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RESEARCH

Life Cycle Assessment of Crop Rotation Systems on Rice Cultivars in Northern Iran

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Abstract

The release of environmental pollutants, which partly emanates from the application of chemical inputs, is a major global concern. Attempt to determine the methods to reduce environmental risk of rice cultivation are required. Selecting the best cover crop in rice rotation is necessary. The novelty of this research versus current knowledge is that life cycle assessment (LCA) has not been applied to assess the environmental impacts of crop rotation systems in paddy fields in Iran. Hence, the life cycle of rice cultivars in different crop rotations was assessed in Neka region, northern Iran from 2017 to 2018. All the management practices/inputs of local ('Tarom Hashemi') and improved ('Shiroodi') rice cultivars were monitored. After recording the data of 100 selected paddy fields for each cultivar, nine cover crop-rice rotations (fallow-rice, clover-rice, rape seed-rice, wheat-rice, barley-rice, faba bean-rice, garlic-rice, lettuce-rice and cabbage-rice) were identified. Functional unit of LCA was 1-ton rice yield. The results demonstrated that the maximum and minimum amount of nitrogen, phosphorus and potassium were applied in fallow-rice and clover-rice rotations, respectively. The highest paddy yield for local (4856 kg ha^{-1}) and improved (7745 kg ha^{-1}) cultivars was produced in clover-rice rotation. Fossil CO_2 eq, biogenic CO_2 eq, global warming potential (GWP) 100a, terrestrial acidification (TA) and fossil depletion (FD) of local cultivar were 11.79%, 34.76%, 13.35%, 15.48%, and 20.13% greater than improved cultivar. The most cumulative energy demand (CED) in both cultivars was obtained for fallow-rice rotation followed by rape seed-rice rotation. The highest emission of biogenic CO_2 eq for both cultivar was observed in rape seed-rice and fallow-rice rotations. The lowest amount of GWP 100a was calculated in clover-rice rotation for local and improved cultivars (248.08 and 240.5 kg CO_2 eq). In both cultivars, the most and lowest amount of TA, freshwater eutrophication (FEU), ozone depletion (OD) and FD was emitted in fallow-rice and clover-rice rotations. Among the crop rotations, clover-rice and fallow-rice had significantly lowest and most emission of heavy metals in the air, water and soil, respectively. As a matter of fact, the environmental emissions of the study is straightly linked to the application of inputs and field management practices. According to this, the lowest amount of environmental emissions for both cultivars was observed in clover-rice rotation. The emissions released from environmental pollutants are positively correlated with the application of inputs and field management practices for crop species in rotation system. In conclusion, clover-rice rotation showed the potential to save non-renewable energies (fuel, nitrogen, and etc.) with higher paddy yield which is considered to be environmentally friendly crop in rotation with respect to reduce emissions of GHG.

Keywords Barley · Clover · Global warming potential · Life cycle assessment · Wheat

Introduction

The most important challenges of the twenty first century is the supply of food for growing populations under a changing climate resulted in application of chemical input (FAO 2013), the larger part of which requires to be met by cereal crops, especially rice crop (Rotter et al. 2015). To ensure the food security and reducing emission of environmental pollutant, there is a need for expansion of the cover crop-rice rotations, as well as the continuous sustainable

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intensification of the rice cultivation to increase the rice production (Oo et al. 2018). In contrast, rice cropping system is facing with the major challenges such as soil fertility depletion, irrigation water scarcity, deterioration of soil health and decline in productivity level, which are considered as serious concerns (Oo et al. 2018; Tivet and Boulakia 2017). Hence, improving productivity on existing farmland is preferable as it prevents the emission of greenhouse gases (GHGs) due to land use change. Identification of opportunities for achieving sustainable intensification be in need of an integrated investigation at field and regional scale levels of past development (Silva et al. 2018). Field and/or farm monitoring especially consideration of crop rotation systems is one of the desirable sustainable intensification ways to enhance productivity and reducing environmental pollution. In contrast, production of rice crop plays a key pattern for security of food in Iran but concerns about environmental emission in rice production are preventable (Habibi et al. 2019; Zhang et al. 2006). Hence, attempt to determine the methods to reduce environmental risk of rice cultivation are required.

Rice (*Oryza sativa* L.) is the earliest stable food crop plants with the global cultivation area of 165 million hectares, accounting for more than one tenth of the worldwide-cultivated area (FAOSTAT 2018; Ling et al. 2016; Tivet and Boulakia 2017). According to the report published in 2018, in Iran, the paddy field cultivation area is about 630,000 million hectares, from which a product with a volume of 2.5 million tons is obtained (Ministry of Jihad-e-Agriculture of Iran 2018). Mazandaran province in northern Iran is the largest rice producing area in Iran with 230,000 ha cultivation area, accounting for 38% of the total cultivation area and production of rice crop in Iran (Ministry of Jihad-e-Agriculture of Iran 2018). The maximum cultivation area a of rice crop in Iran is belong to Mazandaran province, which optimizing application of inputs and selecting the best cropping system for reducing the emission of environmental pollutant are necessary.

