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Assessment of environmental impacts: a life cycle analysis of wheat and rice production in Madhya Pradesh

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Abstract. The production of cereals is one of the primary activities that is responsible for most of the environmental degradation that is caused by agricultural activities. In this study, an attempt was made to determine the ecosystem & resource emissions along with emissions affecting human health, causing due to agricultural activities. LCA is used to conduct an analysis of 17 types of emissions caused by rice and wheat production per hectare in Madhya Pradesh. Based on LCIA and Monte Carlo simulation, the study provides valuable insights into the regional environmental emissions associated with direct seeded rice (DSR), irrigated wheat (IW) and rainfed wheat (RW). Study shows that except for Marine eutrophication (MEUT) and Agricultural land use (ALU), rice production has relatively higher impact than wheat production. Irrigated wheat production found with higher potential of causing non-cancerous diseases caused by air pollution, whereas rice production has the potential to contribute to cancer disease. The production of rice and wheat in Madhya Pradesh state cumulatively contributes 0.008 Gt CO_2 eq. (0.10% of global total) to the global agrifood system GHG emission within farmgate. Since majority of the emissions are caused by soil & crop nutrients and fuel consumption, here it became important to adopt sustainable agricultural practices & biofuel to lessen the environmental impact of wheat & rice production and make sustainable agro-food system of Madhya Pradesh. Based on study results emission mitigation policies have been suggested taking the existing policies into consideration.

Key words: carbon footprint, environmental impact, life cycle assessment, rice, wheat.

INTRODUCTION

Food is one of the most essential items for human beings. However, there are enormous issues created by modern-day food production and consumption activities. The study conducted by Gleick et al. (2014) estimates that about 70 percent of the all-fresh water is used for growing the agriculture crops; Nesheim & Malden (2015) reveals that huge CO_2 are emitted when fossil fuels are used during various aspects of the food cycle. Also, the depletion of natural resources, such as cutting down forests, are some of few negative impacts of food production and consumption activities. Food production and consumption have a serious negative impact on the environment. Since food commodities may travel great distances from production to consumption, the effects of food are spread out and vary over the entire planet due to the nature of the global economy. Studies have revealed that the ecosystem is impacted by the increased CO_2 emission that transpires during different stages of the life cycle of food crops. In 2018, CO_2 emission from Crop and livestock activities within the farm gate increased from 4.6 Gegatonnes CO_2 equivalent to 5.3 Gegatonnes CO_2 equivalent as compared to 2000 (FAO, Analytical Brief 18, 2021). Even among crops environmental stress varies; for example, Pathak et al. (2010) have shown that the production of regular rice results in GHG emissions that are roughly 10.2 and 43.3 times higher than those of wheat and vegetables, respectively.

Agricultural production adds to the climate change by emitting GHG (Jimmy et al., 2017; Green et al., 2018; Taki et al., 2018; Tayefeh et al, 2018; Lynch et al., 2021; Nayak et al., 2022) whereas increased climate change leads to higher temperature and unfavorable weather conditions which ultimately cause a negative impact on production yields (Adams et al., 1998; Arora, 2019; Malhi et al., 2021; Saravanakumar et al., 2022; Sengupta & Mohanasundari, 2023a; Sengupta & Mohanasundari, 2023b). This cycle of cause and effect poses a grave threat to the food security of nations and poses challenges to environmental sustainability.

Wheat and rice production play significant roles in global agricultural systems, but they also contribute to emissions that have environmental implications. These emissions not only contribute to climate change but also contribute to air pollution and impact ecosystem, resources, and human health. At global level Sustainable production and consumption are the hot topic of discussion among the scholarly community. But still there are just a handful of studies on interrogating environmental stress caused by agricultural practices & production generally in India and particularly in Madhya Pradesh state. The studies that demonstrate the environmental impact of a variety of Indian Agri-products from cradle to farm gate will aid in re-evaluating our production and production techniques with an eye towards sustainability.

We need to understand the linkages between agricultural production practices and environmental degradation if we are to reduce agriculture's environmental impact. Several studies have been conducted to measure the regionalized environmental impacts of different agricultural produced across the globe. However, most of the studies are region-specific and using different methods, very few studies has been conducted using LCA for India. Keeping this context, the purpose of this study is to assess the Environmental impact, especially carbon footprint of Madhya Pradesh's agricultural production, with the intention of contributing further to the policy development for agri-food system. Wheat and Rice are two major agricultural products in Madhya Pradesh; hence the study has analyzed the environmental impact of both agricultural produce, which can help in shrinking the carbon emission by adopting sustainable production practices.

Why Madhya Pradesh?

Madhya Pradesh, located in central India, has a predominantly subtropical climate. The state experiences three major seasons: summer (March to June), monsoon (July to September), and winter (October to February). The climatic conditions vary across different regions of Madhya Pradesh, but in general, the state provides favorable conditions for wheat and rice production. Madhya Pradesh is the second largest state in India with a total area use of approximately 6,083' thousand hectares for wheat production & 10th largest in area covered in rice production covering approximately 2,117' thousand hectares (India Stat). The state is mainly agrarian, and agriculture plays a crucial role in the states economy, with varied quantity of production across district as shown in Fig. 1.

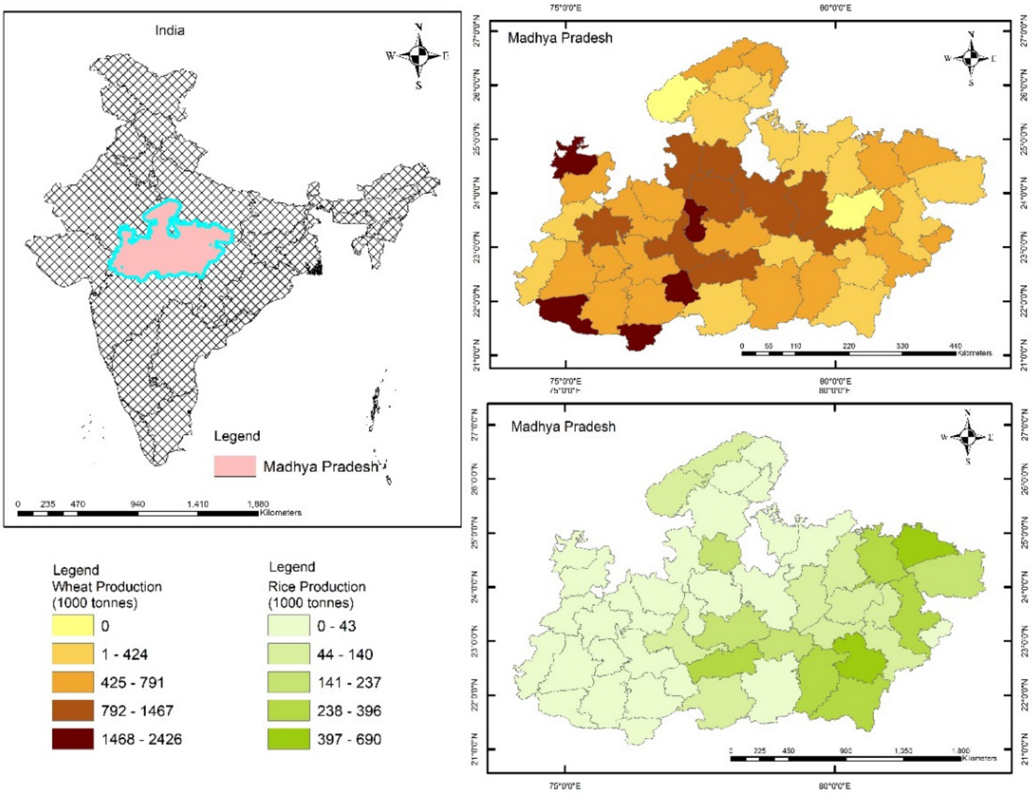

Figure 1. Study area map.

