat across different farm size categories while assessing the contribution of different inputs to it and suggests policy options for precise and effective efforts for mitigation of GHG emissions in the Punjab state.

2. Materials and Methods

Data for the study has been taken from the 'Cost of Cultivation Scheme' run by the Directorate of Economics and Statistics, Ministry of Agriculture, India. Under this scheme, data is collected from 300 farm households in 30 tehsils spread across the three agro-climatic zones of the Punjab state. From each zone, farmers are selected using a three-stage stratified sampling technique, with tehsil as stage one, a village/cluster of villages as stage two, and operational holdings within the clusters as stage three. From each cluster, ten operational holdings with two farmers from the five farm size groups were randomly chosen. Thus, the sample included 60 farmers from each of the five farm categories. Data related to different inputs such as seed, fuel (diesel consumed in diverse farm operations like preparatory tillage, inter-culture operations, harvesting, transport on farm, supervision, etc.), fertilizers (N, P_2O5, and K_2O), chemicals (insecticides/pesticides, fungicides, weedicides), crop yield (economic yield), total working hours of men and women labour as well as draught power used, agri-machinery/implement use for different farm operations, etc. were recorded for rice and wheat during 2018-19. In addition, estimation of by-products has been done from grain yield data for crops by using the crop-to-residue ratio method (Chauhan, 2012).

The amount of GHG emissions from input use during crop cultivation was estimated by using the CO_2 emission coefficients of farm inputs (Table 1). Three key GHGs emissions under consideration were carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The amount of produced CO_2 equivalent was calculated by multiplying the quantity of input (diesel fuel, chemical fertilizer, farm yard manure, and electricity) by their corresponding emission factor.

Off-farm operations i.e. production, formulation, storage and distribution of external inputs are carbon based operations and application with tractorized equipment lead to combustion of fossil fuel, and use of energy from alternate sources, which also emits CO2 and other greenhouse gases (GHGs) into the atmosphere. Accordingly, the GHG emissions were also classified as off-farm emissions (embodied in inputs like chemical fertilizers, Plant protection chemicals and diesel) and on farm emissions (emissions from use of diesel fuel, electricity, CH_4 emissions on the farm. N_2O is emitted directly from agricultural farms and from nitrogen (N) that leaves the field and enters other ecosystems via volatilization and leaching. It was assumed that this includes emissions directly from the field and indirect emissions from N leached or volatilized from the fields. The CH_4 emissions generated from rice fields were also computed according to Intergovernmental Panel on Climate Change's (IPCC, 2006). The carbon footprint was accounted for by individual inputs used in the seeding to harvesting stages of rice and wheat crop production.

Table 1: Emission factors for different inputs used in the cultivation of rice and wheat

	Inputs	Emission factor	Unit	Reference
A	**Off-farm emissions**			
1	**Chemical fertilizers**			
	Nitrogen (N)	1.3	Kg CO_2/ Kg N	Lal, 2004
	Phosphate (P_2O_5)	0.2	Kg CO_2/ Kg P_2O_5	
	Potassium (K_2O)	0.2	Kg CO_2/ Kg K_2O	
2	**Plant protection chemicals**			
	Herbicide	3.9	Kg CO_2/Kg	Soni *et al.*, 2013; Lal, 2004
	Insecticide	6.3	Kg CO_2/ Kg	
	Fungicide	5.1	Kg CO_2/ Kg	
3	Diesel	0.016 Kg CO_2 eq./MJ diesel X 36.4 MJ/ litre diesel	kg CO_2 eq/litre	Nguyen *et al.,* 2012
B	**On-farm emissions**			
1	Nitrogen (N) fertilizer	4.7	Kg CO_2/Kg N	Lal, 2004
2	Diesel	0.074 Kg CO_2 eq./MJ diesel X 36.4 MJ/litre diesel	Kg CO_2eq/litre	Nguyen *et al.*, 2012
3	Electricity	0.8	Kg CO_2 /KWh	Lohsomboon, 2003
4	Irrigation (CH_4 in case of rice)	1.1 Kg CH_4 /Ha/day X 25 Kg CO_2 eq.	Kg/ha/day	Khosa *et al.*, 2011