According to findings of Dastan et al. (2019) and Iriarte et al. (2010) life cycle assessment (LCA) is standard model to investigate the environmental effects and the analysis of crop plants in their sustainability in production systems in a whole life cycle. LCA is a tool to assess the environmental burden of a cropping system along the whole life cycle (Goossens et al. 2017; ISO 2006). Many researches and studies have been done about this method. Dastan et al. (2019) assessed genetically modified *Bt*. rice and non-*Bt*. rice varieties in north of Iran using LCA. They stated that inputs application and field managing practices directly affect environmental productions, based on which the least amounts of these contaminants were found for transgenic cultivars. Habibi et al. (2019) using LCA to study 200 farms of rice crop in Guilan and Mazandaran provinces in northern confirmed that the majority of impact categories of cumulative non-renewable and renewable energies demand (CED), global warming potential (GWP 100a) and climate change (CC) in both regions were calculated for semi-mechanized method in high-input system (Habibi et al. 2019). Mohammadi et al. (2015) by assessing LCA evaluated 82 farms of rice in northern Iran declared that rice transplanting in the spring season shows a less environmental emission ("GWP, TA, FE, CED and WD") than summer season. The major reason for the findings was less use of inputs and bigger production of grain yield of spring transplanting of rice in comparison to summer season. Using LCA, 70 hectares of organic paddy farms in Lomellina of Italy assessed by Bacenetti et al. (2016), and announced that emission of methane in flooded rice fields, nitrogen associated emission, production of compost and the mechanization of the farm operations were the major hotspots of environment in production of organic rice. He et al. (2018) announced that traditional system of rice showed higher emission of environment pollutants compared to organic rice system in sub-tropical China using LCA. They declared that using synthetic fertilizers and pesticides in organic production of rice crop were the major reasons to greater depletion of non-renewable energy, GWP, FE, TA, WD, soil toxicity, human toxicity potential, and land occupation. Using LCA-ReCiPe method in Bangladesh, Literature interview reported that several studies were investigated in terms of environmental analysis of production of rice crop in the world which includes in Italy (Blengini and Busto 2009), USA (Linquist et al. 2012), Taiwan (Yang et al. 2009); Hokazono and Hayashi 2012), Japan (Koga and Tajima 2011), China (Zhang et al. 2010). LCA similar studies conducted to compare of planting systems of sugar beet (Tzilivakis et al. 2005), rice and wheat (Brentrup et al. 2004) and (Coltro et al. 2017; Firouzi et al. 2018; Nunes et al. 2016).

In the recent years, several life cycle assessments have focused on crop rotation systems. Jeuffroy et al. (2013) revealed that leguminous plants emitted around 5–7 times less GHG per unit area compared to other crops. By estimation of N_2O fluxes, they demonstrated that peas emitted 69 kg N_2O ha^{-1}, significantly far less than rape seed (534 kg N_2O ha^{-1}) and winter wheat (368 kg N_2O ha^{-1}). In a comparison between barley and vetch under alkaline soil and Mediterranean environments, N_2O emissions for barley were higher than vetch; in addition, the N_2O emitted from the chemical fertilizers applied to the growth stages of crop plants were 2.5 times greater than barley compared to vetch (Guardia et al. 2016). Schwenke et al. (2015) by assessing farm experiments in sub-tropical Australia, reported that emissions of cumulative N_2O from application of nitrogen in canola production (385 g N_2O-N ha^{-1}) were significantly higher than chickpea (166 g N_2O-N ha^{-1}), faba bean (166 g N_2O-N ha^{-1}) and field pea (135 g N_2O-N ha^{-1}). They concluded that emissions of GHG reduced with cultivation of grain legumes (Schwenke et al. 2015). It is significant to declare that the effect of legume crops for reducing emissions of GHG belongs to field practices, when faba bean cultivated in mon-culture system led to higher emissions of cumulative N_2O (441 g N_2O ha^{-1}) than wheat cropping without application of fertilizers (152 g N_2O ha^{-1}); conversely, when faba bean and wheat cultivated in intercropping system, emissions of cumulative N_2O were 31% lower than wheat cropping without application of fertilizers (Senbayram et al. 2016; Jensen et al. 2012). Legume crops because of their environmental benefits are known competitive crop plants which resulted in reduce of external inputs and increase of crop diversity (Stagnari et al. 2017). For instance, N_2O emissions and part of the nitrogen leaching from ploughing in a clover field will occur in the following crop field (Goglio et al. 2015). In fact, N_2O emissions depends on many items which includes moisture, nitrogen availability in the soil, management of crop residue and soil properties (Saggar 2010). For emissions of CO_2 in soil, which are a key aspect with regard to LCA of cropping systems considering the soil carbon sequestration potential (Petersen et al. 2013). Indeed, soil carbon dynamics can be slow (Paustian et al. 2016) even up to 100 years later in some cold climates (Goglio et al. 2015; Tuomisto et al. 2015).