Source: Authors creation based on production data from - Production statistics, Ministry of Agriculture and Farmers welfare.

The state is one of the major producers of wheat & rice in India (Ranked 2nd and 12th for wheat & rice respectively), and the favorable temperature and moderate precipitation during winter contribute to its successful growth. Rice is predominantly cultivated during the monsoon season, while wheat is primarily grown during the winter season. Adequate irrigation and timely rainfall play crucial roles in achieving successful crop yields. It is widely recognized that there are regional variations in environmental impacts resulting from agricultural crop production. Thus, assessing the environmental impact contribution of these two crops of Madhya Pradesh is important for policymakers to intervene & mitigate emissions and bench marking the best practices to lean towards agricultural sustainability. This study will provide a localized comprehension of the environmental impact of agricultural crop production in Madhya Pradesh. Until now, no study has been conducted specifically on Madhya Pradesh; this study will fill this gap and add to the existing knowledge of study. This would aid in the identification of regional challenges and opportunities for sustainable agricultural practices.

LITERATURE REVIEW

Emissions from agriculture

Agriculture has a significant impact on the ecosystem, human health, and resources through various emissions it generates. These emissions go beyond anthropogenic sources and can have direct consequences on the environment and society. Different studies (Roer et al., 2012; Fusi et al., 2014; Achten et al., 2015; Falcone et al., 2019; Mancuso et al., 2019 and Selvaraj et al., 2021) has been conducted across globe on measuring the emission of different crops including wheat & rice, few major studies have been depicted in Table 1, which have covered many emissions in the study.

Table 1. Studies on environmental impacts of agricultural produce

Author, Year	Method & region	FU	Emission covered		
			Ecosystem	Resources	Human health
Roer et al., 2012	LCA, Central Southeast Norway	kg^{-1} production	GWP, FWET, FEUT, MET, MEUT, TEAF, TETO	FRS	HCT, HNCT, OD, PMF, POF
Fusi et al., 2014	LCA, Italy	Area harvested ha^{-1}	GWP, TEAF, FWET, MET	FRS	OD, HCT, HNCT
Achten et al., 2015	LCA, EU	kg^{-1} production	GWP, TEAF, FWET, MET, ALU	-	-
Falcone et al., 2019	LCA, Italy	Area harvested ha^{-1}	GWP, TEAF, TETO, ALU, ULO, NLT, MET, FWET, MEUT, FEUT	FRS, MRS, WD	OD, HCT, HNCT, IR, POF, PMF
Mancuso et al., 2019	LCA, EU	Ton^{-1} Production	GWP, TEAF, FWET, FEUT, TETO, MEUT, MET	-	-
Selvaraj et al., 2021	LCA, India	Area harvested $season^{-1}$	ALU, GWP, FWET, FEUT, MET, MEUT, TEAF, NLT, TETO	WD, FRS, MRS	IR, HCT, HNCT, OD, PMF
This Study	LCA, M.P.- Central India	Area harvested ha^{-1}	FWET, FEUT, GWP, ALU, MET, MEUT, OFHH, OFTE, TEAF, TETO	FRS, MRS	PMF, HCT, HNCT, IR, OD

Source: Authors' compilation.

Selvaraj et al. (2021) conducted a comprehensive assessment on the overall impact of various agricultural products, such as rice and wheat, in India. Emissions are broadly categorized in 3 categories based on ReCiPe 2016 endpoint indicators: emission to Ecosystem, emission to Resources and emission to Human Health. Represented as, Agricultural land use (ALU), Global warming potential (GWP), Freshwater ecotoxicity (FWET), Freshwater eutrophication (FEUT), Marine ecotoxicity (MET), Marine eutrophication (MEUT), Terrestrial acidification (TEAF), Terrestrial ecotoxicity (TETO), Natural land transformation (NLT), Urban land occupation (ULO), Ozone formation, Human health (OFHH), Ozone formation, Terrestrial ecosystems (OFTE), Water depletion (WD), Fossil resource scarcity (FRS), Mineral resource scarcity (MRS), Ionizing radiation (IR), Human carcinogenic toxicity (HCT), Human non-carcinogenic toxicity (HNCT), Ozone depletion (OD), Fine particulate matter formation (PMF) and Photochemical oxidant formulation as (POF). Numerous studies on a global scale have investigated a wide variety of impact categories associated with agricultural production. These studies have evaluated various emissions and their associated environmental impacts. The table below (Table 1) displays the various studies and emissions covered. In the discussion section, findings from these studies have been compared with those of this study.

GHG emission

Agricultural production is a significant contributor to the overall environmental burden, particularly in terms of global warming. The reduction of agricultural emissions, mainly methane (CH_4) and nitrous oxide (N_2O), could play a crucial role in combating climate change (Lynch et al., 2021). Studies have shown that agricultural practices and the use of nutrients and fertilizers have a substantial impact on emissions. Excessive use of nitrogen fertilizers in wheat and barley cultivation has been found to increase environmental impact (Fallahpour et al., 2012). Conventional tillage in wheat production has also been identified as a contributor to greenhouse gas (GHG) emissions, which can be reduced by implementing zero tillage methods (Aryal et al., 2014). Rice, being a staple for more than half of the global population, is an essential agricultural product, particularly in Asia, where it is widely consumed (FAO, 2011; Muthayya et al., 2014; Miranda et al., 2015). Rice emissions account for more than 30% of CO_2 equivalent emissions in Bangladesh (FAO, 2017). Nitrogen fertilizers used in rice fields have been found to contribute significantly to global warming, with LCA studies indicating that rice fields and nitrogen fertilizers are responsible for 29.29% of global warming (Jimmy et al., 2017). The global warming potential (GWP) of rice production increases linearly with inputs such as fertilizers (Tayefeh et al., 2018). The environmental impact of different crops varies based on geographical region, inputs, and cultivation techniques. Wheat production emits 1.27 t CO_2 equivalent per hectare, while rice production emits 2.44 t CO_2 equivalents per hectare (Nayak et al., 2022). The amount of nitrogen fertilizer used in wheat production significantly influences its carbon footprint, with values ranging between 292.3 and 765.3 kg CO_2 equivalent per hectare (Kumar et al., 2021). LCA studies on wheat production in various regions have estimated emissions at approximately 229.6 kg CO_2 equivalents per ton in New South Wales, 5,455 kg carbon emissions per hectare in China, and 680.36 kg CO_2 equivalents per ton for irrigated wheat production and 381.30 kg CO_2 equivalents per ton for rainfed wheat production (Brock et al., 2012; Zhang et al., 2017; Mondani et al., 2017). Wheat production in different countries also shows variations in carbon emissions, such as 154 kg CO_2 equivalents per ton in Spain and 600–1,400 kg CO_2 equivalents per hectare annually in Canada (Lechón et al., 2005; Gan et al., 2012).

It is important to note that carbon footprint estimates are specific to the geographic region and production systems studied and may not be directly applicable to other regions or systems. Different methodologies and assumptions can lead to variations in carbon footprint estimates. For example, a study in Finland found that wheat production caused 2,330 kg CO_2-eq. per hectare or 590 g CO_2-eq. per kilogram (Rajaniemi et al., 2011). Another study in Iran reported carbon emissions ranging from 805.46 to 1,164.12 kg CO_2 eq. per hectare for different levels of nitrogen fertilizer use (Fallahpour et al., 2012). Studies evaluating the environmental impact of winter wheat production using the life cycle assessment (LCA) method have shown that utilizing less than 150 kg ha^{-1} of nitrogen can significantly reduce the aggregated environmental indicator

(Eco-X) (Brentrup et al., 2004a; Brentrup et al., 2004b). Below Table 2 & 3 dipicted the GHG emission from wheat & rice production from different literatures.