The GHG emissions associated with inputs, including agrochemicals, electricity, and farm machinery, were calculated using the following equation:

$$CF_A = \Sigma(A_i * EF_i)$$

Where CF_A is the sum of GHG emissions (per hectare) due to i^{th} input in t CO_2 eq

A_i is the amount of i^{th} agricultural input, and EF_i is the emission factor of the i^{th} input (in t CO_2 eq per unit volume or mass).

The energy requirement for electricity consumption in lifting groundwater for irrigation has been calculated using the capacity of the submersible pump-set/electric motor along with the duration of use as follows:

Electricity consumption (KWh) = Capacity of the submersible pump-set/electric motor (HP) * duration of use * 0.746

The carbon footprint per unit area (in Kg CO_2eq/Ha) was calculated as follows.

$$CF_{\text{per unit area}} = (CF_{\text{on farm}} + CF_{\text{off farm}}) \;/\; \text{Area under crop (Ha)}$$

The carbon footprint per unit weight (in ton CO_2eq/ton) was calculated as follows.

$$CF_{\text{per unit weight}} = CF_{\text{per unit area}} \;/\; \text{Yield (ton/Ha)}$$

3. Results and Discussion

3.1 Carbon footprint of rice and wheat

Data analysis revealed that the average carbon footprint (CF) per unit of rice production in Punjab state was 6.34 ton CO_2eq per hectare (Ha), and the CF per unit weight was 0.91 ton CO_2eq/ton. On the other hand, in the case of wheat, the value for CF was much lower than for rice, i.e., CF per unit area was 1.41 ton CO_2eq/Ha, and the CF per unit weight was 0.28 ton CO_2eq/ton, as shown in Table 2. Similar results were found in study for North Iran where the GHG emissions for rice was 6.09 ton CO2 eq. per ha while that for wheat was only 1.171 ton CO2 eq. per ha (Mohammadi *et al.*, 2014).

Table 2: The carbon footprint of rice and wheat production across different farm categories in Punjab

Farm category	**Rice**				**Wheat**			
	Yield ($tonha^{-1}$)	**Area (ha)**	**CF per unit area (ton CO_2eqha^{-1})**	**CF per unit weight (ton CO_2eqton^{-1})**	**Yield (ton Ha^{-1})**	**Area (ha)**	**CF per unit area (ton CO_2eq ha^{-1})**	**CF per unit weight (ton CO_2eq ton^{-1})**
Marginal	6.90	22.01	6.12	0.89	5.11	34.26	1.32	0.26
Small	6.95	65.00	6.19	0.89	4.86	84.95	1.22	0.25
Semi-medium	6.93	129.85	6.44	0.93	4.90	162.68	1.42	0.29
Medium	6.80	231.46	6.35	0.93	4.97	278.72	1.38	0.28
Large	7.02	396.23	6.43	0.92	5.05	434.20	1.46	0.29
Overall	6.94	844.55	6.34	0.91	4.99	994.80	1.41	0.28

Farm category-wise analysis indicated that for paddy, the contribution to CF was the least for marginal farmers (i.e., 6.12 ton CO_2eq/Ha, and the CF per unit weight was 0.89 ton CO_2eq/ton), while it was the maximum for large farm category (i.e., 6.43 ton CO_2eq/Ha, and the CF per unit weight was 0.92 ton CO_2eq/ton). In case of wheat, small farm category (1.22 ton CO_2eq/Ha and the CF per unit weight was 0.25 ton CO_2eq/ton) was the least and again the large farm category (1.46 ton CO_2eq/Ha and the CF per unit weight was 0.28 ton CO_2eq/ton) was the major contributor to the CF.

3.2 *Share of different inputs to carbon footprint*

The shares of different inputs in GHG emissions indicate the contribution to the global warming impact by crop production. Contribution analysis for the different farm inputs used in rice cultivation is presented in Figure 1.