The literature review showed the necessity for environmental assessment of rice cropping system through the whole life cycle. Therefore, process of making right decision is one of the most important options for good agricultural practices (GAP) of paddy fields. Hence, the findings of this study can help the farmers, resource managers and policy makers to develop alternative production systems, and energy optimal plan to save non-renewable energy inputs to sustain production without imposing a significant economic burden for the farmers. To the best of our knowledge, LCA has not been applied to specifically assess the environmental impact of rice cultivars in different cover-crop rotations in Iran. Hence, the results of this study can highlight the environmental hotspots and provide solutions for achieving more sustainable production.

According to literature review, previous research has used different methods of LCA, such as IPCC, CML non-baseline, ReCiPe or other methods, many of which overlap in the characterization factors used and each of which provided different impact categories that are not accurate for this choice. In this study, all possible results were analyzed according to different impact categories by different methods so that the reader of the article could have a better analysis. This study was undertaken with the following objectives: (1) to assess the life-cycle of cover crop-rice rotations by different methods; (2) to assess life-cycle of local ('Tarom Hashemi') and improved ('Shiroodi') rice cultivars by different methods; (3) to compare the life-cycle of local and improved rice cultivars in different cover crop-rice rotations by different methods; and (4) to identify sustainable and environmentally safer cover crop-rice rotation for production of local and improved rice cultivars in northern Iran.

Materials and Methods

Description of the Region

Paddy fields monitoring were conducted in Neka region (in the eastern part of Mazandaran province) which located in north of Iran during the periods of 2017 and 2018. This region is geographically situated at 36°, 40′ N latitude and 53°, 20′ E longitude. In rice growing season (from April to September), its climate is temperate sub-humid and its average maximum and minimum temperature, solar radiation, and rainfall are 25.2 and 18.3 °C, 19.5 MJ m^{-2} d^{-1}, and 89 mm, respectively. Rice is usually harvested in September in research area and after that the clover, canola or wheat crop is cultivated in the rice field in a double cropping system or rice transplanting and manage the rice residue for ratoon harvesting (Habibi et al. 2019).

Description of Cover Crop-Rice Rotations and Data Collection

Crop rotation systems in paddy field in northern Iran is usually with two crops within a year available. Identified of paddy fields of local ('Tarom Hashemi') and improved ('Shiroodi') cultivars were done by cooperation of local experts of Rice Research Institute of Iran (RRII) to represent a wide range of selected field situations. Monitoring of field management variables were done without interfere of farmers. After monitoring of fields, 100 paddy fields selected for each cultivar, nine cover crop-rice rotations (fallow-rice, clover-rice, rape seed-rice, wheat-rice, barley-rice, faba bean-rice, garlic-rice, lettuce-rice and cabbage-rice) were identified. More detail and information of selected cover crop-rice rotations are presented in Table 1.

Identification of the studied fields were done based on the Cochran equation (Cochran 1977):

$$\mathrm{n} = \frac{\mathrm{z2pq}/d2}{1 + 1/N\left[z2pq/d2 - 1\right]}, \quad (1)$$

where n is the sample size; N is statistical population size; Z is normal value of standard unit; p is the estimated proportion of an attribute that is present in the population; q is 1 − p; d is permissible error value. The value for Z is found in statistical tables which contain the area under the normal curve. E.g. Z = 1.96 for 95% level of confidence.

For each field, the detected information were frequency and time of tillage operations (e.g. plough and disk

Table 1 Description of cover crop-rice rotations for local and improved rice cultivars

