International Journal of Environment and Climate Change

Volume 13, Issue 11, Page 390-398, 2023; Article no.IJECC.107599
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

Comparative Study on Carbon Footprint Assessment of Rice-Wheat Production System

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2023/v13i113182

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/107599

Original Research Article

Received: 02/08/2023
Accepted: 05/10/2023
Published: 09/10/2023

ABSTRACT

The carbon footprint is a robust tool to guide sustainable food production system. It is widely accepted as an indicator of GHGs emissions and their impact on global warming. An assessment was undertaken to measure the carbon footprint (CF) of rice-wheat production for two different locations i.e., Damoh (L_1) and Ludhiana (L_2), comes under central plateau and hill region, and Trans-Gangetic plain region of India, respectively. Further, variability in CF among these two climatically diversified regions having different soil type and management practices was analysed and compared. Results showed that, CF per unit area of rice and wheat production was obtained as 0.497 t Ce/ha and 0.481 t Ce/ha, respectively. Key contributors to CF were nitrogen fertilizer and energy use (diesel for tillage, sowing, harvesting and transport, and electricity for irrigation) for both

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crops in both regions. Nitrogen fertilizer comprised 27% and 31% of CF in rice, and 30% and 42% in wheat, for L_1 and L_2, respectively. Diesel and electric energy contributed 36% and 18% (rice, L_1), 26% and 27% (rice, L_2), 32% and 30% (wheat, L_1), and 30% and 18% (wheat, L_2). As the contributing factors to the CF vary between regions, mitigation strategies that account for regional diversity are likely to yield greater effectiveness than approaches solely focused on the country level.

Keywords: Carbon footprint; agroclimatic zones; regional diversity; rice-wheat production system; life cycle assessment.

1. INTRODUCTION

India has witnessed to attained a notable record of food grain production, with output increasing from 52 million tonnes (MT) in 1951-52 to approximately 323.55 MT in 2022-2023 (PIB, 2023). Among all the cereal crops, rice and wheat are the predominant ones in India, occupying the land area of nearly 43.8 million hectares (Mha) and 29.3 million hectares (Mha), resulting in a total production of 130.83 million tonnes (MT) and 112.18 MT in the fiscal year 2022-2023, respectively [1,2]. After the green revolution, the farmers were encouraged to adopt the high-yielding varieties with intensive use of agricultural inputs i.e., seeds, water, fertilizers, pesticides and other chemical and mechanical inputs to increase the productivity of the crops. The country has largely attained self-sufficiency as it transformed itself from a status of importer to an exporter over the past 70 years [3]. On the other hand, in achieving targeted food production, the intensive use of agricultural inputs created new challenges for future agriculture. The indiscriminate and injudicious use of agricultural inputs resulted in emission of greenhouse gases (GHGs), which has direct impacts on the environment. Estimates suggest that nitrogen alone contributes to over 50% of the overall carbon emissions in crop production [4].

In the context of its continuously expanding population, India is presently confronted with the dual challenges of enhancing food production with its available finite resources, while concurrently mitigating greenhouse gasses (GHGs) emissions attributed to this sector. Therefore, handling of this issue is paramount to reduce imprudent use of different forms of energy in the various field operations and improve the viability of agricultural production systems in long-term. Keeping the above problem in view, carbon footprint (CF) estimation was made in this study by critically analysing the rice-wheat production systems of climatically diversified regions using the approach of Life Cycle Assessment (LCA).

LCA is a powerful tool in environmental management, as it comprehensively evaluates the entire lifespan of a product or service, spanning from resource acquisition to manufacturing, distribution, usage, potential recycling, and eventual disposal. The LCA methodology proves particularly beneficial for gauging the ecological sustainability of crop production systems and facilitating comparisons between them from an environmental standpoint. Notably, recent studies have undertaken the quantification of environmental impacts across various cropping systems by employing LCA-based assessments [5,6,7]. However, the comprehensive quantification of CF at a high resolution has not been previously documented within the scope of any LCA based studies conducted in India, that encompasses the detailed considerations of crop management approaches and inputs used in various soil types of climatically diversified regions. Therefore, it is imperative to study the variations in CF of rice-wheat production systems on a regional basis to classify the hotspot points across the regions. This will enable to implement mitigation strategies to precisely and effectively target the particular region. To address this, we selected two climatically diverse regions and analysed the energy inputs and usage at individual step of the rice-wheat cropping system. The findings of this study hold the potential to improve the cultivation practices involved in the rice-wheat production system in a sustainable way.