Among different sources of carbon emissions, methane emissions contributed a highly significant share, i.e., about 61 percent of the total emissions. It may be due to continuously submerged rice cultivation followed in the state. A similar study by Hokazono and Hayashi reported that the direct rice field emissions (mainly CH_4) contributed about 75percentto the total global warming potential in conventional systems. Among other sources, electricity use for irrigation formed another 18 percent share followed by soil N_2O emissions (10.8 %), plant protection chemicals (7.5 %), i.e., insecticides, weedicides, and fungicides and diesel fuel (6.1 %) involved in all operations, mainly tillage and harvesting, which significantly contribute to the direct emissions from crop production.

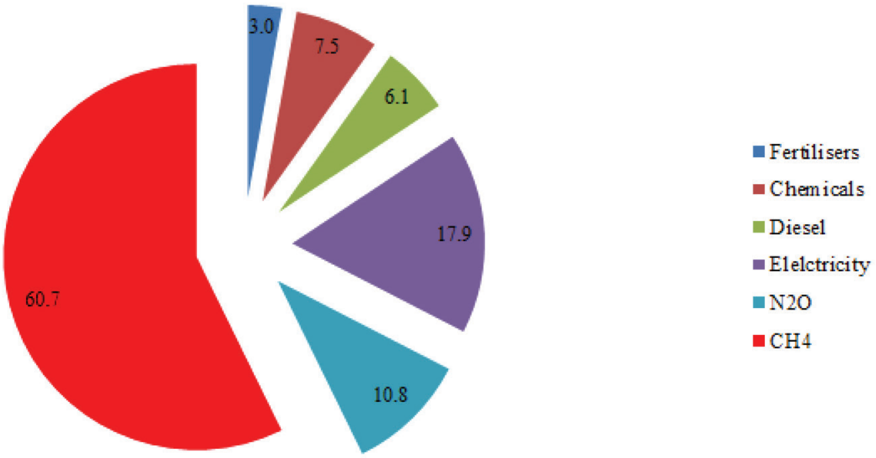


Figure 1: Carbon footprint of rice in Punjab (% share)

Off-farm emissions due to the production of fertilizers had a share of threepercent. In the state, Rice is immediately followed by wheat and the average N fertilization rate (including both urea and DAP) was 36 percent and 18 percent higher than the recommended dose of N for rice and wheat respectively (PAU, 2017). In addition to this, High Yielding Variety (HYV) seeds require higher fertilizer and water inputs leading to higher CF. The increase in the use of fertilizers over time in the state to boost productivity is reflected in the GHG emission trends (Benbi, 2018).

In the case of wheat, direct emissions from N fertilizer were the major contributor to GHG emissions (41.3 %), followed by diesel fuel (28.1 %), electricity energy (10.6 %), while off-farm emissions were from fertilizers (11.8 %), and chemicals (8.1 %) as shown in Figure 2. In earlier studies, the application of fossil energy use has been reported as the primary contributor to GHG emissions (West and Marland, 2002; Liu *et al.*, 2010). Thus, N_2O and diesel fuel are among the most important sources of CO_2 emissions for wheat.