Table 2. Carbon emission from Wheat production

GHG emission	Study area	Method	Author, Year
1.27 t CO_2 eq. h^{-1}	India	Emission coefficients	Nayak et al. (2022)
292.3–765.3 kg CO^2 eq. h^{-1}	Jharkhand	Cool Farm Tool	Kumar et al. (2021)
229.6 kg CO^2 eq. t^{-1}	NSW	LCA	Brock et al. (2012)
600–1,400 kg CO^2 eq. h^{-1} yr^{-1}.	Canada	Site-specific data & empirical modeling	Gan et al. (2012)
0.2–0.6 kg CO^2 eq. kg^{-1}	Sweden	LCA	Röös et al. (2011)
805.46–1,164.12 kg CO_2 eq. h^{-1}	Iran	LCA	Fallahpour et al. (2012)
154 kg CO^2 eq. t^{-1}	Spain	LCA	Lechón et al. (2005)
Wheat (2,330 kg CO_2-eq. ha^{-1}) (590 g CO_2-eq. kg^{-1})	Finland	LCA	Rajaniemi et al. (2011)
Irrigated (680.36 kg CO_2 eq. t^{-1}) Rainfed (381.30 kg CO_2 eq. t^{-1})	Iran	Emission coefficients	Mondani et al. (2017)
5,455 kg CO_2 eq. h^{-1} or 0.75 kg CO_2 eq. kg^{-1}	China	LCA	Zhang et al. (2017)

Table 3. Carbon emission from Rice production

GHG emission	Study area	Method	Author, Year
8.80 ± 5.71 t CO_2 eq. h^{-1}	Punjab	CROPWAT Model	Kashyap & Agarwal (2021)
2.44 t CO_2 eq. h^{-1}	India	Emission coefficients	Nayak et al. (2022)
2,000 kg CO_2 eq. ha^{-1} yr^{-1} (Upland rice)	India	CFT	Vetter et al. (2017)
20,000 kg CO_2 eq. ha^{-1} yr^{-1} (Paddy rice)	India	CFT	Vetter et al. (2017)
11,881 kg Carbon emission ha^{-1} or 1.60 kg Carbon emission kg^{-1}	China	LCA	Zhang et al. (2017)
0.37 kg CO_2 eq. ha^{-1}	China	Emission coefficients	Cheng et al. (2014)
0.333 for rice and 0.413 for basmati rice	India	Emission coefficients	Pathak et al. (2010)
1.34 kg CO_2 eq. kg^{-1} (monsoon season) 2.85 kg CO_2 eq. kg^{-1} (dry season)	Bangladesh	IPCC Tier 1 method	Shew et al. (2019)

Source: (Table 2 & 3) Authors compilation.

Agricultural activities not only contribute to climate change & ecosystem emissions, but they also attribute harm to resources & society. However, it is 'well-documented that regional variations in these impacts exist due to diverse climatic and geographic factors. Surprisingly, until now, no impact assessment has been reported for the state of Madhya Pradesh in India, despite it being situated in the central region and having an exceptionally suitable climate. This cutting-edge study is the first of its kind to thoroughly assess the impacts on region's ecosystem, resources, and environment. The objective of the study is to assess the environmental impact of the Wheat & Rice production in central region of India, specially focusing on GHG emission. As evidenced, the variations in emissions across geography, study questioned, what is the level of average environmental degradation caused from wheat and rice production per hectare in Madhya Pradesh?

DATA AND METHODS

Data collection & Conversion

The data of production, yield, and cultivated area of various foodgrains were collected from 'India stat' and all the sowing requirements (Seed rate, Fertilizers, FYM, Pesticides & Nutrients) of various crops is collected from Farmer Welfare and Agriculture Development Department, Madhya Pradesh, given as a blanket requirement of the foodgrains. Since the data on Electricity and Fuel consumption in agricultural production for India is not available on 'Agribalyse' and 'Ecoinvent' database of LCA. Lieu to that information related to other inputs such as fuel and electricity consumption is collected from various sources and considering them as proxy inputs. The energy use is converted for present scenario by multiplying the specific energy requirement (Singh et al., 2007) per kg to the study time yield of wheat, For Rice energy requirement proxy was taken from Ranguwal & Singh (2022) and converted by reducing the energy used in sowing/ seedling, diesel and fertilizers from total MJ h^{-1} used in rice production. The production yield data for the crops for Madhya Pradesh is collected from 'India Stat' for the year 2020–2021, along with the fuel & energy use from Singh et al. (2007) and Ranguwal & Singh (2022).

Methodology

Life cycle assessment (LCA) is a method for quantifying and evaluating the environmental consequences of a product, process, or activity over its life cycle. It is the accumulation and assessment of a product system's inputs, outputs, and potential environmental impacts throughout its life span. LCA can assist in identifying more sustainable options. To reach the objective of the study, and measure environmental stress caused by crop production system- Life Cycle Assessment (LCA) approach has been used utilizing 'OpenLCA' software and 'Ecoinvent' and 'Agribalyse' data sources and some secondary information collected from various sources like government reports and research to assess the environmental impact. ReCiPe 2016 Midpoint method has been used to assess the detailed environmental harm. The uncertainty in the inputs is reduced using sensitivity analysis using Monte Carlo simulation of 1,000 iterations. ReCiPe 2016 Midpoint has used below mentioned impact calculation equation to estimate the midpoint impact scores for each category:

$$Ii = \sum_{i=1}^{n} (C_i * P\,i * Di)$$

where: I_i is the midpoint impact score for a specific impact category (e.g., climate change, human toxicity, freshwater eutrophication, etc.). n is the number of elementary flows within the impact category. C_i represents the characterization factor of the i^{th} elementary flow, representing the relative contribution of the flow to the impact category, typically in a unit of kg CO_2-eq, kg PM2.5-eq, or similar impact units (Emission conversion factor). P_i shows the amount of the i^{th} input consumed in the production process. And lastly, D_i shows the regional (or country-specific) damage potential of the i^{th} elementary flow, characterizing the damage to the region or country because of the flow's emissions or consumption per unit of the elementary flow. Characterization factor & region specific damage potential in ReCiPe 2016 has been mentioned by Huijbregts et al. (2017a, 2017b).

Since the data exerted from Practice of Package is for whole Madhya Pradesh, it is assumed to be normally distributed. 1,000 random value of inputs (P_i) are generated for Monte carlo simulation. LCA was perfromed with each random input. At last the mean of all emission from 1,000 runs of calculations is considered as most possible emission potential. 'OpenLCA' software has been used for these analysis.

Goal & Scope: This study's objective is to (1) to assess and compare the environmental burdens (on Ecosystem, Resources and Human Health) associated with the production of two of the most prevalent crops in Madhya Pradesh (India), namely Rice and Wheat. A cradle-to-farm gate method (within system) was utilized to carry out the research for this study.

System boundaries: System boundaries play an important role in starting life cycle assessment for any produced. The system investigation includes all the inputs in the form of fertilizer, pesticides & nutrients, fuel, along with other basic and suggested (blanket) sowing requirements. System analyzed conventional tillage scenario in crop production and measured the output in form of crop grain meanwhile excluded subsequent processes like the transformation of grain into feed, consumption, and crop residue management as shown in Fig. 2. ReCiPe (2016) Midpoint method was used to assess the environmental impact of the wheat and rice production at farm gate. System also undertakes the backward linkages associated with the inputs, where 'Agribalyse' databased is used for India or global level with utmost priority.