2. MATERIALS AND METHODS

2.1 Study Area

The research was undertaken for districts of Damoh (L_1) and Ludhiana (L_2) comes under two dissimilar agro-climatic regions of India i.e., Central plateau and hill region, and Trans-Gangetic plain region, respectively. Both the districts i.e., L_1 and L_2, have the subtropical climate with average annual rainfall of 1095 mm [8] and 561 mm [9], respectively. The major portion of the L_1 district covered with shallow to medium black soil while in L_2, sandy loam to clayey soil is dominant throughout the area [10,11].

2.2 Objective and Scope Delineation

The primary objective of the research was to examine and compare the variability in GHGs emissions of the rice-wheat production system, cultivated in two climatically diversified regions having different types of soil and management practices. For that, the data collection was done from 42 farmers of both districts (18 from L_1 and 24 from L_2), cultivating paddy varieties (L_1: PA-6201 and JRH-4; L_2: PR-121 and PR126) through manual transplanting, and wheat varieties (L_1: MP-1203 and GW-322 L_2: HD-2967 and DBW-550) in most of the selected regions. Also, data was collected from secondary sources i.e., the package of practices [12] for *Rabi* and *Kharif* crops, issued by the Punjab Agricultural University, Ludhiana [13,14], related to tillage practices commonly followed by the farmers in both the regions for rice-wheat cropping systems. It includes the tillage practices that usually followed by the farmers in both the region for rice-wheat cropping system, seeding rate, quantity of fertilizer and pesticide applied, fertilizer varieties, irrigation, man-hour requirement throughout the growing season, and yield of the crops, etc. (Table 1). After that, CF assessment for each agricultural activity of rice and wheat cropping system was carried out by utilizing the LCA approach as outlined in the PAS 2050:2011 protocol [15], and analysed. In our study, emissions from the manufacturing of applied agrochemicals, mechanical operations for tillage, fertilization, irrigation, harvesting as well and transportation are included in the carbon emissions. This study does not consider the emissions of nitrous oxide (N_2O) and methane (CH_4) originating from cropland, as well as emissions resulting from post-harvest operations and crop production system waste.

2.3 Functional Component and System Perimeter

The functional unit plays a central role in LCA-based research by providing a critical reference point for quantifying both input and output data during the inventory analysis of any process. Therefore, two distinct functional units were employed: first, CF per unit area of production, written as tonnes of CO_2-equivalents per hectare (t CO_2eq/ha), enabling assessment of emissions relative to the land area utilized. Second, CF per unit weight of production, written as tonnes of CO_2-equivalents per tonne of grain (tCO_2eq/t). It facilitates evaluation of emissions concerning the yield of the agricultural production. These dual functional units were essential for comprehensive carbon footprint accounting within the study's scope.

Since, the assessment of CF was done for the single life cycle of rice-wheat production system. Therefore, system boundary was chosen as farm gate from agricultural inputs (tillage, seed, fertilizer, irrigation, pesticide, herbicide and up to harvesting) to the farm gate (transport of produce). It guarantees that all emissions linked to the utilized inputs, physical activities within the field and transport of the produce, are included. Note that, this analysis included the emission of greenhouse gases caused by agricultural inputs, practices, and energy carriers i.e., agricultural inputs, applied during rice-wheat cultivation only within the defined system boundary (Fig. 1).

2.4 GHGs emission from Agricultural Inputs

The quantification of CF rice-wheat production system was done by accounting the emission coming from the various direct and indirect sources of energy including fuel, seed, fertilizers, pesticides, herbicides, and other sources. It is estimated by summing the product of matching carbon emissions conversion coefficients (E_i) with corresponding input factors (X_i) and expressed as follows:

$$\text{GHGs emissions} = \sum_{i=1}^{n} E_i \times X_i \qquad (1)$$

Where, GHGs emissions are the overall carbon emissions per hectare; X_i is the applied agricultural input factors, e.g., diesel (l/ha), electricity (kW-h/ha), seed, fertilizer, pesticide and herbicide (Kg/ha), and labour requirement (man-h) etc.; and E_i is the appropriate carbon emission conversion coefficient for that particular factor of X_i.

