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A Life Cycle Assessment of Rice–Rice and Rice–Cowpea Cropping Systems in the West Coast of India

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Abstract: Crop diversification is essential in lowland rice cropping systems to achieve sustainability, improve soil health, and as a climate-resilient practice to reduce greenhouse gas (GHG) emissions. A life cycle assessment (LCA) was conducted for the farms in the west-coast region of India to assess the environmental impact of the rice–rice and rice–cowpea cropping systems. The life cycle impact assessment (LCIA) was evaluated in a "cradle-to-gate" perspective. A higher energy consumption was found in the rice–rice system (32,673 vs. 18,197 MJ/ha), while the net energy output was higher in the rice–cowpea system (211,071 vs. 157,409 MJ/ha). Energy consumption was 44% lower in the rice–cowpea system, which was coupled with a higher energy efficiency (11.6 vs. 4.8), attributed to the lower energy consumption and the higher energy output. Further, the results indicated an energy saving potentialin the rice–cowpea system due to the higher use of renewable resources such as farmyard manure. Field emissions, fertilizer production, and fuel consumption were the major contributors to the greenhouse gas (GHG) emissions in both cropping systems. The total GHG emissions were 81% higher in the rice–rice system (13,894 ± 1329 kg CO_2 eq./ha) than in the rice–cowpea system (7679 ± 719 kg CO_2 eq./ha). The higher GHG emissions in the rice–rice system were largely due to the higher use of fertilizers, diesel fuel, and machinery. Hence, diversifying the winter rice with a cowpea crop and its large-scale adoption on the west coast of India would provide multiple benefits in decreasing the environmental impact and improving the energy efficiency to achieve sustainability and climate resilience in rice-based cropping systems.

Keywords: greenhouse gases emissions; environmental impact assessment; life cycle inventory; lowland ecosystem; rice–cowpea systems

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1. Introduction

In India, rice is grown on 43.86 million hectares, yielding 104.80 million tons at 2390 kg/ha. Rice is produced in many soil and climatic conditions, despite its modest productivity compared to many other countries. Improved rice cultivars with higher yields degrade soil fertility faster than local landraces. The rice crop uptakes 20, 11, and 30 kg of N, P_2O_5, and K_2O, respectively, from the soil for each ton of paddy produced [1]. Farmers frequently use indiscriminate amounts of chemical fertilizers to compensate for nutritional losses, particularly of macro-elements. The rice development program encourages the use of modern technology, leading to soil compaction, micronutrient deficiency, soil erosion, nutrient leaching, submergence, reduction in soil biodiversity, salinization, and pollution from heavy metals and pesticides [2,3]. These adverse effects from the mono-cropping of rice and climate change are important challenges that threaten the rice production on the west coast of India [4].

Paddy cultivation is critical to India's food security. Therefore, improvements in energy use can help to ensure food security with a minimal environmental impact. However, approximately 10–12% of greenhouse gases emissions (GHGs) that are due to anthropogenic pollution worldwide are connected to agriculture, particularly paddy farming [5], and the increased energy use in such farms [6]. According to Linquist et al. [7], methane (CH_4) emissions, followed by N_2O emissions, are the major sources of GHGs from paddy fields. In the different types of cultivation systems, such as irrigated or flooded/submerged fields or upland cultivation, the emissions of GHGs are due to the anaerobic conditions that produce CH_4 and nitrous oxide (N_2O) emissions from paddy fields [5]. Rice fields are predicted to emit increasing levels of GHGs to meet the growing global food demand of human population [8]. Rice production accounts for 10–13% of global CH_4 emissions; thus, rice systems have a strong influence on global warming [9,10]. In countries such as India, rice farms use a substantial amount of nonrenewable energy sources and water for crop irrigation. Synthetic fertilizers are also one of the most crucial inputs for improving rice productivity [11,12], even though they are a significant cause of soil and water pollution [8,13–16]. As a result, estimating the environmental consequences and identifying effective strategies for reducing energy consumption, environmental impacts, and enhancing climate resilience is critical [17].

A life cycle assessment (LCA) is a comprehensive methodology for assessing the environmental impact of a production system or process, including food products and agricultural operations. LCAs are primarily employed in agricultural systems [18] for calculating GHG emissions and other environmental consequences of production systems, such as arable crops [8,19–23] and perennial crops [15,24,25]. A LCA study helps to provide the comprehensive environmental performance of a whole production system [26] and aids in identifying the hot spots in a given system that describe the primary contributing sources to the selected environmental impact categories. This allows for the identification of sustainable, climate-resilient, and more environmentally friendly choices [27]. As a result, LCA studies may be used as one of the decision-making tools.