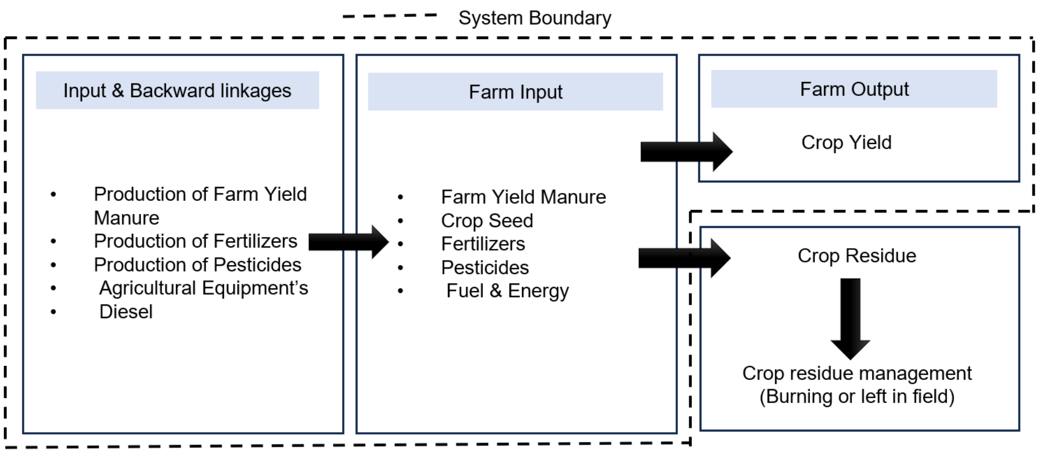

Figure 2. Schematic representation of the agricultural activities carried out as system boundaries. Source: Authors selected study boundaries.

Data quality: As inventory data plays an important role in the output emission results, the overall data quality in the study has been assessed to be fair using International Reference Life Cycle Data System (ILCD). Fairly representing the Time, Technology, Geography, Completeness, Precision and Methodological appropriateness. Data is used from authenticated government sources as a blanket requirement for the state, hence representing the geographic representativeness. As per the objective 'ReCiPe 2016 (Midpoint)' method was used to measure the other Environmental impacts along with Global warming Impact. This methodology is employed and preferred over other calculation methods because it can provide more comprehensive, specific, and coherent results regarding the environmental impacts than other methodologies. This is confirmed by the fact that most rice and wheat production LCA analysis has used the 'Recipe 2016

Midpoint' technique (Jimmy et al., 2017; Yodkhum et al., 2018; Habibi et al., 2019; Shew et al., 2019; Harun et al., 2021; Rezaei et al., 2021; Escobar et al., 2022; Xu et al., 2022) in last 5 years.

Functional unit: Defining a functional unit in life cycle assessment is essential specifying the amount or quantity of a product, process, or service that is being studied. It is a way to standardize the comparison of environmental impacts across different products, processes, or services. The functional unit determines the boundaries and scope of the assessment and helps to ensure that all environmental impacts are accounted for in a consistent and meaningful way. In this study, the functional unit for emission from wheat and rice production is measured in Crop production in kg ha^{-1}.

RESULTS AND DISCUSSION

Life Cycle Inventory

The research investigated the use of all inputs in the production of both wheat and rice, beginning with the preparation of the soil and continuing through planting, the management of fertilizer and pesticides, and the utilization of resources such as fossil fuel, energy, and water, along with pre farm activities linked to the input activities. Input inventory for the wheat and rice has been gathered from MP Govt (POP) reports. Due to the lack of specific data regarding the fuel consumed by agricultural apparatus, data exerted from Chen (2015). All inputs considered in producing rice & wheat in Madhya Pradesh are displayed in the Table 4 below. In rice production consideration was given to a hybrid DSR (Direct Seeded Rice) scenario of rice production. The fuel and energy data from Ranguwal & Singh (2022) have been extracted and converted.

LCA result

The study was performed in accordance with the ISO 14044 series procedural framework for

Table 4. Inputs considered in Wheat & Rice LCI

Input	Unit	Crop		
		(IW)	(RW)	(DSR)
(01) Seed rate				
Seed rate	kg ha^{-1}	100	100	16
(02) Fertilizers & Soil Nutrients				
N	kg ha^{-1}	120	40	100
P	kg ha^{-1}	60	20	40
K	kg ha^{-1}	30	0	25
Zn	kg ha^{-1}	25	25	
Manure (FYM)	kg ha^{-1}	-	-	50
(03) Crop protection chemicals				
Pendimethalin	kg ha^{-1}	1	1	-
Sulfosulfuron	g ha^{-1}	33.5	33.5	-
Metribuzin	g ha^{-1}	250	250	
Dichlorophenoxyacetic acid	g kg^{-1} seed	0.5	0.5	
Carbendazim	g kg^{-1} seed	3	3	
Tebuconazole	g kg^{-1} seed	1	1	
Azospirillum	kg ha^{-1}			5
Carbendazim	g kg^{-1} seed			2.5
Mancozeb	g kg^{-1} seed			3
Imidacloprid (Guicho/Imidate)	kg ha^{-1}			
Dichlorophenoxyacetic acid	mL ha^{-1}			1,000
Pretilchlor	mL ha^{-1}			1,250
bensulfuran methyl	kg ha^{-1}			10
Fenoxaprop-p-ethyl	mL ha^{-1}			500
(04) Fuel				
Fuel (Diesel)	L ha^{-1}	37.2	63.9	144

* IW – Irrigated wheat; RW – Rainfed wheat; DSR – Direct seeded rice.
Source: Authors own data compilation from MP Govt (POP) reports.

carrying out LCA. The collected inventory data was analyzed using OpenLCA 1.11.0 software developed by GreenDelta. After the sensitivity analysis with 1,000 iterations of Monte Carlo simulation, the results are discussed below in 3 categories i.e., Emission to Ecosystem, Emission to Resources and Emission causing impact on Human Health.

Emission to Ecosystem. The LCA results of the study indicate that the emission from rice (DSR) has the highest GHG emission of 1,387.44 kg CO_2 eq. h^{-1} whereas irrigated and rainfed wheat production GHG emission was found to be 853.52 & 613.33 kg CO_2 eq. h^{-1} respectively based on the inputs given on the farm. ALU (Agriculture land use) represents the ecological devastation caused by the steady use of land for agricultural purposes. Every farming activity on a specific area of land used for agriculture over a specific time can cause damage. Therefore, when calculating ALU, all activities associated with agriculture's LCA are considered. Again, the ecological damage caused by land occupation is dependent on the level of environmental quality that is maintained throughout the occupation. Rice cultivation was observed with land use potential of 110.15 m^2 a crop eq (square meters per year of crop equivalent), whereas rainfed wheat requires slightly more land compared to irrigated wheat. Ozone formation (OFHH & OFTE) emission can negatively impact terrestrial vegetation by NO_2 emission which contributes to the formation of ground-level ozone. The study found that rice production has the highest impact on ozone formation in terrestrial ecosystems, followed by rainfed wheat and then irrigated wheat. Similar impacts were found in ozone formation impacting human health. Study results indicate that DSR cultivation methods result in higher emissions of NO_x {The term 'Nitrogen oxides' (NO_x) typically encompasses a combination of two distinct gases: Nitric oxide (NO) and Nitrogen dioxide (NO_2)}, which can contribute to the formation of ground-level ozone and potentially harm terrestrial plant life and ecosystems.

Terrestrial acidification (TEAF) is another major emission caused by the application of application of fertilizers which can harm plants, disrupt soil ecosystems, and affect nutrient availability. It can also indirectly impact other organism's dependent on healthy plant communities. Rice (DSR) production found with the highest potential impact on TEAF, with a value of 6.56 kg SO_2 eq. Irrigated wheat follows with a value of 4.03 kg SO_2 eq, and rainfed wheat has the lowest potential impact with a value of 3.27 kg SO_2 eq. Agricultural production activities have potential to release various toxic substances/ pollutants during crop production cycle, causing 'Terrestrial ecotoxicity' (TETO). This study revealed that rice production has more than 3 times higher TETO potential than irrigated & rainfed wheat. The emissions among the produced illustrated in Fig. 3 below.