Cover crop-rice rotation	Cultivation area (%)	Seed (kg ha^{-1})	Electricity (kWh)	Machinery (h ha^{-1})	Fuel (l ha^{-1})	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})	Zinc (kg ha^{-1})	FYM (kg ha^{-1})	Pesticides (kg ha^{-1})	Paddy yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index (%)
Local cultivar ('Tarom Hashemi')														
Fallow-rice	18	63 c	145 cd	55 c	95 c	150 a	100 a	95 a	15 ab	1200 a	6.5 bc	4445 d	9711 ab	31.4 bc
Clover-rice	19	64 c	130 d	58 c	100 bc	80 d	60 e	55 d	0 c	0 c	6.1 c	4856 a	9640 b	33.5 a
Rape seed-rice	13	74 ab	185 ab	65 b	115 ab	130 ab	90 b	75 b	10 b	700 b	8.2 ab	4454 d	9868 a	31.1 c
Wheat-rice	17	63 c	155 c	61 bc	105 bc	120 b	80 c	70 bc	18 a	0 c	8.5 ab	4645 bc	9603 b	32.6 ab
Barley-rice	14	68 b	145 cd	57 c	102 bc	115 bc	85 bc	75 b	8 bc	0 c	7.9 b	4658 bc	9587 c	32.7 ab
Faba bean-rice	8	82 a	195 a	72 a	125 a	105 c	65 d	55 d	0 c	0 c	8.9 a	4775 b	9608 b	33.2 a
Garlic-rice	5	64 c	165 b	64 ab	116 ab	110 bcd	80 c	60 cd	0 c	0 c	7.8 b	4559 c	9643 b	32.1 ab
Lettuce-rice	4	68 b	160 bc	55 c	110 b	115 bc	80 c	75 b	15 ab	500 bc	7.4 b	4587 c	9838 a	31.8 b
Cabbage-rice	2	66 bc	165 b	67 ab	118 ab	110 bcd	80 c	70 bc	0 c	0 c	7.6 b	4544 c	9881 a	31.5 bc
Mean	–	68	161	62	110	115	80	70	7.33	267	7.66	4614	9709	32.2
SE	–	2.10	6.74	1.96	3.25	6.29	4.0	4.17	2.51	146.25	0.30	45.67	40.30	0.28
CV (%)	–	9.27	12.60	9.55	8.91	16.41	14.99	17.86	102.73	164.53	11.74	2.97	1.24	2.60
Improved cultivar ('Shiroodi')														
Fallow-rice	16	75 b	210 cd	72 bc	105 c	250 a	120 a	150 a	20 a	1500 a	7.4 bc	6845 d	6369 c	51.8 b
Clover-rice	15	72 c	215 cd	75 b	115 bc	150 e	80 d	100 cd	15 b	0 d	6.9 c	7745 a	6466 bc	54.5 a
Rape seed-rice	17	83 ab	235 ab	82 ab	125 ab	210 b	100 b	130 b	0 d	0 d	8.3 ab	7125 cd	6421 bc	52.6 ab
Wheat-rice	18	75 b	225 abc	75 b	120 b	200 bc	100 b	110 bcd	0 d	750 b	7.6 bc	7263 c	6493 bc	52.8 ab
Barley-rice	11	72 c	220 bc	72 bc	118 b	190 bcd	90 bcd	100 cd	10 c	0 d	7.4 bc	7254 c	6723 b	51.9 b

Table 1 (continued)

Cover crop-rice rotation	Cultivation area (%)	Seed (kg ha^{-1})	Electricity (kWh)	Machinery (h ha^{-1})	Fuel (l ha^{-1})	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})	Zinc (kg ha^{-1})	FYM (kg ha^{-1})	Pesticides (kg ha^{-1})	Paddy yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index (%)
Faba bean-rice	9	87 a	255 a	87 a	130 a	170 de	80 d	90 d	18 ab	0 d	8.8 a	7355 bc	6899 ab	51.6 b
Garlic-rice	6	76 b	205 bcd	78 b	120 b	190 bcd	95 bc	110 bcd	0 d	0 d	7.8 ab	7425 b	6745 b	52.4 ab
Lettuce-rice	5	78 b	195 d	70 c	115 bc	180 cde	100 b	115 bc	10 c	0 d	7.4 bc	7385 b	6955 a	51.5 b
Cabbage-rice	3	75 b	200 bcd	75 b	125 ab	185 cd	90 bcd	110 bcd	0 d	450 c	7.8 ab	7365 bc	6908 a	51.6 b
Mean	–	77	218	76	119	192	95	113	8.11	300	7.7	7307	6664	52.3
SE	–	1.67	6.24	1.79	2.43	9.28	4.08	5.96	2.78	175	0.19	80.69	76.74	0.32
CV (%)	–	6.49	8.60	7.05	6.10	14.52	12.89	15.85	102.86	175	7.26	3.31	3.45	1.82
pr > *F**					Analysis of variance (ANOVA)									
Cultivar	–	*	**	*	ns	**	*	**	ns	*	ns	**	**	**
Crop rotation	–	*	**	*	*	**	**	**	**	**	*	**	**	**

*The *pr* > *F** is the probability of significant F-test to compare different treatments

ns, * and **: non-significant and significant in 5% and 1% probability level, respectively

*Values within a column followed by same letter are not significantly different at LSD test ($P \leq 0.05$)

cultivation), sowing date, seeding date, transplanting time, seeding rate, seedling age, plant density, frequency and the amount of nitrogen fertilizer, the amount of nitrogen, phosphorus and potassium fertilizers, the amounts of herbicides and pesticides (insecticide and fungicide), water for irrigation (frequency and regimes), time and frequency of weed, disease and pest controls and harvesting time. Time of practices (e.g. transplanting date) was considered as day since 20 April. The manner of identifying fields covers all main production methods. Then, information pertaining to field management was collected. For data collecting, all agricultural variables were first separated. In total, paddy fields were different with respect to field area, production operations, application of inputs (organic and synthetic) and crop yield were evaluated over the growing seasons from nursery preparation to harvest. At the end of the growing season, the actual paddy yield was registered.

Methodology of Life Cycle Assessment (LCA)

"LCA is an applied method for analysis of environmental pollution impacts related to products life style from extraction of raw material to processing of materials, manufacturing, transportation, usage, disposal or recycling" and transportation" (ISO 2006; Pishgar-Komleh et al. 2011; Habibi et al. 2019). Main phases of LCA which includes scope and goal definition, inventory analysis, assessment of impact and interpretation (Habibi et al. 2019). Hence, four phases of LCA were planned to investigate the life cycle indices (Fig. 1).