Rice and rice-based cropping systems have a significant role in GHG emissions due to the seasonal variations in temperature and moisture regimes, varying lengths of cropping cycles, variations in crop output (and productivity), the efficiency of energy and feedstock use, input of nutrients (fertilizer), residues, and carbon returns, among other factors [28,29]. Considering energy-efficient rice-based cropping systems with a minimal environmental impact is thus essential for overall sustainability. Understanding the environmental implications of rice farming is also helpful when making long-term decisions regarding paddy-field designs [30]. Climate change impacts necessitate the adoption of environmentally friendly, rice-based cropping systems to achieve climate resilience. The cultivation of different crops during the year (rotations in different seasons) can ensure food production stability (thereby promoting food security), promote nutritional diversity and revenue generation, and lower risks associated with market fluctuations, disease, pests, and climate change [31]. Crop rotation with pulses can increase soil fertility and water-use efficiency [2,3]. Thus, the development of cultivation practices and crop diversification options to maintain natural resources and soil health for long-term rice production are essential. In addition, crop diversification provides several services to the ecosystem, especially by enhancing food security within an environmental impact perspective.

Comprehensive research regarding an ecological impact analysis of rice–rice and rice–cowpea production in the west coast of India is very limitedly addressed. This study evaluates the ecological performance of rice farms in Goa state, India, based on rice systems that were not considered by any other previous research. Therefore, the objective of the current study is to perform an environmental life cycle assessment of the rice–rice and rice–cowpea systems under lowland situations in Goa, India. Furthermore, the study aims to highlight the benefits of replacing winter rice with pulse crops, such as the cowpea, from an environmental impact perspective to achieve sustainability and climate resilience. Hence, we have evaluated the rice-cowpea system to investigate the environmental tradeoffs.

2. Materials and Methods

2.1. Description of the Region

The research region in Goa state (14°53′47′′–15°47′59′′ N, 73°40′54′′–74°20′11′′ E) is a part of the Western Ghats, which has a 110 km long shoreline near the Arabian Sea of the Indian Ocean. The main crop of Goa is rice (*Oryza sativa* L.), followed by cashew (*Anacardium occidentale*), banana (*Musa acuminata),* mango (*Mangifera indica* L.), arecanut (*Areca catechu* L.), and coconut (*Cocos nucifera*). The mean temperature of the region is 27.8 °C, and the mean maximum and minimum temperatures are 30.2 °C and 26.4 °C, respectively. The southwest monsoon accounts for 2910.5 mm of yearly precipitation. June has the highest rain (828.8 mm), although April and May have many pre-monsoon showers. The rice-growing soils are acidic, deep, and high in phosphorus and aluminum, with sandy loam to sandy textures. This study used two land-use systems: rice–rice and rice–cowpea rotations.

2.2. Data Collection and Sampling

A structured questionnaire was used to gather data from a random sample of 60 farmers who adopted the rice–rice system (30 farms) and the rice–cowpea system (30 farms) between 2020 and early 2021. The estimating method known as post-stratification, which is often used in survey analysis [32,33] was used. The farmer's fields were selected with the help of local, progressive farmers and state agriculture departments to achieve uniformity in agronomic management. All management inputs and practices (variables) were tracked and documented without interfering with the farmers' methods. Data on labor, farm equipment, diesel fuel, farmyard manure (FYM), fertilizer, and outputs (rice and cowpea grains) were gathered and further analyzed.

2.3. System Description and Evaluation Approach

A life cycle impact assessment (LCA) was conducted using the survey data collected from the selected farms (Figure 1, see Table 1 and Supplementary Tables S1 and S2 for details). The data from farmers were collected through face-to-face interviews and group discussions. The crop mix in the farms comprised: (i) in the rice–rice system, rice production during the monsoon season and winter, with straw as a by-product; and (ii) in the rice–cowpea system, rice production during the monsoon season and cowpea production in the winter, along with their respective residues. The evaluation was made per 1 ha of land for each farm. A cultivated hectare of land (1 ha) was used as the functional unit measurement of the "land management function", producing rice and cowpeas, along with the equivalent straw production from the respective farms. To do this, a "basket of products", such as "rice + cowpea, as relevant + straw", produced in one hectare (ha) of land was selected based on Nemecek et al. [33], who argued the significance of considering the whole farm context in the environmental evaluation of farm systems. Since the farms produced grain and straw from the cowpeas and rice, it was necessary to calculate the equivalent yields with straw production. We further evaluated the environmental impacts on a yield-basis. Thus, the environmental impact was allocated, which was based on the potential revenue generated from the produced products. The equivalent revenue was calculated using the price of rice, cowpeas, and straw, and was used to estimate with respect to the "reference unit", which was used in the formulation of the life cycle inventory (LCI) and eventually for the systemic LCIA.