Madhya Pradesh is well resourced with river flows. Several small rivers get merged with major rivers in the state like 'Narmada' & 'Tapti' which lastly get merged in ocean. There is a risk that fertilizers & pesticides can run off agricultural sewage containing agricultural pollutants in nearby water bodies & rivers during rainfall. which eventually flow into the oceans. Once these pollutants get mixed in the marine environment, these contaminants can have adverse effects on marine organisms. The study found rice production with 389,969 kg 1,4-DCB (1,4-Dichlorobenzene) of indirect MET potential followed by wheat production; 22,795 & 186,328 kg 1,4-DCB of irrigated & rainfed wheat respectively. Additionally, these toxic pollutants possibly cause FWET potential of approximately 36 kg 1,4-DCB in wheat production, and more than 5 times higher (191 kg 1,4-DCB) in rice production. Whereas, when the excessive enrichment of nutrients, particularly N & P, gets mixed in marine water & freshwater resulted in Marine eutrophication (MEUT) and Freshwater eutrophication (FEUT).

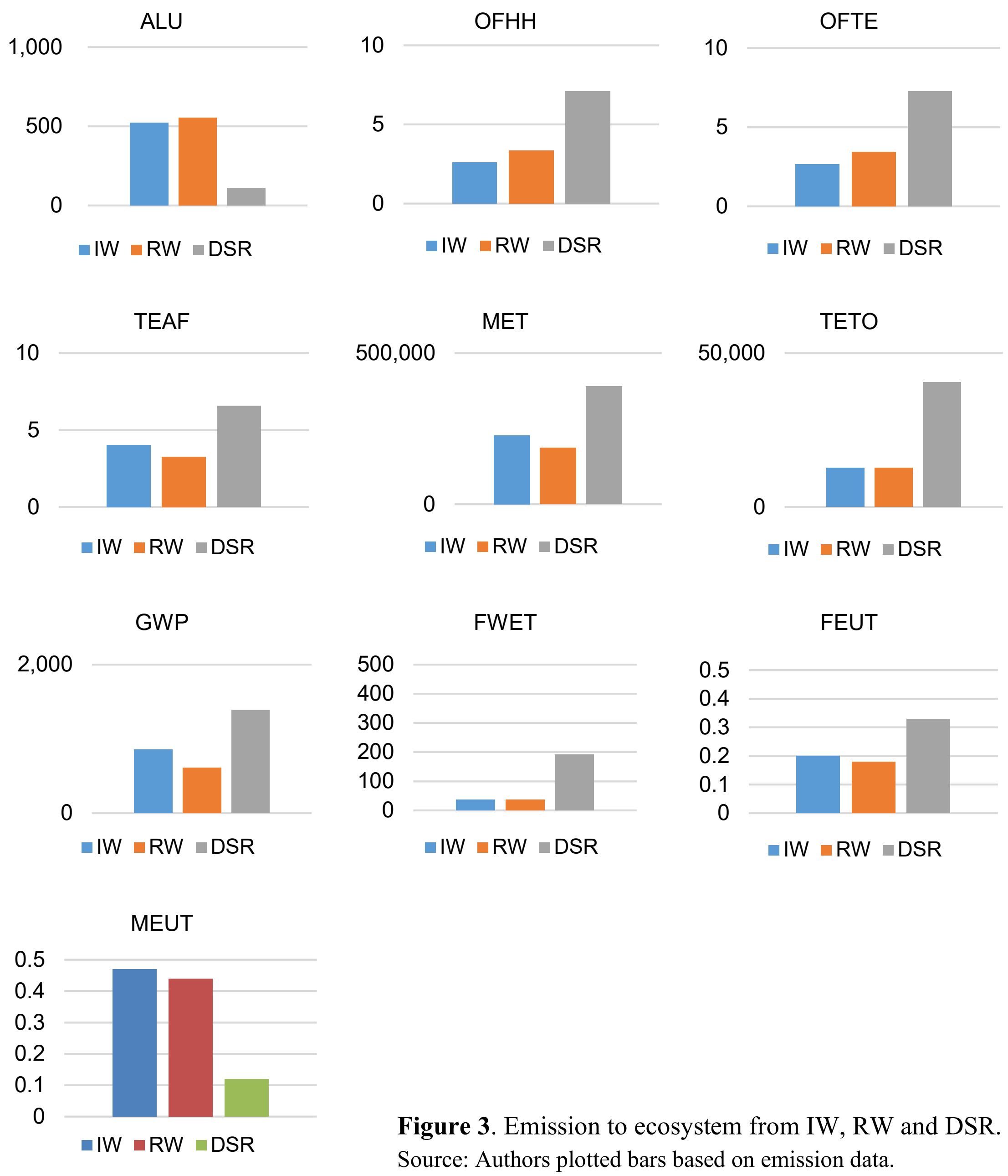

Figure 3. Emission to ecosystem from IW, RW and DSR.
Source: Authors plotted bars based on emission data.

Rice production potentially causes 0.32 kg P eq of FEUT potential and 0.12 kg N eq of MEUT potential. MEUT in wheat production was found higher as compared to rice. All the emissions from the production system of the crops are depicted below in Table 5.

Table 5. Environmental emissions per hectare

Emission categorization (ReCiPe 2016)	Impact category	Reference unit	IW*	RW*	DSR*
			Result	Result	Result
Emission to ecosystem	ALU	m^2 a crop eq	524.43	553.78	110.15
	OFHH	kg NO_x eq	2.61	3.35	7.09
	OFTE	kg NO_x eq	2.67	3.43	7.26
	TEAF	kg SO_2 eq	4.03	3.27	6.56
	MET	kg 1,4-DCB	2,27,975.63	1,86,328.58	3,89,969.43
	TETO	kg 1,4-DCB	12,658.07	12,719.23	40,474.92
	GWP	kg CO_2 eq	853.53	613.33	1387.45
	FWET	kg 1,4-DCB	36.36	36.22	191.67
	FEUT	kg P eq	0.2	0.18	0.33
	MEUT	kg N eq	0.47	0.44	0.12
Emissions affecting human health	PMF	kg PM2.5 eq	1.29	1.36	2.9
	HCT	kg 1,4-DCB	2,040.61	2,420.14	5,514.36
	HNCT	kg 1,4-DCB	2,08,032.68	1,71,148.54	3,46,564.03
	IR	kB_q Co-60 eq	55.03	64.73	143.16
	OD	kg CFC11 eq	0.02	0.01	0.02
Emission to resources	FRS	kg oil eq	265.98	188.5	429.2
	MRS	kg Cu eq	35.93	4.97	38.61

* IW – Irrigated wheat; RW – Rainfed wheat; DSR – Direct seeded rice.

{Agricultural land use (ALU), Global warming potential (GWP), Freshwater ecotoxicity (FWET), Freshwater eutrophication (FEUT), Marine ecotoxicity (MET), Marine eutrophication (MEUT), Terrestrial acidification (TEAF), Terrestrial ecotoxicity (TETO), Ozone formation emission affecting human health (OFHH), Ozone formation emission affecting terrestrial ecosystems (OFTE), Fossil resource scarcity (FRS), Mineral resource scarcity (MRS), Ionizing radiation (IR), Human carcinogenic toxicity (HCT), Human non-carcinogenic toxicity (HNCT), Stratospheric ozone depletion (OD), Fine particulate matter formation (PMF)}.

Source: Authors own calculations.