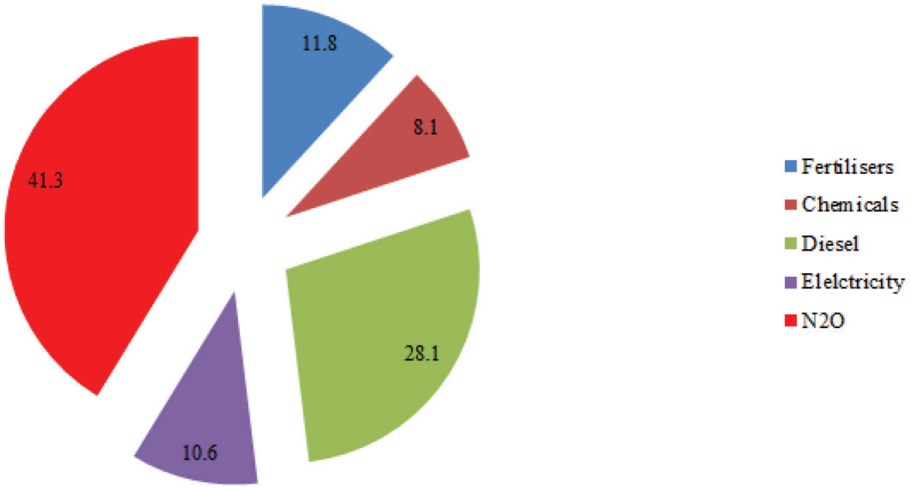


Figure 2: Carbon footprint of wheat in Punjab (% share)

3.3 *Variation of carbon footprint across different farm categories*

The study further calculated the farm category wise share of inputs in carbon emissions. The results are plotted in Figure 3. The results indicated that the share of CH_4 emissions remained more than 60 percent for all the farm categories. Among other contributing inputs, the percentage of fertilizers in terms of on-farm (11.2 %) and off emissions (3.1 %) remained the maximum for marginal farmers because of the overuse of fertilizers, especially urea which is readily available at subsidized rate. Similar results were found in a study at national level where increased use of fertilizer on small holdings was the major reason for higher contribution to the GHG emissions by the small farmers in comparison to large ones (Sinha *et al.*, 2020). N_2O emissions increase exponentially beyond a fertilization rate of 200 Kg N/ ha (Linquist *et al.*, 2011). In the case of Punjab, the fertilization rate is presently below 200 Kg N/ha; however, if the current increasing trend in fertilization continues, the GHG emissions are likely to increase at an accelerated rate. With the declining fertilizer N use efficiency (Benbi, 2018), this might be a possibility in the future if steps to decrease fertilizer use are not taken urgently. Therefore, reducing N fertilizer use is the greatest hotspot for mitigation in the study area. Even though an increase in yield has been suggested as a mitigation measure to justify the negative environmental impacts associated with higher inputs (Ali *et al.*, 2017), the amount of inputs (including water) required to achieve a certain yield level needs to be carefully considered, and region-specific benchmarks need to be set.

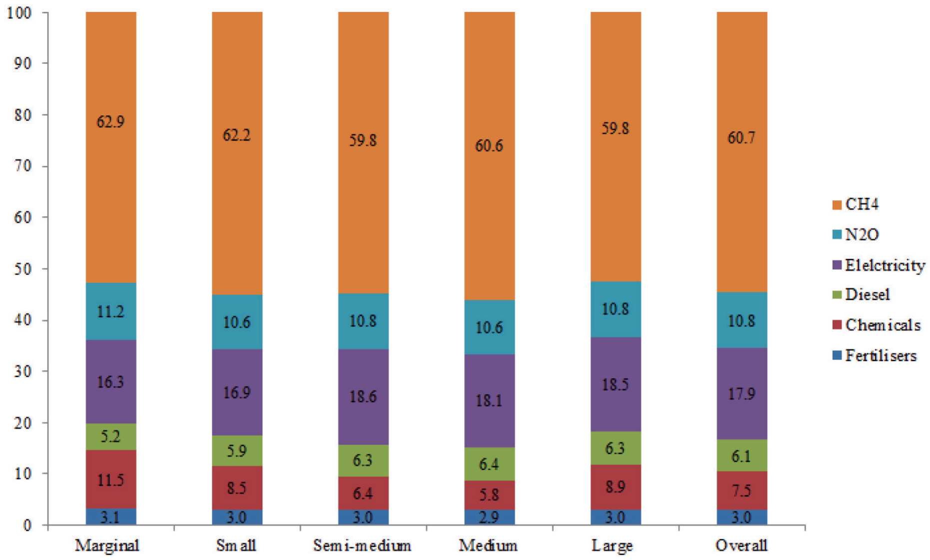


Figure 3: Farm category-wise carbon footprint of rice (% share)