The Harmonized ReCiPe 2016 Midpoint protocol was selected for the LCA [34]. The selected environmental impact categories (Figures 1 and 2), along with their units, were: global warming potential (GWP_{100}) (kg CO_2 eq.), potential for fine particulate matter formation (FPM-kg PM2.5 eq.), terrestrial acidification (TA-kg SO_2 eq.), freshwater eutrophication (FE-kg P eq.), terrestrial ecotoxicity (TE-kg 1,4-DCB eq.), freshwater ecotoxicity (FET-kg 1,4-DCB eq.), mineral resource scarcity (MRS-kg Cu eq.), human carcinogenic toxicity (HCT-kg 1,4-DCB eq.), and fossil resource scarcity (FRS-kg oil eq.). Since the general objective of the current study was to examine several farms with a diverse range of farm inputs (by quantity and type, for example, crop nutrients, and fuel inputs), and varying production practices (i.e., rice + cowpea and rice only), it was anticipated that the selection of the above environmental categories was adequate to characterize the possible changes in the elementary flows that resulted from the application of varying levels of farm inputs. Examples include the variable rate of chemical fertilizers and the use of FYM to quantify the fluxes of GHGs (such as CO_2 and N_2O per FU) and assess the potential for global warming. The eutrophication potential was measured using the elementary fluxes of pollutants such as PO_4, NO, NO_2, and NH_4, which fluctuate depending on the crop(s) grown and/or the fertilizers used. The release of these pollutants are varied across the background or foreground system flows or both [35], for example, the differences in the amount of agrochemicals used and the amount of fuel consumed in our study, which can largely influence the selected environmental impact indicators. In addition, flows of SOx, NOx, NH_4, etc., were also helpful to understand the acidification potential. Additionally, the scope of the research served as a comprehensive reference for choosing the impact categories [26]. Decisions are often made depending on the needs of LCA practitioners to achieve the study's goal. Finally, a computational model (SimaPro-9.1) was used to calculate the environmental implications [36].

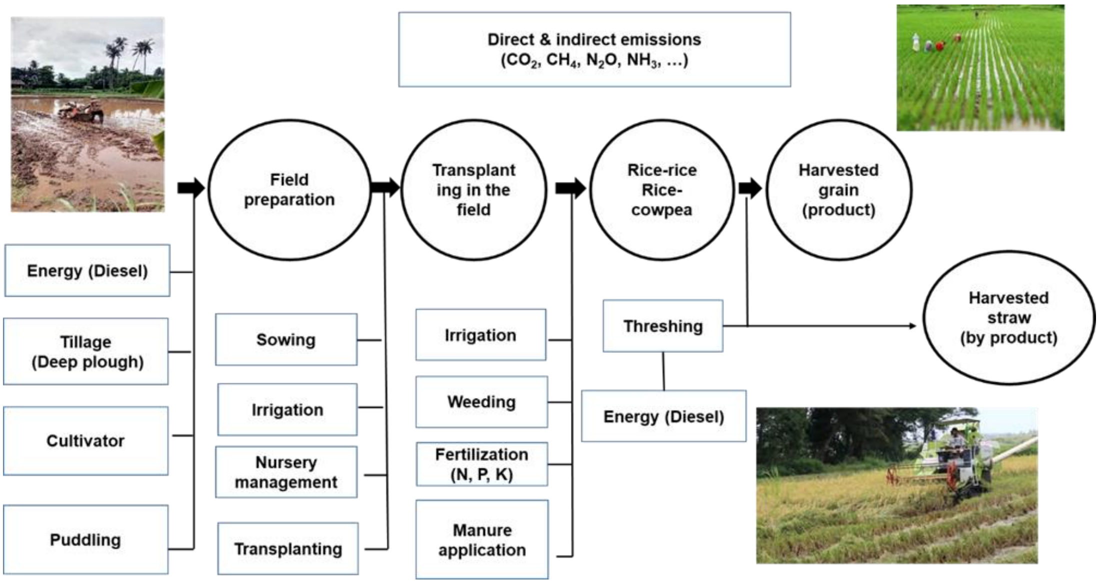

Figure 1. LCA Framework and system boundaries of rice–rice and rice–cowpea systems.

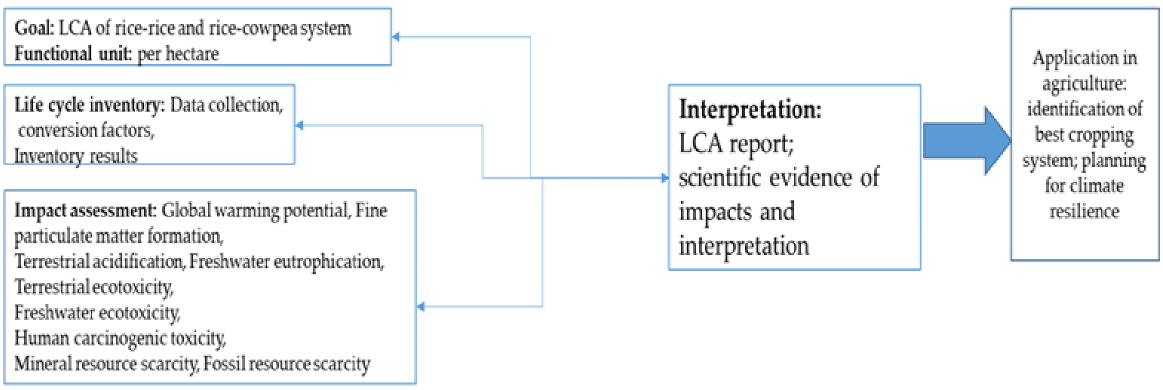

Figure 2. LCA flowchart depicting phases and steps.