Emissions affecting Human Health. FPM (Fine particulate matter) can have detrimental effects on air quality and human health. Comparing the three productions, DSR (Direct-Seeded Rice) has the highest impact potential of PM2.5 formation, followed by rainfed wheat and then irrigated wheat. Irrigated and rainfed wheat production in Madhya Pradesh causes 1.28 & 1.36 kg PM2.5 eq of FPM potential whereas, DSR causes emission of 2.89 kg PM2.5 eq. similarly DSR has the higher potential {5,514 kg 1,4-DCB} to cause cancer decease (Human carcinogenic toxicity: HCT), followed by rainfed wheat and then irrigated wheat {2,420 & 2,040 kg 1,4-DCB respectively}. Whereas it was noticed that non-cancer deceases attributed by air pollution (HNCT) are majorly caused by Irrigated wheat, followed by rainfed wheat and then DSR. Radiological effects can damage our DNA and can be a major reason for Acute Radiation Syndrome (ARS) or Cutaneous Radiation Injuries (CRI). Selvaraj et al. (2021) witnessed that agricultural machinery production, tillage, diesel burned in building machines, and power sawing are the major factors contributing to IR. This study has measured Ionizing radiation potential (IR) to measure the impacts on human health. The potential radiological effects were found higher in DSR. DSR has potential of 143 kB_q Co-60 eq (kilobecquerels of Cobalt-60 equivalent) whereas wheat possesses the potential of 55 & 64 kB_q Co-60 eq in irrigated & rainfed wheat production respectively.

Emission from oxides of nitrogen (NOx) contribute to the formation of ground-level ozone, which can have negative impacts on human respiratory health as well as terrestrial ecosystems. Study found that DSR cultivation methods result in higher emissions of NOx, which can contribute to the formation of ground-level ozone and potentially have adverse effects on human respiratory health and ecosystem compared to rainfed and irrigated wheat production. Whereas, among the three cultivation methods, irrigated wheat has the relatively higher impact potential on stratospheric ozone depletion (OD) with a value of 0.024 kg CFC11 eq. and rainfed wheat has a lower impact on stratospheric ozone depletion with a value of 0.009 kg CFC11 eq. Direct-Seeded Rice has a slightly higher impact than rainfed wheat but lower than irrigated wheat. The emissions among the produced illustrated in Fig. 4 below.

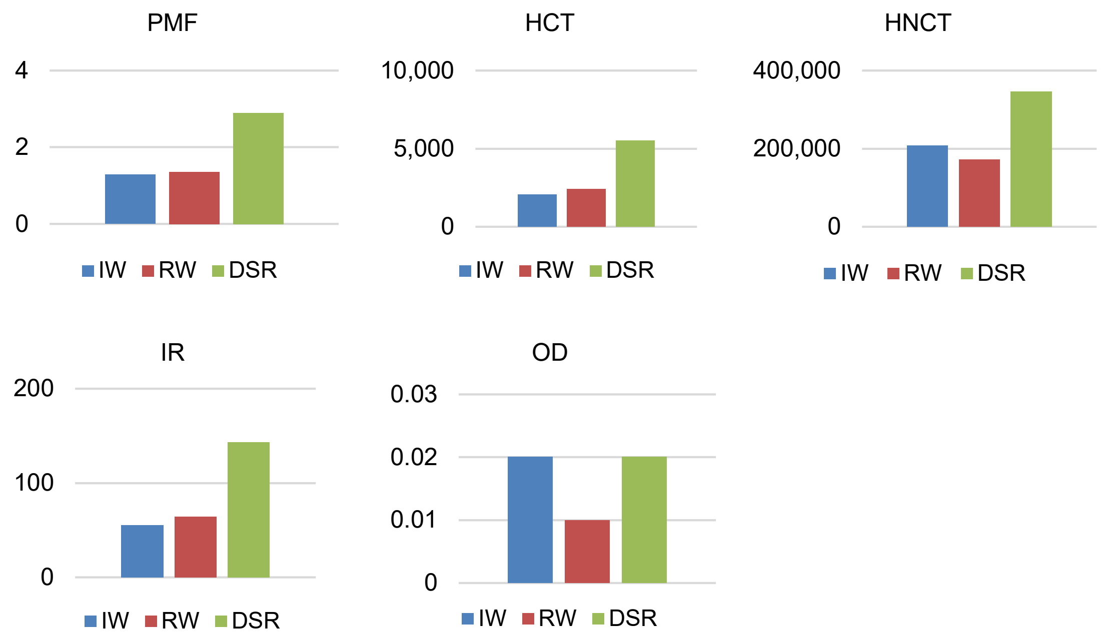

Figure 4. Emissions affecting human health from IW, RW and DSR.
Source: Authors plotted bars based on emission data.

These values suggest that irrigated wheat cultivation has the greatest potential for contributing to stratospheric ozone depletion among the three cultivation methods, followed by DSR and then rainfed wheat. Fig. 4 above depicts various emissions using bar graphs to facilitate comprehension of the differences.

Emission to resources. Agricultural activities not only influence the ecosys tem and have an impact on human health, but they also deplete the resources in terms of consumption of fossil resources specifically in terms of oil and consumption of mineral resources specifically in terms of copper equivalence with a focus on the limited availability of these resources. DSR, which was determined to have the possibly highest influence on fossil resource scarcity (FRS), had a value of 429.19 kg oil equivalent, whereas rainfed wheat had a value of 188.49 kg oil equivalent, making it the agricultural product with the lowest possible impact on FRS. With a value of 265.98 kg oil equivalent, the influence of irrigated wheat is the least significant one on the scarcity of fossil resources. According to these values, the DSR cultivation method has the most potential among the three cultivation methods to contribute to the shortage of fossil resources. Irrigated wheat comes in second, followed by rainfed wheat as the third. The research also showed that DSR cultivation has the largest potential for contributing to to mineral resource scarcity (MRS) among these three produced, followed by irrigated wheat and then rainfed wheat in that order (Fig. 5). This highlights the necessity for sustainable resource management practices as well as the research of alternative materials or recycling ways to decrease the effects of these impacts.

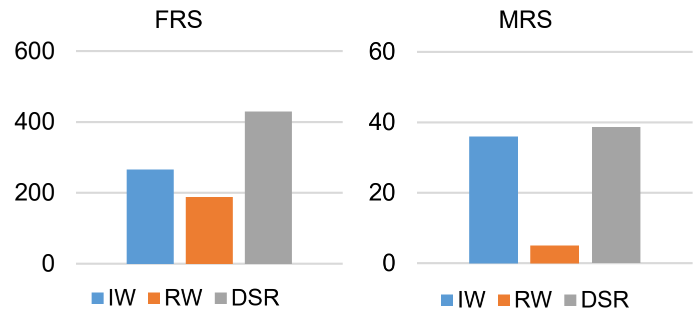

Figure 5. Emissions affecting resources from IW, RW and DSR.
Source: Authors plotted bars based on emission data.

Discussion

Agriculture follows a cyclical pattern, where agricultural production contributes in GHG emission (Jimmy et al., 2017; Tayefeh et al, 2018; Taki et al., 2018; Lynch et al., 2021) which is major reason for climate change and that changed climate in return negatively affects the productivity of the crop (Adams et al., 1998; Arora, 2019; Malhi et al., 2021) reflecting in thread to food security and sustainability. But agricultural production doesn't only contribute to affecting the climate, it creates a burden for the entire ecosystem including resources, and humans. The present study corroborates the findings of Fusi et al. (2014) by affirming that the primary environmental impacts associated with wheat and rice production stem from fuel consumption and emissions released in the field. Among the 17 emissions considered, approximately 06 burdens on the environment can be directly and indirectly attributed to the use of fossil fuels, particularly diesel fuel consumed by agricultural machinery. On the other hand, 09–10 emissions are generated by factors such as soil nutrients and crop protection chemicals. When converting the life cycle impact assessment (LCIA) results based on functional units, our study observed that the outcomes closely aligned with those reported by Fusi et al. (2014) & Korsaeth et al. (2012) in terms of global warming potential (GWP) and Fossil resource depletion (FRS). However, the categories of ozone depletion potential (OD), terrestrial acidification potential (TEAF), and freshwater ecotoxicity potential (FWET) exhibited higher values in the findings of Fusi et al. (2014). We attribute these differences to the study's limitation of not considering water-flooded paddy fields, which could account for the variances in results, particularly with higher methane emission. Furthermore, our investigation revealed that relative fuel consumption in rice production in the Madhya Pradesh region exceeded that of Vercelli (Italy), leading to comparatively higher carbon emissions. As for wheat production, our emission results closely resembled those reported by Roer et al. (2012), Achten et al. (2015), and the Indian study conducted by Selvaraj et al. (2021) across various emission categories. In terms of a comparative analysis, wheat production exhibited lower acidification potential and marine ecotoxicity potential but higher freshwater ecotoxicity potential.