The electric energy consumption (E_c) for irrigation per hectare was calculated by using the following formula:

$$\text{Electric energy consumption, } E_c = hp \times F_c \times d \times n \qquad (2)$$

Table 1. Amounts of agricultural inputs used and outputs of rice-wheat production systems

Crop	Region	Diesel, l/ha	Seed kg/ha	Fertilizer, kg/ha			Pesticide, kg/ha	Herbicide, kg/ha	Electricity, kW-h/ha	Labour requirement, man-h/ha	Yield, kg/ha
				N	P	K					
Rice	L_1	46	32	110	57.5	30	1.8	1.5	253.125	242	5300
	L_2	52.5	45	135	62	30	1.5	3	492	257	6500
Wheat	L_1	38.5	105	137.5	57.5	30	0.8	0	450	32	4800
	L_2	55.5	110	165	69	40	1.2	0.8	295.31	39	5800

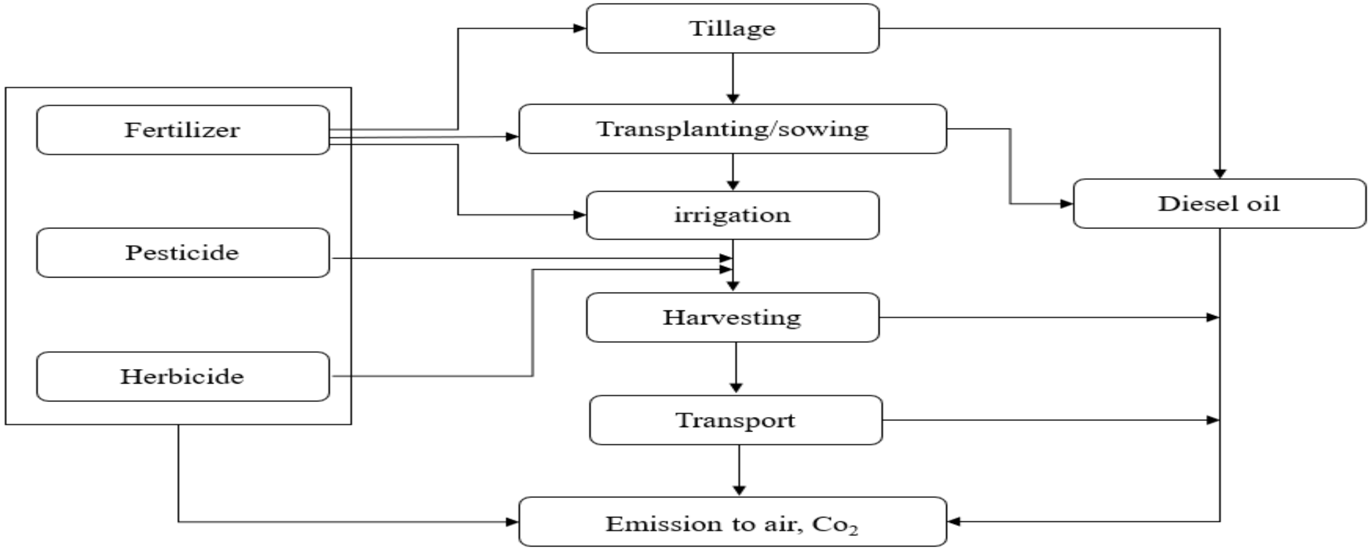

Fig. 1. Practices mainly contributing in CF of rice-wheat production system

Table 2. Emission factors of different agricultural inputs

Emission Source	Emission Factor	Reference
Wheat seed	0.12 kg Ce/kg	Pathak et al., [16]
Paddy seed	1.35 kg Ce/kg	Pathak et al., [16]
N fertilizer	1.3 kg Ce/kg	Lal, [17]
P fertilizer	0.2 kg Ce/kg	Lal, [17]
K fertilizer	0.15 kg Ce/kg	Lal, [17]
Pesticides	5.10 kg Ce/kg	Lal, [17]
Herbicide	6.30 kg Ce/kg	Lal, [17]
Diesel for machine	2.76 kg Ce/L	Dyer and Desjardins, [18]
Farm labour	0.108 kg Ce/h	Lal, [17]
Electricity	0.3023 kg Ce/kW-h	Li and Sun, [19]

Where, E_C is the electric energy consumption in kilowatt-hour (kW-h); hp is the pump energy rating (horsepower), F_c denotes the factor used for converting horsepower hours (hp.h) into kilowatt-hours (kW-h), taken as 0.75, n represents the quantity of pumps, and d signifies the estimated duration of pump operation during the entire crop season, measured in hours.