2.4. Life Cycle Inventory

Based on ecoinvent v3.6, the evaluation system generated the impacts of the raw materials and the associated emissions (related to the upstream activities) [37]. Each production system was assessed at the foreground level (primary concern) based on the measured raw materials consumed in each farm and their corresponding yields. Table 1 provides detailed information on the LCI that characterizes the foreground processes. Following the IPCC recommendation [38], N emissions were calculated. N leaching was computed using a partial-field N-balance method [39–42]. N inputs from all possible sources and the N-content in all agricultural products were considered for calculating the inputs and outputs related to nitrogen. Based on the emissions variables described, direct and indirect emissions of nitrous-oxide (N_2O-N) were calculated [38]. Based on previous studies, assumptions for NH_3 emission from the nitrogenous fertilizers were made [33]. The amount of nitrogen deposited was estimated for each selected farm area and the total amount of nitrogen deposited (31.8 kg N) in India's agricultural field [43].

For field GHGs emitted, CH_4 emissions were calculated by the emission factor reported in ecoinvent v3.6 (0.041 kg of CH_4 per kg rice). In the case of straw, 30% of the produced residues were incorporated into the field, 30% were used as animal feed, and 40% were burnt in the area. N emissions related to the straw incorporated into the soil were calculated using the emission factor suggested in the literature [33,38,44]. In the case of field burnt residues, CO_2 emitted was not included in the net source of CO_2 as it is assumed that the carbon released into the atmosphere in the form of CO_2 during the process of burning is reabsorbed during the next crop-growing season. The field burning of crop residues, however, accounted for the emission of N_2O and CH_4, which were considered a net source of GHG emissions [45]. Emission factors and methods to estimate the GHG emissions due to residue burnt were adopted [38]. The detailed LCIs for the rice–rice and rice–cowpea systems are shown in Table 1.

Table 1. LCI for the crop production systems. Values are weighted average (yield based) calculated from the selected farms (30 for each of the two cropping systems).

	Units	Amount		Notes
		Rice–Rice System	**Rice–Cowpea System**	
Inputs [a]				
Land occupied	ha/yr	1	1	Annual land occupation
Seeds				
Rice	kg	121	63.5	
Cowpea	kg	-	18.1	
Crop nutrients [b]				
N-synthetic	kg N	177	90.33	
Manure N	kg N	24.1	29.46	
P-synthetic	kg P_2O_5	78	63.5	
Manure P	kg P_2O_5	13	15.91	
K-synthetic	kg K_2O	109	68.58	
Manure K	kg K_2O	39	47.72	
Farmyard manure (FYM)	kg	4813	5891	Used in the above manure-based crop nutrients applied
Primary energy input	MJ	3794	1750	Diesel used in farm operations
Outputs [a]				
Rice	kg	9401	4914	
Cowpea	kg	-	1282	
Straw	kg	12,691	8685	

Table 1. *Cont.*

	Units	Amount		Notes
		Rice–Rice System	Rice–Cowpea System	
Emissions				
N emissions [c]				
N_2O	kg	2.76	2.61	
NH_3	kg	14.83	7.59	
NO_x	kg	4.34	2.61	
NO_3	kg	608	409	
Field GHG emissions [d]				
CH_4 [±]	kg	382	200	
Residue burnt ($CO_{2\ eq.}$) [±±]	kg	325	222	GHG emissions equivalent from the emitted CH_4 and N_2O due to residual burnt
P-emission [e]				
P-losses	kg	0.45	0.4	

Assumptions in Table 1: [a] Input and output data collected from the farm. Straw for rice–cowpea includes both straw and residues generated from each crop. [b] Crop nutrients (synthetic and manure) applied at each farm based on farm data. Nitrogen (N), phosphorus (P), and potassium (K) content of the FYM were assumed to be 0.5%, 0.27%, and 0.81% per kg of manure, respectively. Nutrient management aspects were also reviewed from other studies [46–48]. [c] N emissions = N emissions from added N fertilizers (synthetic plus manure). Emission factors based on [38]. [d] Field GHG emissions accounted for methane. [±] Methane emissions were assumed at 0.041 kg of CH_4 per kg of rice (ecoinvent v3.6). [±±] Emissions from residue burnt are shown in CO_2 equivalent. Emissions related to residues burnt accounted for 40% of the straw/residues produced (Field data). Field burning of crop residues accounted for emissions of N_2O and CH_4 [45]. The combustion factor was assumed to be 0.8, and emission factors for CH_4 and N_2O were assumed to be 2.7 and 0.07 kg per ton of dry matter burnt, respectively [38]. [e] P-emission = P-surplus [δ] ∗ 5%. [δ] P-surplus = P-input minus P-uptake [µ]. [µ] P-uptake = 90% of P-input.