This LCA aimed to estimate the environmental impacts of cover crop-rice rotations in paddy field of local and improved rice cultivars. The functional unit of the LCA was 1-ton paddy yield based on moisture content of 12%. Since straw (stem + leaf) is a co-product in rice fields and economic allocation was applied to allocate the total environmental impacts to the main and co-products by the LCA method of SimaPro8.2.3 software (Rebitzer et al. 2004; SimaPro 2011). For economic allocation, 90% and 10% of dry matter were attributed to paddy and straw, respectively (Habibi et al. 2019; Pishgar-Komleh et al. 2011). More details of LCA methodology (Life Cycle Inventory) are shown in the electronic supplemental material.

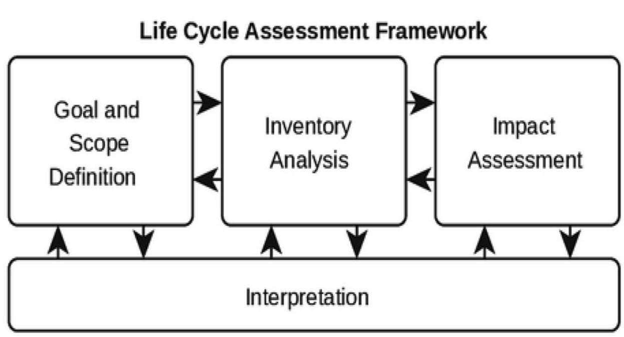


Fig. 1 Life cycle assessment framework

Statistical Analysis

All data were analyzed by using statistical analysis system (SAS) software ver. 9.1 (SAS institute Inc., Cary NC, USA, 2013). Analysis of variance (ANOVA) was performed by procedure of the Generalized Linear Model (GLM) and, the least significant difference (LSD) test was used to compare the differences between the treatment means at a 5% of probability level.

Results

Documentation of Cover Crop-Rice Rotations

The cultivation area of cover crop-rice rotations for both cultivars are presented in Table 1. According to the findings, the most cultivation area for local cultivar was belonged to clover-rice, fallow-rice and wheat-rice rotations (from 17 to 19%), but the highest cultivation area of improved cultivar was observed in wheat-rice, rape seed-rice, fallow-rice and clover-rice rotations (from 15 to 18%). The least cultivation area for both cultivars was recorded in cabbage-rice, lettuce-rice and garlic-rice rotations (Table 1).

Findings of analysis of variance (ANOVA; Table 1) indicated that all the investigated inputs (seed usage, electricity, machinery, fuel, nitrogen, phosphorus, potassium, zinc, farmyard manure (FYM) and pesticides) and outputs (paddy yield and straw yield along with harvest index (HI) were statistically significant ($P \leq 0.05$; $P \leq 0.01$) under the effect of rotation. But, all inputs except fuel utilization, zinc application and pesticides usage along with outputs and HI were statistically different ($P \leq 0.05$; $P \leq 0.01$) on cultivars (Table 1).

Mean comparison shows statistical differences between local and improved cultivars for different rotations in terms of all inputs and outputs (Table 1). In terms of utilization of seed, electricity, machinery, fuel, nitrogen, phosphorus, potassium, zinc, FYM and pesticides, improved cultivar ('Shiroodi') showed 13.24%, 35.40%, 22.58%, 8.18%, 66.96%, 18.75%, 61.43%, 10.64%, 12.36% and 0.52% greater amount than local cultivar ('Tarom Hashemi'). In addition, paddy yield (7307 kg ha^{-1}) and HI (52.3%) of improved cultivar were significantly greater than local cultivar (4614 kg ha^{-1} and 32.2%), but straw yield of local cultivar (9709 kg ha^{-1}) was significantly greater than improved cultivar (6664 kg ha^{-1}). Mean comparison of cover crop-rice rotations demonstrated that the most utilization of seed, electricity, machinery, fuel and pesticides of both cultivars was observed in faba bean-rice rotation, but the maximum application of nitrogen, phosphorous, potassium and FYM was recorded in fallow-rice rotation. The maximum paddy yield for local (4856 kg ha^{-1}) and improved (7745 kg ha^{-1}) cultivars was produced for clover-rice rotation, but straw yield of local cultivar for rape seed-rice, lettuce-rice and cabbage-rice rotations (9868, 9843 and 9881 kg ha^{-1}) was greater than other rotations, but straw yield of improved cultivar in lettuce-rice and cabbage-rice rotations (6955 and 6908 kg ha^{-1}) was more than others. HI of clover-rice and faba bean-rice rotations (33.5% and 33.2%) for local cultivar and HI of clover-rice rotation (54.5%) for improved cultivar was significantly greater than other rotations (Table 1).