The carbon emission per unit weight was calculated by the following formula

$$\text{Carbon emission per unit weight (t Ce/t)} = \frac{Carbon\ emission\ per\ unit\ urea\ (t)}{Yield\ of\ the\ crop\ per\ unit\ area\ (t)} \quad (3)$$

The emission conversion coefficients used in this study were gathered from prior literature sources and are presented in (Table 2). These coefficients were employed to convert the inputs for rice-wheat production into energy coefficients, expressed as t Ce/ha.

3. RESULTS AND DISCUSSION

3.1 Carbon Footprint (CF) of Rice and Wheat

The CF for the rice-wheat production system was calculated on the basis of per unit area of production and weight of produce. The average CF per unit area of production and weight of produce for rice was found to be 0.497 t Ce/ha and 0.0835 t Ce/t, respectively. It was observed that, the CF per unit area and weight of rice was 32 % and 8% higher for L_2 (0.565 t Ce/ha, 0.087 t Ce/t) compared to L_1(0.428 t Ce/ha, 0.080 t Ce/t), respectively, (Table 3). The higher CF for L_2 in both the cases i.e., per unit area of production and weight of produce, was because of increased demand of irrigation due to less rainfall during the cropping season and higher use of herbicide compared to L_1, (Figs. 2, 3). The more use of electric energy for irrigation and herbicide for weed control caused the increased carbon emission per unit area of production and weight of produce for L_2 than L_1. Siyal et al*.,* [20] reported that energy used for irrigation through groundwater pumping, contributed significantly in the associated CF.

In case of wheat production, the average CF per unit area of production and weight of produce for wheat was found to be 0.481 t Ce/ha and 0.091 t Ce/t, respectively. The CF per unit area was found 10% higher for L_2 (0.505 t Ce/ha) compared to L_1 (0.457 t Ce/ha) but the CF per unit weight was less. The CF per unit weight was of 0.095 t Ce/t for L_1 and 0.087 t Ce/t for L_2, revealed that the CF per unit weigh of produce was 9.2% higher for L_1 than L_2. (Table 3). The higher CF per unit weight of produce for L_1 was because of greater use of electric energy for irrigation and less productivity compared to L_2, (Figs. 4, 5).

Previous studies reported higher CF per unit area production and weight of produce for rice and wheat cultivation in India [16,21] in comparison to this study. This is because, the mentioned previous researches accounted the emission of nitrous oxide (N_2O) and methane (CH_4) from cropland, and also emissions from the post-harvest operations and waste disposal, in the total GHGSs emission. The aim of this research was only to compare the CF caused by the different management practices and inputs used in two different soil type in dissimilar climatic conditions of India. Therefore, the induced emission from the cropland and other sources was avoided to consider in the study.

3.2 Source Wise Contribution to CF

Use of nitrogen fertilizer and consumption of electric energy in irrigation, and diesel (in tillage, pudding, sowing, harvesting and transportation) were the major factors contributing to the CF for rice and wheat cultivation in both the region. The contribution of nitrogen fertilizer to the CF was 27% and 31% in rice production and 30% and 42% in wheat production in both L_1 and L_2 region, respectively. Whereas, the contribution of diesel and electric energy to the CF in rice was about 36% and 18 % for L_1, and 26% and 27% for L_2, respectively, (Figs. 2 & 3). Similarly, in case of wheat production, the percentage contribution of diesel and electric energy to the CF was 32% and 30% for L_1, and 30 % and 18% for L_2, respectively, (Figs. 4 & 5). Arunrat et al., [22] compared the emission from two different rice farming practices and found that, organic farming resulted lesser GHG compared to conventional rice farming. Zhou et al., [23] found that straw return practices reduce the requirement of chemical fertilizer by 16% and improve the production of rice-wheat cropping system. Also, these results were in agreement with previous study conducted by Chen et al., [24] in 2001-2018, while identifying the key contributors to CF.

The overall results revealed that, the nitrogen consumption per hectare was higher for L_2 during both the crop i.e., rice and wheat, compared to L_1 resulted in increased yield with greater GHGs emission per hectare. Whereas, the increased use of electric energy for L_2 in rice production was because of low rainfall in the area during cropping season resulted more irrigation requirement compared to L_1. On the other hand, the higher electric energy consumption for L_1 in wheat production is due to less efficient irrigation practices (flood irrigation) adopted by the farmer resulted more time requirement to irrigate the field. Fagodia et al., [25] reported that use of efficient irrigation techniques like drip or sprinkler, increased the water productivity along with reduced emission due to lesser energy required for irrigation.