The marginal farmers were observed to be applying high dose of plant protection chemicals leading to a high share of about 12 per cent to the emissions. In case of electricity and diesel use, the large farmers contributed the most to the emissions by using free electricity for pumping irrigation water (18.5 %) and 6.3 per cent, respectively. Earlier study also revealed that more dependency on mechanized means, resulted in higher GHG emissions due to more on-farm fossil fuel use by large farmers (Sinha *et al.*, 2020). Same as in the paddy crop, the marginal farmers in the wheat crop (Figure 4) were the significant contributors to carbon emissions through the use of N fertilizers (about 45 %) and chemicals (12.9 %) on the farm. In comparison, the medium category contributed the most in the form of high use of diesel (31.8 %), followed by large (28.9 %) ones. Like in rice, the large farmers also contributed the most to the emissions by using free electricity (12.8 %). In Punjab, most wheat straw is removed after harvest and used as fodder (Kumar *et al.,* 2019), while rice straw is considered unsuitable as fodder and is removed before sowing the next crop.

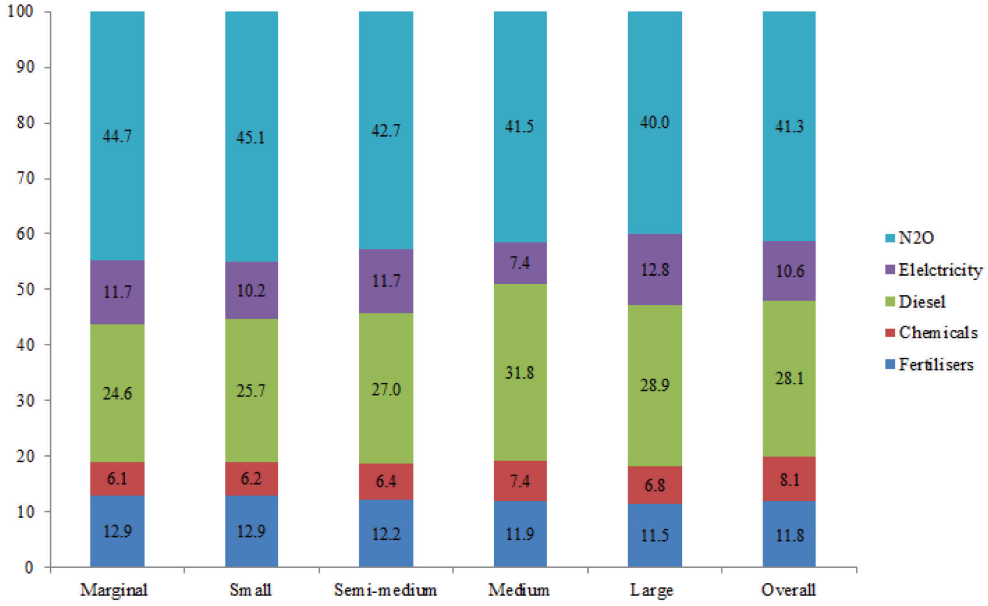


Figure 4: Farm category-wise share carbon footprint of wheat (% share)

Analysis of on-farm and off-farm emissions of rice and wheat revealed that the share of on-farm emissions was higher for rice (95.5 %) than for wheat (80.1 %) because of methane emissions in the case of rice cultivation only (Figure 5 and 6). The off-farm emissions formed about 20 percent share of the total emissions from wheat, and this figure was only 4.5 percent for rice. It was so because of the farmers' practice of applying DAP in wheat (@143 Kg/ha), though the urea dose was almost the same for both crops.