Interpretation of LCA Results

LCA results for ReCiPe method for both cultivars in different cover crop-rice rotations are presented in Tables 2, 3 and Fig. 2. Table 4 and Figs. 3 and 4 showed renewable and non-renewable cumulative energy demand (CED). Tables S1, S2 and Fig. S1 demonstrated non-renewable and renewable

Table 2 Life cycle assessment (LCA) of cover crop-rice rotations for local and improved rice cultivars by ReCiPe method

Cover crop-rice rotation	Climate change (kg CO_2 eq)	Terrestrial acidification (kg SO_2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)	Ozone depletion (g CFC-11 eq)	Water depletion (m^3)	Metal depletion (kg Fe eq)	Fossil depletion (kg oil eq)
Local cultivar ('Tarom Hashemi')								
Fallow-rice	427.40 a	2.46 a	0.0585 a	0.2272 ab	0.2321 abc	14.85 ab	64.09 ab	123.67 a
Clover-rice	247.82 d	1.40 c	0.0348 c	0.1822 c	0.1740 d	11.53 c	52.75 c	79.03 c
Rape seed-rice	402.41 ab	2.31 ab	0.0552 ab	0.2485 a	0.2602 a	15.82 a	69.77 a	121.69 a
Wheat-rice	339.22 b	1.94 b	0.0474 b	0.2081 bc	0.2480 ab	13.27 bc	62.75 abc	104.63 ab
Barley-rice	323.12 c	1.86 bc	0.0479 b	0.2149 abc	0.2321 abc	13.76 b	58.91 bc	99.50 b
Faba bean-rice	322.88 c	1.81 bc	0.0417 bc	0.2394 a	0.2438 ab	14.79 ab	66.55 ab	101.76 ab
Garlic-rice	326.56 bc	1.87 bc	0.0468 b	0.2093 bc	0.2338 abc	13.33 bc	64.15 ab	103.18 ab
Lettuce-rice	344.93 b	1.98 b	0.0477 b	0.2192 abc	0.2283 c	13.98 b	58.66 bc	106.80 ab
Cabbage-rice	332.94 b	1.90 b	0.0474 b	0.2145 abc	0.2326 abc	13.71 b	66.85 ab	105.16 ab
Mean	340.23	1.94	0.0473	0.2179	0.2315	13.88	62.97	104.98
SE	17.02	0.10	0.0023	0.0064	0.0080	0.40	1.73	4.33
CV (%)	15.01	15.51	14.45	8.82	10.32	8.74	8.25	12.37
Improved cultivar ('Shiroodi')								
Fallow-rice	404.97 a	2.67 a	0.0479 a	0.1898 a	0.1915 a	12.39 a	56.25 a	111.10 a
Clover-rice	242.05 d	1.34 c	0.0297 d	0.1408 c	0.1398 d	9.08 d	45.13 c	72.27 e
Rape seed-rice	326.79 b	1.80 b	0.0392 b	0.1831 a	0.1837 ab	11.73 b	55.49 a	94.06 b
Wheat-rice	316.66 bc	1.77 b	0.0380 bc	0.1668 abc	0.1682 bc	10.70 bcd	50.48 ab	90.65 bc
Barley-rice	290.81 c	1.61 bc	0.0347 c	0.1583 bc	0.1624 bcd	10.18 bc	48.43 abc	84.81 cd
Faba bean-rice	290.57 c	1.60 bc	0.0336 cd	0.1765 ab	0.1773 abc	11.15 bc	54.44 a	86.12 c
Garlic-rice	287.64 c	1.59 bc	0.0353 c	0.1611 abc	0.1643 bc	10.35 bcd	50.09 ab	83.62 cde
Lettuce-rice	278.53 cd	1.56 bc	0.0362 bc	0.1623 abc	0.1589 cd	10.53 bcd	46.80 bc	81.61 de
Cabbage-rice	291.24 c	1.62 bc	0.0347 c	0.1609 abc	0.1646 bc	10.25 cd	48.85 abc	85.16 c
Mean	302.07	1.68	0.0364	0.1662	0.1673	10.68	50.48	87.39
SE	14.97	0.08	0.0017	0.0049	0.0050	0.32	1.31	3.55
CV (%)	14.87	15.19	13.78	8.82	9.02	8.99	7.77	12.18
$pr>F^*$			Analysis of variance (ANOVA)					
Cultivar	*	*	*	*	*	**	**	**
Crop rotation	**	**	**	*	*	**	**	**

The $pr>F$ is the probability of significant F-test to compare different treatments

ns, * and **: non-significant and significant in 5% and 1% probability level, respectively

*Values within a column followed by same letter are not significantly different at LSD test ($P \leq 0.05$)

Table 3 Life cycle assessment (LCA) of cover crop-rice rotations for local and improved rice cultivars by ReCiPe method