The diesel consumption in case of wheat and rice production for L_1 was higher because of the soil type (black soil) required a greater number of tillage practices to make it favourable for healthy crop growth compared to L_2 having sandy loam to clayey soil.

Table 3. CF of rice-wheat cropping system in two diverse climatic regions of India

	Rice		Wheat	
	CF per unit area, (t Ce/ha)	**CF per unit weight, (t Ce/t)**	**CF per unit area, (t Ce/ha)**	**CF per unit weight, (t Ce/t)**
L_1	0.428	0.080	0.457	0.095
L_2	0.565	0.087	0.505	0.087
Mean	**0.497**	**0.0835**	**0.481**	**0.091**

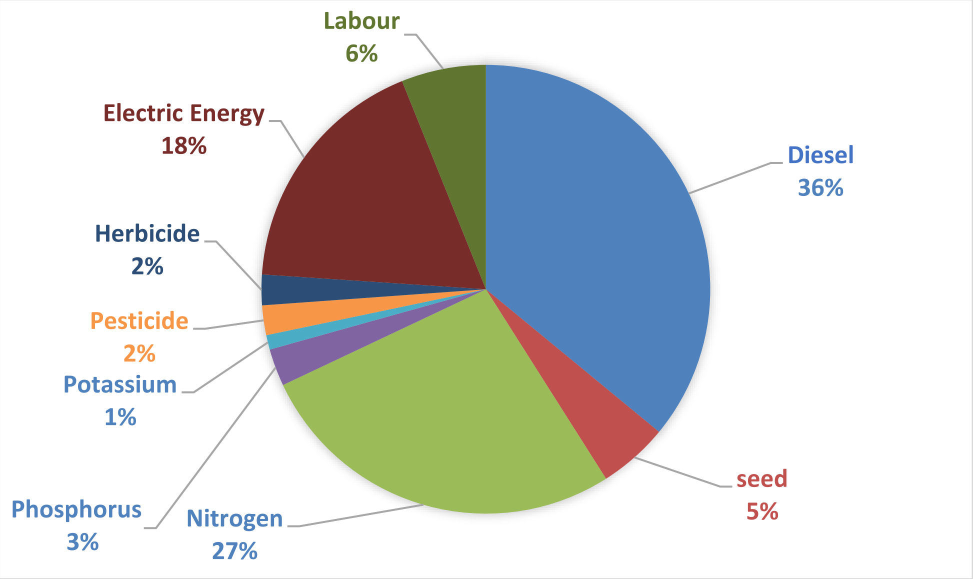

Fig. 2. Percentage breakdown of carbon emissions sources for rice in L_1

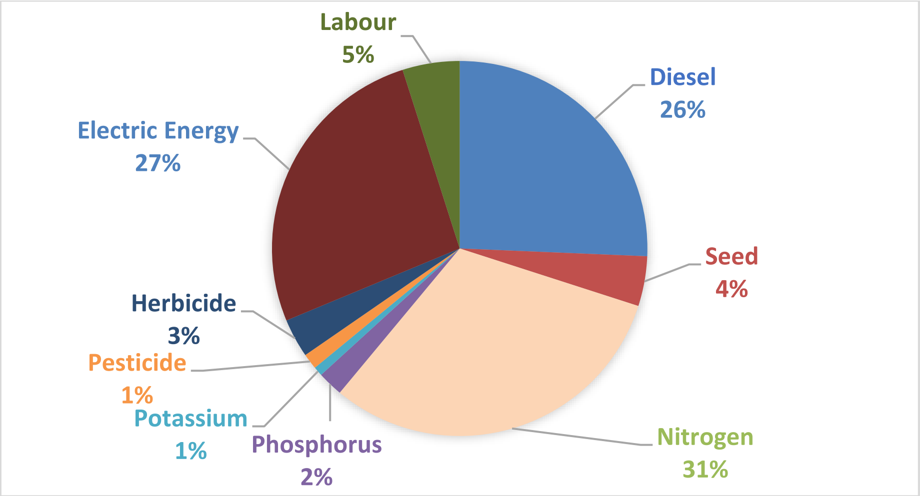

Fig. 3. Percentage breakdown of carbon emissions sources for rice in L₂

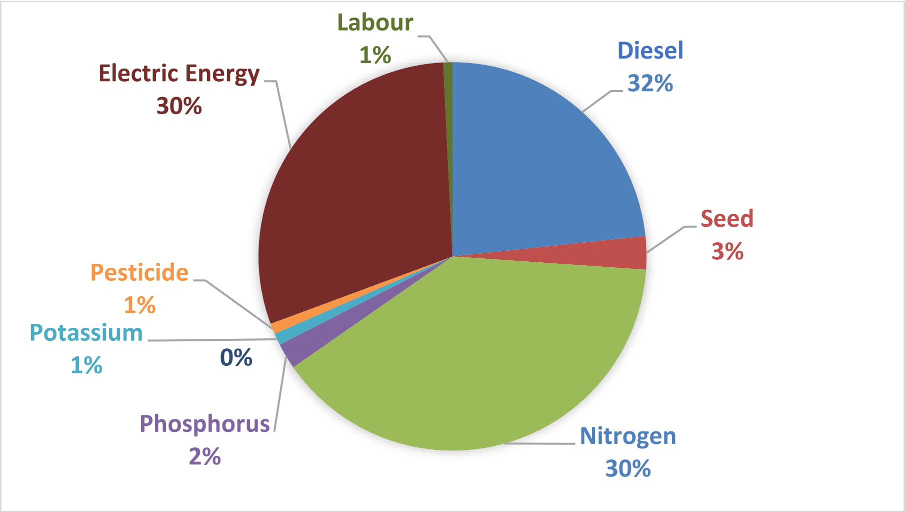

Fig. 4. Percentage breakdown of carbon emissions sources for wheat in L_1

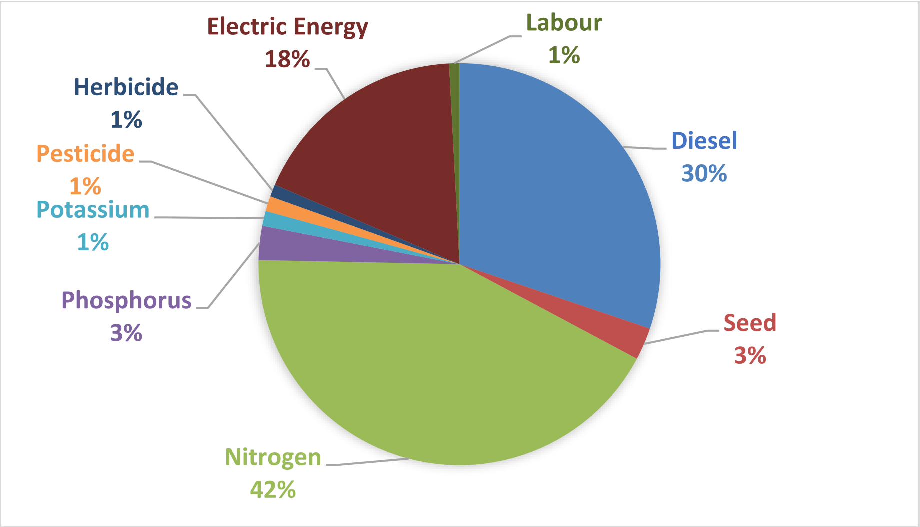

Fig. 5. Percentage breakdown of carbon emissions sources for wheat in L_2

4. CONCLUSION

CF of rice-wheat cropping systems were quantified for two different agro-climatic regions of India using the data collected from survey and secondary sources. It was found that, the CF per unit area of production of rice and wheat, was found higher for Ludhiana (L_2) compared to Damoh (L_1). Whereas, the CF per unit weight of wheat cultivation was higher for Damoh (L_1) compared to Ludhiana (L_2). The N fertilizer, electric energy for irrigation and diesel consumption (in tillage, pudding, sowing, harvesting and transportation) were the principal determinant responsible for variation in CF among the regions. Rice production exhibited both a greater carbon footprint (CF) and a broader range of CF variations across different regions in comparison to wheat production. Given that the factors influencing CF levels differ from one region to another, implementing mitigation strategies that account for regional variations would likely yield superior results compared to strategies based solely on national assessments. It is advisable to conduct additional research to gain insights into the factors driving the adoption of specific management practices. This approach holds promise, especially for countries with diverse climatic conditions, in achieving long-term effectiveness.

ACKNOWLEDGEMENTS

We would like to express our sincere thanks to the farmers of Damoh and Ludhiana for sharing their data, which has greatly enriched our research.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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