3. Results and Discussion

3.1. Energy Analysis

The energy inputs and the outputs of the rice–rice and rice–cowpea systems are depicted in Table 2. Among the different inputs, the use of nitrogenous fertilizers was higher in the rice–rice cropping system. The lower nutrient efficiency under puddled conditions was due to several losses such as leaching, volatilization, and denitrification, coupled with the exhaustive nature of the rice crop that requires more nitrogenous fertilizers. The total chemical fertilizer consumption in terms of NPK was found to be higher in the rice–rice system. The results of this study are consistent with previous, comparable studies that were conducted for rice, wheat, and potato, showing that fertilizer is the primary source of energy input in those crops [49–53]. Alluvione et al. [54] reported N fertilizer to be the primary contributor (78.9%) to energy input in a wheat–soybean–maize system. Bockari-Gevao et al. [55] calculated an input of 12,400 MJ/ha energy in rice crops, with a significant contribution from chemical fertilizer (7700 MJ/ha). Agha-Alikhani et al. [56] also showed that rice crops had a greater share of energy coming from fertilizer (43%). In a study conducted in India, irrigation and fertilizers accounted for a significant percentage (20–22%) of the energy used in rice production systems [57]. The lower nutrient requirement of the cowpea crop with N-fixation reduced the fertilizer consumption in the rice–cowpea system. The consumption of pesticides was found to be nil from the surveyed farmers. In general, there was very little or no pesticide consumption by rice farmers in the region due to lower instances of pests and disease infections. Most farmers were found to use FYM, which was found in higher amounts in the rice–cowpea system. The labor requirement was found to be higher under the rice–rice system due to the double need of transplanting, weeding, fertilizing, and crop maintenance compared to the rice–cowpea system. Likewise, the rice–rice system used a high amount of diesel fuel to prepare land and mechanically harvest using a combined harvester. These observations suggest that N fertilization, fuel, and machinery contribute majorly to the energy input in both the cropping systems. Studies conducted in Myanmar revealed that alternative rice-growing techniques need a much lower energy input than traditional techniques. Compared to the transplanting method and the direct planting methods, energy efficiency of the modified system of rice intensification method was more significant [58]. Hence, enhancing the input use efficiency in a rice–rice cropping system through the development of alternative techniques and crop diversification can reduce the energy inputs.

Table 2. Energy analysis of rice-based cropping systems in the coastal region of Goa.

Categories *	Rice–Rice System (MJ/ha)	Rice–Cowpea System (MJ/ha)
Labor	1323 (4.1)	547 (3.1)
Machinery	5817 (17.9)	4129 (22.7)
Diesel	5543 (17)	2550 (14.1)
Seeds	1776 (5.5)	1276 (7.1)
Nitrogen	11,743 (36)	6132 (33.7)
Phosphorus	973 (3)	848 (4.7)
Potassium	1211 (3.8)	842 (4.7)
FYM	1446 (4.5)	1873 (10.3)
Irrigation	2841 (8.7)	0

* Numbers in brackets indicate the % contribution of each category.

3.2. Energy Indices

The estimated mean energy input for rice–rice and rice–cowpea systems was 32,670 and 18,053 MJ/ha, respectively, and the energy output was higher in the rice–cowpea system (211,071 MJ/ha) compared to the rice–rice system (157,409 MJ/ha). The data indicate that energy consumption was 44% lower in the rice–cowpea system, and the energy output was approximately 34% higher than in the rice–rice system (Table 3). Chaudhary et al. [59] and Dev [49] also observed a higher energy input in the paddy rice–wheat crop rotation system. Due to the lower energy consumption and the higher energy output in the rice–cowpea system, the energy efficiency in the rice–cowpea system (11.6) was higher than in the rice–rice system (4.8). The average net energy of the rice–cowpea system was found to be higher due to higher energy output, and it increased with the increase in the energy use efficiency. The results indicated that energy was saved in the rice–cowpea system, mainly due to the use of renewable energy sources [60] such as the application of FYM and the fact that the cowpea crop does not require irrigation. The specific energy, indicating the amount of energy consumed per kg of product, was found to be higher in the rice–rice system (3.6 kg/MJ). Conversely, the mean energy productivity in kg of output produced per unit of energy input was higher in the rice–cowpea system (0.69 MJ/kg). This result indicates a need to improve the energy productivity of the rice–rice system in the region as the lower energy productivity was largely due to the higher use of fertilizers, diesel, and machinery [53,61,62].

Table 3. Energy indices as influenced by rice-based cropping systems in the coastal region of Goa.

Energy Indices	Rice–Rice System	Rice–Cowpea System
Energy input (MJ/ha)	32,673	18,197
Energy output (MJ/ha)	157,409	211,071
Energy use efficiency	4.8	11.6
Specific energy (kg/MJ)	3.6	1.5
Net energy (MJ/ha)	124,736	193,018
Energy productivity (MJ/kg)	0.28	0.69

3.3. Life Cycle Assessment

Table 4 shows the environmental characterization indicators for the rice–rice and rice–cowpea systems. The rice–rice system was found to have higher impacts than the rice–cowpea system, including GWP_{100}, FPM, TA, FE, TE, FET, HCT, MRS, and FRS. For instance, the overall GHG emissions in the rice–rice system were higher by 81% than in the rice–cowpea system, the rate of terrestrial acidification was 90.9% lower in the rice–cowpea system than in the rice–rice system. Further, these results were supported by the GHG emissions per kg of crop production; the higher GHG emission was reported in the rice–rice system (1.260 kg CO_2 eq. per kg) compared to the rice–cowpea system (0.561 kg CO_2 eq. per kg). The increased irrigation and N use in the summer fields, which led to higher direct emissions as well as energy for irrigation, were the primary causes of the difference in GHG emission between the rice–rice and rice–cowpea systems. A study conducted in Japan reported that the diversification of a continuous rice-production system into crop rotations was effective and reduced GHG emissions [23]. Crop rotations with legumes are always advantageous in restoring soil fertility [1], nutrient recycling [63], and in reducing environmental impact [64]. Additionally, compared to typical rice–rice systems in the west coast region, the reduced tillage method for cowpeas following rice and the enhanced residual inputs resulted in a significant saving of GHGs at both pre-farm and on-farm stages [20].