Cover crop-rice rotation	Human toxicity (kg 1,4-DB eq)	Photochemical oxidant formation (kg NMVOC)	Particular matter formation (kg PM10 eq)	Terrestrial ecotoxicity (kg 1,4-DB eq)	Freshwater ecotoxicity (kg 1,4-DB eq)	Marine ecotoxicity (kg 1,4-DB eq)	Ionising radiation (kBq U235 eq)	Agricultural land occupation (m^2a)
Local cultivar ('Tarom Hashemi')								
Fallow-rice	65.22 a	1.34 a	1.02 a	0.1798 a	0.4767 a	1.56 a	21.77 a	33.88 ab
Clover-rice	30.21 e	0.85 b	0.62 b	0.0473 d	0.2390 d	0.49 c	13.54 c	26.34 d
Rape seed-rice	57.74 bc	1.31 a	0.98 a	0.1431 b	0.4365 b	1.27 ab	21.02 a	36.23 a
Wheat-rice	59.43 b	1.10 ab	0.82 ab	0.1848 a	0.4362 b	1.53 a	17.91 abc	29.73 c
Barley-rice	47.87 c	1.05 ab	0.79 ab	0.1169 bc	0.3682 b	1.04 b	17.31 bc	30.66 bc
Faba bean-rice	38.65 d	1.09 ab	0.79 ab	0.0614 c	0.3035 c	0.63 bc	17.17 bc	33.92 ab
Garlic-rice	40.24 cd	1.09 ab	0.81 ab	0.0630 c	0.3209 bc	0.67 bc	17.89 abc	29.95 c
Lettuce-rice	55.81 bc	1.12 ab	0.84 ab	0.1651 ab	0.4168 ab	1.38 ab	18.41 ab	31.81 abc
Cabbage-rice	40.96 cd	1.12 ab	0.82 ab	0.0638 c	0.3239 bc	0.68 bc	18.18 ab	30.90 bc
Mean	48.31	1.12	0.83	0.1131	0.3679	1.02	18.11	31.47
SE	3.90	0.05	0.04	0.0187	0.0260	0.14	0.79	0.97
CV (%)	24.22	12.73	13.98	49.58	21.16	41.19	13.01	9.22
Improved cultivar ('Shiroodi')								
Fallow-rice	59.74 a	1.21 a	0.92 a	0.1586 a	0.4102 a	1.42 a	19.41 a	27.86 a
Clover-rice	37.58 bcd	0.77 b	0.57 b	0.1028 abc	0.2629 bc	0.89 bc	12.22 d	20.36 d
Rape seed-rice	38.97 bc	1.00 ab	0.75 ab	0.0589 c	0.2785 bc	0.66 bcd	16.24 b	25.86 ab
Wheat-rice	36.84 cd	0.97 ab	0.73 ab	0.0552 c	0.2667 bc	0.62 cd	15.76 bc	24.03 b
Barley-rice	40.81 bc	0.89 ab	0.67 ab	0.0946 bc	0.2862 bc	0.88 bc	14.59 bcd	22.36 c
Faba bean-rice	45.31 b	0.93 ab	0.68 ab	0.1268 ab	0.3144 b	1.09 b	14.41 bcd	25.20 ab
Garlic-rice	34.53 d	0.89 ab	0.67 ab	0.0522 c	0.2491 c	0.58 d	14.49 bcd	22.83 c
Lettuce-rice	39.72 bc	0.86 ab	0.65 ab	0.0932 bc	0.2850 bc	0.86 bc	14.17 cd	23.13 bc
Cabbage-rice	34.26 d	0.91 ab	0.68 ab	0.0516 c	0.2488 c	0.58 d	14.75 bcd	23.01 bc
Mean	40.70	0.93	0.70	0.0879	0.2880	0.84	15.06	23.79
SE	2.61	0.04	0.03	0.0125	0.0166	0.09	0.65	0.73
CV (%)	19.26	12.85	13.97	42.83	17.30	33.01	13.00	9.23
*pr > F**			Analysis of variance (ANOVA)					
Cultivar	*	*	*	*	*	*	**	**
Crop rotation	**	**	*	*	*	**	**	**

*The *pr > F** is the probability of significant F-test to compare different treatments

ns, * and **: non-significant and significant in 5% and 1% probability level, respectively

*Values within a column followed by same letter are not significantly different at LSD test ($P \leq 0.05$)

cumulative exergy demand (CExD). Table 5 along with Figs. 5, 6 and 7 revealed the results of greenhouse gas protocol (GGP) and IPCC 2013 GWP100a. Table S3 presented the findings of CML non-baseline methods. Table S4 and Fig. S2 displayed the results of Ecopoint 97 (CH) method.

ReCiPe Method

In the ReCiPe method, the most important impact categories including climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (MEU), ozone depletion (OD), water depletion (WD), metal depletion (MD), fossil depletion (FD), human toxicity (HT), photochemical oxidant formation (POF), particular matter formation (PMF), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FE), marine ecotoxicity (ME), ionising radiation (IR) and agricultural land occupation (ALO) were assessed (Tables 2, 3; Fig. 2).