In terms of carbon emissions, our study specifically examined the global warming potential (GWP) and found that the results for wheat production align closely with those reported by Nayak et al. (2022), Brock et al. (2012), Gan et al. (2012), Röös et al. (2011), and Fallahpour et al. (2012). Similarly, the GWP potential for rice production in our study closely resembles the findings of Cheng et al. (2014) and Pathak et al. (2010). It is important to note that due to limited data availability, our study did not account for water usage during the irrigation phase of rice cultivation & residue management of both crops. Consequently, the emission associated with rice production (paddy field flooding) was disregarded, resulting in variations compared to other studies. Recognizing the extensive environmental consequences associated with crop residue burning, which encompass its contribution to climate change, adverse effects on air quality and public health (Mittal et al., 2009; Zhang et al., 2011; Lohan et al., 2018), this study has excluded field burning of crop residue in its analysis due to unavailability of regional data.

This highlights that life cycle assessment (LCA) results are influenced by the system boundaries followed and inputs used, which can differ based on factors such as farming style, cropping patterns, seasons, geographic locations, and other variables. Furthermore, our study focused specifically on the Direct Seeded scenario, which is already considered a low-emission practice and presents a viable alternative to conventional puddle-based transplanted rice production (Pathak & Aggarwal, 2012). The present study conducted in Madhya Pradesh has revealed intriguing disparities in crop production emissions when compared to similar studies conducted globally. Notably, the TEAF and the MET in Madhya Pradesh's arising from crop production were found to be lower than those reported in other studies. Conversely, the FWET and TETO were observed to be higher in Madhya Pradesh (Roer et al., 2012; Achten et al., 2015). These observed differences can be attributed to multiple factors, including varying inputs and the influence of favorable climatic conditions. It is plausible that the specific combination of inputs employed in crop production practices within Madhya Pradesh diverges from region specific practices, leading to the observed discrepancies. Additionally, the region's climatic conditions, which are distinct from those found in other regions, may significantly impact the outcomes of agricultural production. Since Madhya Pradesh is a land locked state resulting in less MET potential whereas have higher FWET potential comparing to coastal region studies (Roer et al., 2012; Achten et al., 2015), (MET in landlocked state is unlikely, however Madhya Pradesh have rivers within its territory, which can affect the aquatic life due to runoff of the pollutants from rivers to sea). An intriguing aspect arising from this study is the revelation that Madhya Pradesh requires fewer soil nutrients and crop protection chemicals for wheat and rice production highlighting the potential efficiency and sustainability of agricultural practices. However, the study also detected a higher fuel consumption in rice production in Madhya Pradesh. This disparity highlights the need for a focused approach towards reducing fuel consumption and optimizing production practices for long-term sustainability.

CONCLUSION

The study exhibits that wheat and rice production in Madhya Pradesh contribute to environmental impacts in terms of harm to Ecosystem, Resources and Human health. In order to optimize production yield and maintain food security, the use of Nitrogen-based fertilizers has been enhanced, but this is having a serious negative impact on the environment. N - fertilizers and fuel are the most significant contributors to the emissions such as Freshwater eutrophication (FEUT), Fine particulate matter formation (PMF), Fossil resource scarcity (FSR), Freshwater ecotoxicity (FWET), Global warming (GWP), Human toxicity (HT) {Human carcinogenic toxicity & Human non-carcinogenic toxicity}, Terrestrial ecotoxicity (TETO) and Stratospheric ozone depletion (OD) etc. In all the categories, except for Marine eutrophication (MEUT) and Agricultural land use (ALU), rice production has relatively higher impact than wheat production. Irrigated wheat production has a higher potential of causing non-cancerous diseases caused by air pollution, whereas rice has the potential to contribute to cancer disease.

The study examines the environmental effects of Direct-Seeded Rice (DSR), irrigated wheat, and rainfed wheat. DSR cultivation's greenhouse gas (GHG) emissions, ozone generation, terrestrial acidification, and terrestrial ecotoxicity are the highest of the three production methods. It emits the most GHGs, contributes to terrestrial ozone production, and has the greatest potential for terrestrial acidification and ecotoxicity. Fine particulate matter (FPM), HCT, HNCT, IR, and ozone emissions vary by cultivation method. DSR emits the most FPM and HCT, exposing respiratory and cancer risks. Irrigated and rainfed wheat production increase HNCT. DSR cultivation has more IR-measured radiological impacts than wheat cultivation. FRS and MRS emissions show how agricultural activities stress scarce resources. DSR consumes the most oil equivalent, followed by rainfed and irrigated wheat. DSR cultivation has the most potential to contribute to MRS, highlighting the need for sustainable resource management and finding alternative methods & innovative technologies for sustainable agriculture.

In addition to considering the functional unit, when examining emissions for the entire state of Madhya Pradesh over the course of a year, significant environmental impacts are observed across all categories (as indicated in Table 6). The total global agrifood system emission of 7.4 Gt CO_2 eq. is primarily originated from all crop and livestock production activities within the farmgate (FAO, 2022). Notably, within this global total, the production of rice and wheat in Madhya Pradesh state alone contributes 0.0086 Gt CO_2eq (8056197.81 t CO_2 eq), that is 0.10 % of global total.

Agricultural production is a substantial source of greenhouse gas emissions, with the majority of these emissions arising in the sector's different activities. These emissions are principally caused by using fossil fuels in agricultural machinery, the application of soil nutrients such as fertilizers, and the use of crop protection chemicals such as herbicides and insecticides (Fig. 6). Fuel burning in agricultural machinery, such as tractors and harvesters, adds to greenhouse gas emissions, specifically carbon dioxide (CO_2). To power these machines, fossil fuels are burnt, releasing CO_2 into the atmosphere, and creating fossil resource scarcity on the other hand. Continuous and heavy use of agricultural machinery, particularly in large-scale farming operations, has resulted in increased fuel consumption and emissions. Soil nutrients, such as fertilizers, are critical for encouraging plant development and increasing agricultural productivity.

Table 6. Total Environmental emissions potential (tons/emission) in Madhya Pradesh for the year 2020–2021

Impact category	Reference unit	IW*	RW*	DSR*
		Overall impact	Overall impact	Overall impact
PMF	t PM2.5 eq	7,454.72	413.64	6,139.30
FRS	t oil eq	1,537,058.52	57,332.28	908,616.40
FWET	t 1,4-DCB	210,118.99	11,016.31	405,765.39
FEUT	t P eq	1,155.77	54.75	698.61
GWP	t CO_2 eq	4,932,421.84	186,544.32	2,937,231.65
HCT	t 1,4-DCB	11,792,379.10	736,085.58	11,673,900.12
HNCT	t 1,4-DCB	1,202,189,652.82	52,054,828.44	733,676,051.51
IR	tBq Co-60 eq	318,010.12	19,687.63	303,069.72
ALU	km^2 a crop eq	3,030,602.31	168,432.19	233,187.55
MET	t 1,4-DCB	1,317,436,969.43	56,671,837.61	825,565,283.31
MEUT	t N eq	2,716.06	133.83	254.04
MRS	t Cu eq	207,634.08	1,511.63	81,737.37
OFHH	t NOx eq	15,082.80	1,018.90	15,009.53
OFTE	t NOx eq	15,429.53	1,043.23	15,369.42
OD	t CFC11 eq	115.58	3.04	42.34
TEAF	t SO2 eq	23,288.77	994.57	13,887.52
TETO	t 1,4-DCB	73,149,087.82	3,868,553.80	85,685,405.64

Source: Authors own calculations.