Table 4. Life cycle environmental impacts assessed per 1 ha basis and per kg basis for rice–rice and rice–cowpea system.

Impact Categories	Units	RR	RC	RR	RC
		Per ha Basis		Per kg of Production	
GWP_{100}	kg CO_2 eq.	13,894 ± 1329	7679 ± 719	1.260	0.561
FPM	kg PM2.5 eq.	11 ± 1	7 ± 1	0.001	0.0003
TA	kg SO_2 eq.	43 ± 6	24 ± 2	0.004	0.002
FE	kg P eq.	4 ± 1	4 ± 1	0.000	0.00003
TE	kg 1,4-DCB eq.	9103 ± 949	5132 ± 424	0.838	0.369
FET	kg 1,4-DCB eq.	135 ± 15	78 ± 7	0.012	0.006
HCT	kg 1,4-DCB eq.	60 ± 6	34 ± 3	0.005	0.002
MRS	kg Cu eq.	24 ± 3	17 ± 2	0.002	0.001
FRS	kg oil eq.	434 ± 42	233 ± 18	0.040	0.017

RR—Rice–rice, RC—Rice–cowpea, GWP_{100}—global warming potential, FPM—potential for fine particulate matter formation, TA—terrestrial acidification, FE—freshwater eutrophication, TE—terrestrial ecotoxicity, FET—freshwater ecotoxicity, HCT—human carcinogenic toxicity, MRS—mineral resource scarcity, and FRS—fossil resource scarcity.

The rice–rice system recorded 77, 73, and 78% higher TE, FET, and HCT, respectively, than the rice–cowpea system. In the rice–cowpea system, MRS and FRS were reduced by 60 and 85%, respectively (Table 4). Due to background emissions from the fertilizer production and including its higher use, field emissions, and higher fuel use, the rice–rice system had a greater environmental impact. Considering the higher GWP from the rice–rice system, it is relevant that sustainable and ecological management solutions should be implemented, such as crop diversification by including legumes. Strategies including reduced tillage, the direct seeding of rice, and introducing nitrogen-fixing plants in a crop rotation (green manure crops) to compensate for soil nutrient deficiencies [15,16] are imperative.

Field emissions were shown to have a predominant role, especially in terms of the potential for global warming potential, primarily driven by the contributions from the use of various raw materials and processes. For instance, field emissions contributed by 83 and 84%to the total GWP in the rice–rice and rice–cowpea systems, respectively. The contribution of CH_4 alone was 90.9 and 84.1% in the rice–rice and rice–cowpea systems, respectively. The main reason for the increased CH_4 emission from the rice–rice and rice–cowpea systems in the study region were the incorporations of paddy straw after rice harvest and residue burning. Koga and Tajima [65] also supported these results, as they also reported a 78% contribution from CH_4 emissions to the total GHG emissions in the case in which paddy straw was incorporated into the soil. Mohammadi et al. [9] reported a 41% contribution of CH_4 to the field emissions from the rice–rice system. After submergence (within few hours), anaerobic, saturated rice soil conditions are generated and thus encourage the growth of methanogenic bacterial populations, leading to the formation of the byproduct CH_4 by anaerobic microbial respiration [66,67]. According to Phong et al. [19], the GHG emissions in the rice production system are caused by both the indiscriminate and excessive use of synthetic fertilizers and the CH_4 emission from rice fields. Additionally, crop rotations, particularly with legume crops, decrease the N emission following rice harvest since the legume crops require less tillage and have a lower N demand [68]. According to Lal et al. [12], N emission will rise under puddled situations as organic matter input increases. Catch crops such as cowpeas improve soil quality, decrease nutrient leaching, and benefit ecology [69]. According to Alam et al. [21], during both rice and mustard crop seasons, adopting conservation agriculture methods resulted in decreased CH_4 emission under submerged rice soils and a lowered N_2O emission. Under cowpea soil conditions following rice harvest, which restrict the heterotrophic microbial respiration (CO_2) and emission of N_2O, the reduced disturbance may sustain lower soil microbial activity. The N_2O emissions were found to be lower in the rice–rice cropping system (Figure 3) as the direct N_2O emissions from flooded paddy fields are minimal because nitrification does not occur under anaerobic conditions [70].