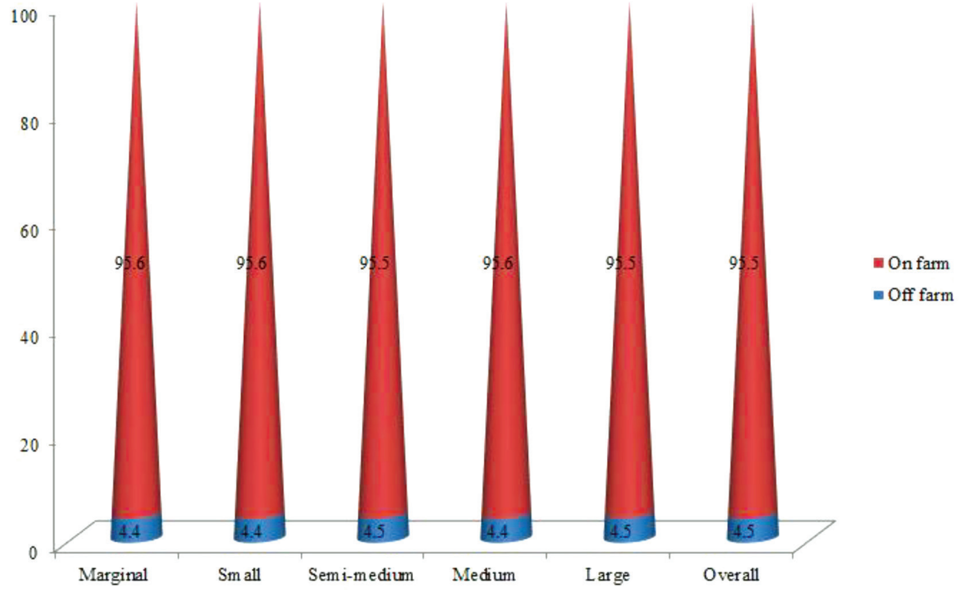


Figure 5: Farm category-wise on and off-farm emissions in rice (% share)

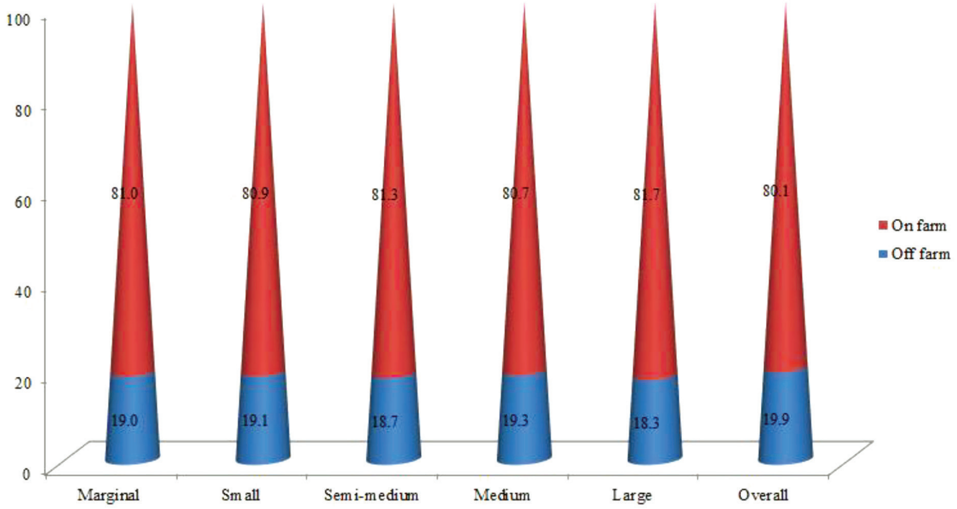
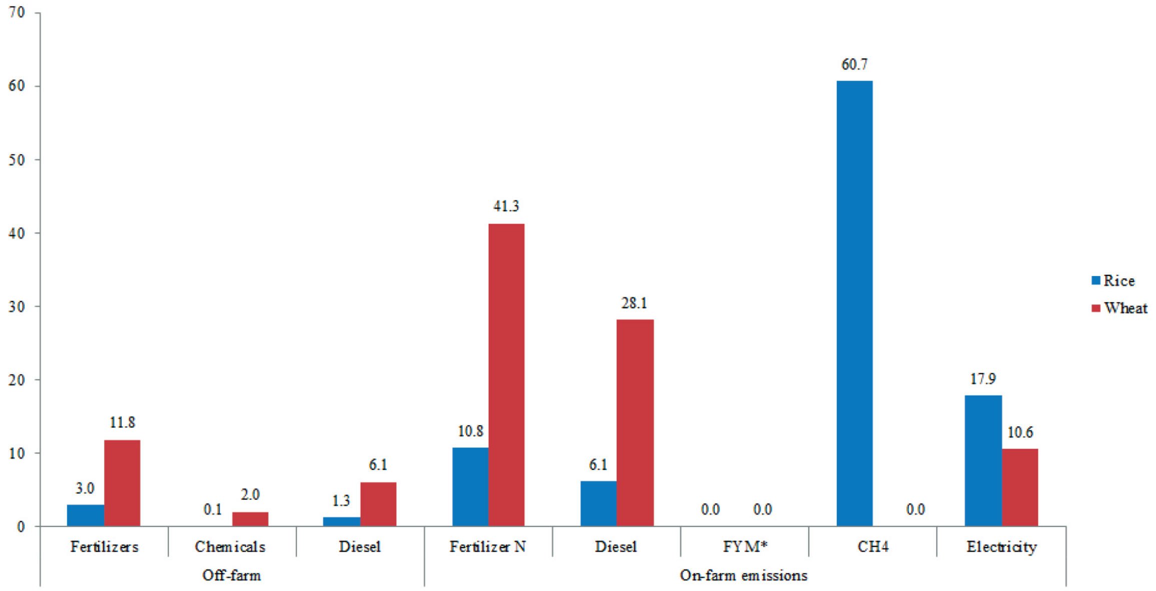