However, unrestricted and inefficient fertilizer use can have negative environmental implications. Nitrous oxide (N_2O), a strong greenhouse gas, can be produced through the breakdown of nitrogen molecules in fertilizers. Nitrous oxide has a far larger potential for global warming than carbon dioxide. Furthermore, if fertilizers are not adequately handled and applied, they may leach into waterbodies, causing pollution and eutrophication. Herbicides and pesticides are crop protection agents that are used to manage pests, weeds, and illnesses that can harm crops. However, their broad use may result in environmental emissions. Some of these substances are volatile and may evaporate into the atmosphere, adding to pollution. Furthermore, when they wash off from fields or leak into groundwater, they can contaminate soil and water, posing dangers to ecosystems and human health.

To reduce agricultural emissions and ameliorate the ecological impact of crop production, it is critical to focus on the three activities that contribute to these emissions: fossil fuel combustion, soil nutrient management, and crop protection chemical application. Environmentally friendly practices and technologies can assist address these issues. One strategy is to reduce fuel usage in agricultural machinery or perhaps to phase out the use of fossil fuels entirely. This can be accomplished by using more fuel-efficient machinery, alternative energy sources like biofuels or electric power, and precision agriculture techniques. Precision agriculture entails using advanced technologies such as GPS and remote sensing to optimize input usage and decrease waste and reduce the need for unnecessary fuel consumption.

Efficient and responsible soil nutrient management is crucial for reducing emissions associated with fertilizer use. This includes adopting precision agriculture techniques to apply fertilizers only where and when they are needed, using slow-release or controlled-release fertilizers to minimize nutrient losses, and integrating organic farming practices that rely on natural sources of nutrients. In conclusion, addressing the environmental emissions associated with agricultural production requires a multi-faceted approach. By focusing on optimizing fuel consumption or transitioning to alternative energy sources, implementing efficient soil nutrient management practices, and promoting integrated pest management strategies, significant strides can be made in reducing the ecological impact of crop production and mitigating agricultural emissions. These efforts are essential to ensure sustainable food production while minimizing harm to the environment.

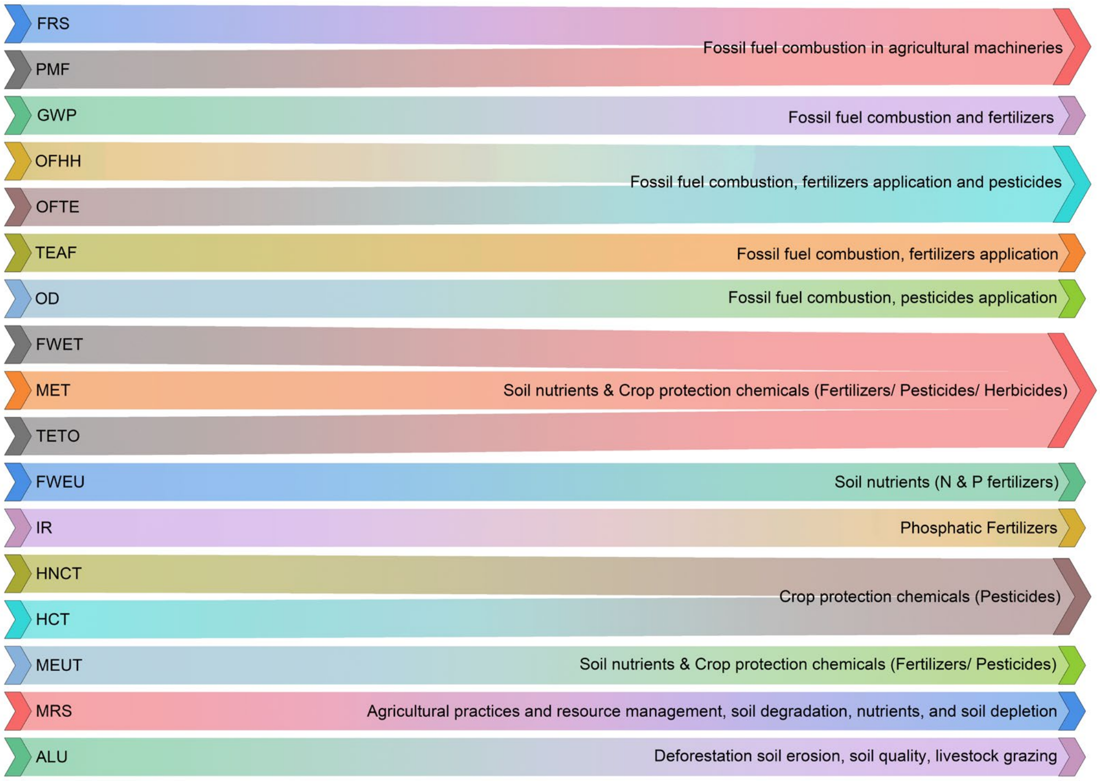

Figure 6. Environmental emissions from crop productions and causes.
Source: Authors own compilation.

In Madhya Pradesh Environmental Policy-1999, policymakers concentrated on agricultural practices and lowering emissions from fertilizers and herbicides; nevertheless, there is still a need to raise farmer awareness about sustainable farming and reducing emissions produced by fuel combustion. Keeping in mind the emissions that agriculture leaves behind and the goal of reaching 'Net Zero Emission by 2070,' it becomes apparent that the primary focus should be on the 'Sustainable production of crops' This can be accomplished through the implementation of sustainable practices such as 'Zero tillage,' the use of fuel-efficient or battery-operated technologies, and limiting the use of external nutrients, pesticides, and herbicides, or the discovery of sustainable alternatives to these things.

POLICY IMPLICATIONS & SUGGESTIONS

The study emphasizes sustainable farming practices to reduce agricultural production's environmental impact. Sustainable Ecosystem policies should reduce chemical fertilizer and pesticide consumption. Climate-smart agriculture and biofuel research can minimize agricultural emissions. Policy initiatives should reduce PMF and other pollutants that hinder human health. Air quality can be improved by regulating agricultural emissions and increasing biofuel use. For Madhya Pradesh's sustainable agro-food system, the following policy recommendations might be made.

- Increase investment in research and development to identify and promote environmentally friendly farming technologies and practices. Create research funds and encourage collaborations among research institutions, farmer collectives, and industry players to create and test sustainable agriculture solutions.
- Creating policies that encourage ecologically sustainable agriculture practices can be beneficial. To conserve ecosystems and minimize pollution, implementing emission limits and restricting the use of chemical fertilizers can help in emission reduction.
- In agrarian perspective 'Madhya Pradesh Environmental Policy - 1999' focused on application of bio fertilizers & pesticides ignoring the fact that fuel combustion also hampers ecosystem. As a result, the usage of biofuel should be encouraged in agricultural activities. Production & promotion of biofuel can contribute to environmental sustainability and add in aligning with the 'National biofuel policy of India', which aims to achieve 20% blending of ethanol in petrol and 5% blending of biodiesel in diesel by 2030 to reduce GHG emission from fuel.
- Tractors are enormous agricultural machines that use fossil fuels. The inclusion of an electric tractor in the 'E-Krishi Yantra Yojana' could be beneficial. Subsidies under the 'E-Krishi Yantra Yojana- 2023' can boost demand for electric tractors and can aid in the reduction of air pollution and other ecosystem and resource emissions.
- Encourage more environmentally responsible farming practices among state farmers with the help of farmers collectives (FPO's), an awareness programs should be initiated focusing on spreading knowledge about environment & health-friendly farming practices and policies.

LIMITATIONS

The study was conducted on secondary database (Blanket requirement) for optimum production of grains by government, Meanwhile the on-farm scenario may refer across farm locations, soil, and climate. Data on fuel and energy use at the aggregate level has been re-used because it is not readily available for individual crops. Subsequent research endeavors may address this limitation by conducting primary surveys to acquire comprehensive data, thereby filling this critical research gap.

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