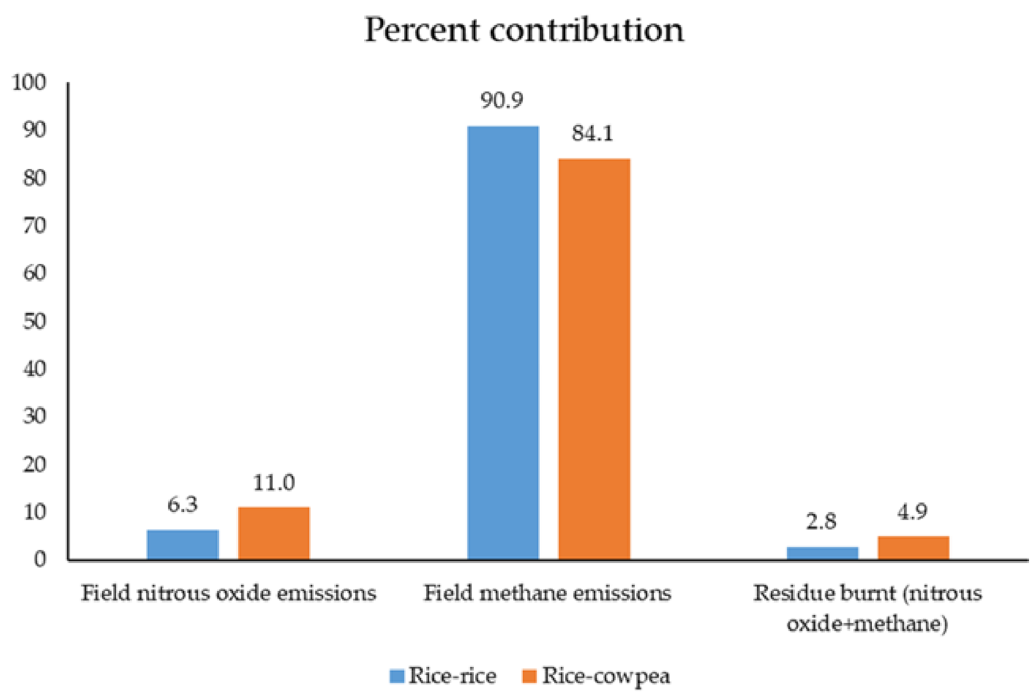

Figure 3. Contribution of different GHG to field emissions (labels are data in kg CO_2 eq./ha).

Among the remaining inputs, the production of fertilizer was primarily responsible for the environmental effects. In the rice–rice and rice–cowpea systems, the production of fertilizers accounted for approximately 12% of all GHG emissions (Table 5). Alam et al. [20] reported that 10% of the GHG contribution from fertilizer production in Australia was during monsoon rice cultivation. Li et al. [71] reported annual N_2O emissions from Australia's rainfed wheat fields of 0.2–0.227 kg N_2O-N/ha (0.06–0.11% of nitrogen consumption). They attributed this to the use of nitrogen fertilizers. The fuel consumptions that accounted for the GHG emissions (from machinery used mainly in field preparation) were 476 and 220 kg CO_2 per ha, respectively, in the rice–rice and rice–cowpea systems. Likewise, the fertilizer production and fuel contributed more to the terrestrial ecotoxicity by 50 and 12%, respectively, in the rice–rice system, and by 52 and 10% in the rice–cowpea system, respectively. Direct field emissions (especially NH_3) are the largest contributor to the impact, and are dependent mainly on the applied nitrogen fertilizers [72]; hence, the improvement of fertilizer use efficiency might reduce the impact, mainly on the terrestrial ecotoxicity of rice paddy fields in the region. In this scenario, crop diversification with legumes and green manuring is a worthy option. Green manures and legumes are included in most farming systems as an important source of nitrogen because of their ability to fix atmospheric nitrogen. In the rice systems, growing green manure crops or short-duration legumes either before or after the rice crop and incorporating them into the soil can have considerable effects on soil nutrient enrichment [7,67]. Fallahpour et al. [22] assessed how different nitrogen fertilizer rates affected the life cycles of wheat and barley. The findings of their research demonstrated that using high amounts of nitrogen fertilizer has adverse effects on the ecosystem, even if crop productivity is increased. Iriarte et al. [73] evaluated the environmental consequences of the sunflower and canola production system, and found that the excessive use of chemical fertilizers to boost crop yield had a greater environmental impact. Traditional crops such as pulses, oilseeds, and local landraces other than rice have the potential to restore soil fertility by fixing atmospheric nitrogen. They also have lower crop requirements. Crops such as cowpeas, moong, vegetables, and groundnuts can be cultivated under the west coast situations of India, especially under rice fallows, to take advantage of the residual soil moisture. Mabhaudhi et al. [74] opined that the cultivation of traditional crops such as pulses is beneficial, as these crops provide nutrient food and are resilient and adapted to marginal land. They further argued these crops can be increasingly included in monocultural cropping systems to reduce GHG emissions and pest incidence. Béné [75] revealed that both improved cultivars of early wheat types and their landraces can provide sustainable alternatives for organic farmers and for the diversification of agriculture in Europe. According to research performed in Mali on the conservation, sustainable use, and value-chain development of a variety of underappreciated and neglected commodities (Bambara groundnut, fonio, jute mallow, and leaf amaranth), based on a community biodiversity management approach that prioritized addressing climate change, there have been considerable advances in productivity, revenue creation, and the restoration and strengthening of the role that agrobiodiversity plays in rural communities [76]. Therefore, although the ecosystems of high-yield agricultural systems do not conflict with environmental issues, the excessive use of agricultural inputs and practices worsens the environmental impact by increasing the emission of pollutants into the environment both directly and indirectly during crop production. Hence, crop diversification with crops such as the cowpea is essential to restoring environmental quality.