Figure 6: Farm category-wise on and off-farm emissions in wheat (% share)

The component-wise analysis indicated that the major contributors to the higher off-farm wheat emissions were fertilizers (11.83 %), especially P_2O_5, followed by the use of diesel fuel (6.09 %) and plant protection chemicals (2.02 %), while the respective figures for rice were 3.01, 1.33, and 0.12 per cent (Figure 7).



*less than 0.01

Figure 7: Component-wise on-farm and off-farm emissions for paddy and wheat in Punjab (% share of total emissions)

In the case of on-farm emissions, rice cultivation was the leader by being the sole contributor to CH_4 emissions, contributing to as high as about 61 per cent of these on-farm emissions, followed by the use of electricity (17.9 %) for pumping irrigation water. On the other hand, wheat had the lead in on-farm activities for the use of fertilizers (41.28 %), diesel (28.15 %), and electricity (10.6 %), with figures for rice being 10.80 and 6.13 per cent, respectively.

4. Conclusions

Rice production has a higher carbon footprint than wheat production in the Punjab state. Among different sources of carbon emissions, methane emissions for rice (61 %) and direct emissions from N fertilizer (41.3 %) in the wheat crop are the significant contributors. Across farm categories, the share of fertilizers (in terms of on-farm (11.2 %) and off emissions (3.1)) remained the maximum for marginal farmers while large farmers contributed the most to the GHG emissions (18.5 %) by using free electricity to pump irrigation water. The share of on-farm emissions was higher for rice (95.5 %) than for wheat (80.1 %) because of methane emissions in the case of rice cultivation only while higher off-farm wheat emissions were from fertilizers (11.83 %). Punjab agriculture is based on extensive use of fertilizers, agrochemicals, and mechanized means of farming along with paddy cultivation under flooded irrigation conditions.All this point towards a strong need for sustainable management of agro-inputs which will not only offset the associated GHG emissions but will improve the soil health also.Additionally, shifting from conventional tillage to conservation tillage methods like zero-tillage , reduced-tillage and ridge-tillage practices in wheat production and zero–tillage transplanting or non-puddled transplanting and direct seeding in rice can reduce fossil fuel consumption and also be a pathway towards sustainable agriculture.

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Author contributions

All authors have contributed, read and agreed to the published version of the manuscript.

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Conflict of Interest: No

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