Table 5. Emissions from different major inputs to different impact categories.

Impact Categories	Units	Field Emissions (N_2O, CO_2, CH_4)		NPK Production		Seeds		Fuel	
		RR	**RC**	**RR**	**RC**	**RR**	**RC**	**RR**	**RC**
GWP_{100}	kg CO_2 eq.	11,597 ± 1334	6451 ± 722	1642 ± 209	896 ± 81	179 ± 10	102 ± 6	476 ± 31	220 ± 13
FPM	kg PM2.5 eq.	5 ± 1	3 ± 1	3 ± 1	2 ± 1	1 ± 1	1 ± 1	2 ± 1	1 ± 1
TA	kg SO_2 eq.	31 ± 4	16 ± 2	8 ± 2	5 ± 1	1 ± 1	1 ± 1	3 ± 1	2 ± 1
FE	kg P eq.	1 ± 1	1 ± 1	1 ± 1	1 ± 1	1 ± 1	1 ± 1	1 ± 1	1 ± 1
TE	kg 1,4-DCB eq.	0	0	6955 ± 860	4038 ± 387	435 ± 24	304 ± 16	1713 ± 109	790 ± 44
FET	kg 1,4-DCB eq.	0	0	104 ± 13	62 ± 7	8 ± 1	5 ± 1	23 ± 2	11 ± 1
HCT	kg 1,4-DCB eq.	0	0	34 ± 5	21 ± 3	3 ± 1	2 ± 1	23 ± 2	11 ± 1
MRS	kg Cu eq.	0	0	18 ± 3	13 ± 2	1 ± 1	1 ± 1	5 ± 1	3 ± 1
FRS	kg oil eq.	0	0	276 ± 35	157 ± 15	19 ± 2	12 ± 1	139 ± 9	64 ± 4

RR—Rice–rice, RC—Rice–cowpea, GWP_{100}—global warming potential, FPM—potential for fine particulate matter formation, TA—terrestrial acidification, FE—freshwater eutrophication, TE—terrestrial ecotoxicity, FET—freshwater ecotoxicity, HCT—human carcinogenic toxicity, MRS—mineral resource scarcity, and FRS—fossil resource scarcity.

3.4. Implications of Study

Changes in the frequency and severity of natural disasters have a severe impact on the agriculture sector by endangering the lives and livelihoods of numerous populations. Farming vulnerability to climate change is exacerbated by biodiversity loss, water scarcity, and land degradation, which are all threats to the farming sector. Improved agricultural methods and adaptation strategies have the potential to lessen the vulnerability to negative effects of climate change. The majority of adaptation technologies provide co-benefits of mitigation that include eliminating, lowering, or substituting the emission of nitrous oxide, methane, and carbon dioxide into the atmosphere. The present study demonstrated the benefits of crop diversification with legumes to significantly reduce the environmental impact compared to the rice–rice system. The crop diversification further helps to reduce the loss of biodiversity and enhances ecosystem services to achieve food and nutritional security. In addition, crop diversification with legumes has multiple advantageous in improving soil fertility, sequestering atmospheric carbon and nitrogen, and breaking the pest and disease cycles. Further, the diversification of the rice–rice system with legumes restores the terrestrial ecosystem by conserving water and nutrients. Policy intervention to promote pulse cultivation under rice fallows is essential in coastal regions to reduce the energy consumption, and environmental pollution and restore the terrestrial ecosystem.

4. Conclusions

In the current study, an environmental impact and energy analysis of a set of 60 farms (30 rice–rice and 30 rice–cowpea farms) under lowland situations in the west coast of India was performed using the life cycle assessment methodology. The mean energy input was found to be higher in the rice–rice system (32,670 MJ/ha), and the energy output was found to be higher in the rice–cowpea system (211,071 MJ/ha). The higher energy efficiency was recorded in the rice–cowpea system (11.6). Based on the use of resources, the direct connection between the operational and environmental performance of the systems was emphasized. The LCA results implied that the rice–cowpea system has a lower environmental impact with regard to global warming potential (7679 $\pm$ 719 kg CO_2 eq.). Likewise, the potential for fine particulate matter formation, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, mineral resource scarcity and fossil resource scarcity (calculated per ha) are lower in rice-cow pea system compared to the rice–rice system. The results further indicated that the direct field emissions had a high potential to increase global warming potential in both cropping systems, followed by fertilizer production, fuel use, and seeds. The methane emission from the rice fields had the highest contribution to field emissions in both cropping systems. Thus, increasing the input use efficiency in both cropping systems would be required. Crop diversification through the inclusion of legumes (cowpea) after the rice harvest was found to be essential for this region and represents a first step for improving the energy efficiency and environmental performance and achieving the climate resilience of rice-based systems.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land12020502/s1, Table S1: Input and output data collected from farmers' fields in the rice–rice system; Table S2: Input and output data collected from farmers' fields in the rice–cowpea system.

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