Findings of ANOVA of ReCiPe method indicated that all the investigated impact categories were significantly

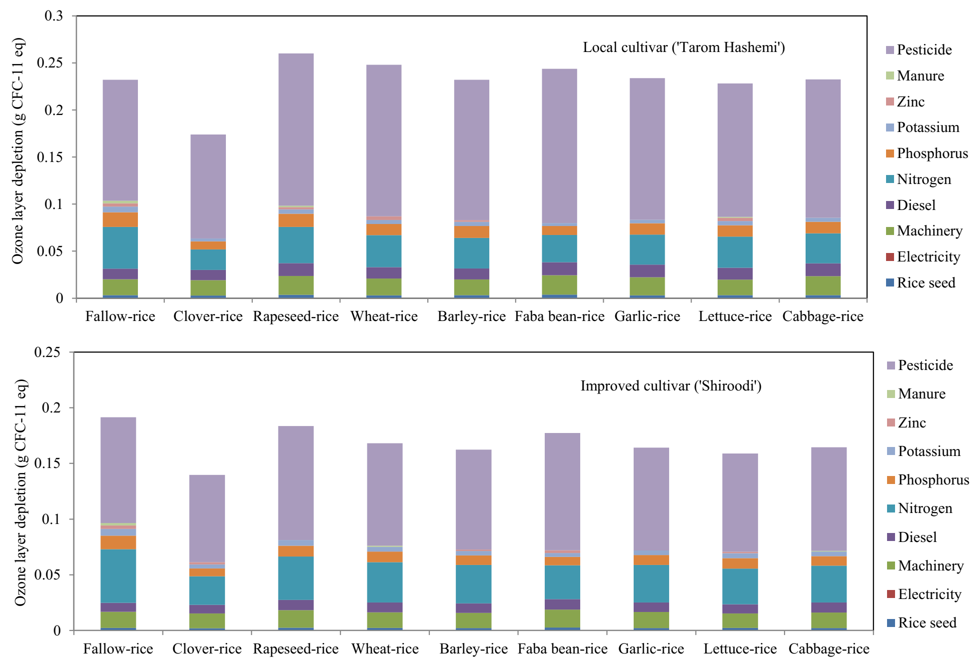


Fig. 2 Contribution of ozone layer depletion (OLD) of cover crops-rice rotation for local and improved rice cultivars by ReCiPe method

different under the effect of cultivar and rotation ($P \leq 0.05$; $P \leq 0.01$). Mean comparison of all investigated impact categories of ReCiPe method shows statistical differences between cultivars and cover-crop-rice rotations (Tables 2, 3). According to findings, all the impact categories of ReCiPe method for local cultivar was significantly greater than improved cultivar. In terms of CC, TA, FE, OD, WD, MD and FD, the local cultivar emitted 12.63%, 15.48%, 29.95%, 38.37%, 29.96%, 24.74% and 20.13% greater than improved cultivar. In both cultivars, the most CC, TA, FE, HT, and FE was emitted in fallow-rice rotation, but other impact categories (FE, ME, OD, WD, MD, FD, HT, POF, PMF, TE, FE, ME, IR and ALO) was varied that fallow-rice, rape seed-rice, faba bean-rice and lettuce-rice demonstrated greater amounts than other rotations (Tables 2, 3). In both cultivars, clover-rice rotation showed the lowest CC (247.82 and 242.05 kg CO_2 eq), TA (1.4 and 1.34 kg SO_2 eq), FE (0.0348 and 0.0297 kg P eq), ME (0.1822 and 0.1408 kg N eq), OD (0.1740 and 0.1398 g CFC-11 eq), MD (52.75 and 45.13 kg FE eq) and FD (79.03 and 72.27 kg oil eq). In addition, the lowest amount of POF, POD, PMF, TE, FE, ME, IR and ALO for local cultivar was recorded in clover-rice rotation, but these impact categories for improved cultivar was varied and the lowest amount was observed in clover-rice and cabbage-rice rotations (Table 3). According to findings of different input shares on ozone layer depletion (OLD) in both cultivars, pesticides, nitrogen and machinery utilization shows the greatest amount of OLD, after that, phosphorus and diesel stood rank next (Fig. 2).

Cumulative Energy Demand (CED)

Results of ANOVA displayed that all the impact categories of CED including non-renewable, fossil; non-renewable, nuclear; non-renewable, biomass; total non-renewable energy; renewable, biomass; renewable, wind, solar, geothe; renewable, water; and total renewable energy) were statistically significant ($P \leq 0.05$; $P \leq 0.01$) by cultivar and rotation treatment (Table 4). The mean comparison results of cover crop-rice rotations ranking demonstrated that all the impact categories of CED method for local cultivar were significantly greater than improved cultivar (Table 4). The most CED in both cultivars was observed fallow-rice rotation and rape seed-rice rotation got rank next. In terms of total non-renewable energy, fallow-rice rotation utilized 5847 MJ for local cultivar and 5244 MJ for improved cultivar. After that, rape seed-rice rotation by decreasing 2.1% for local cultivar and 18.05% for improved cultivar stood rank next. But, the maximum utilization of total renewable energy for local cultivar recorded in rape seed-rice rotation (482.46 MJ), but for improved cultivar was observed in fallow-rice rotation (378.31 MJ). The least cumulative non-renewable and renewable energy demand indices for both cultivars were calculated in clover-rice rotation (Table 4). The findings of input contribution on non-renewable CED revealed that utilization of nitrogen, diesel and machineries for both cultivars shows the most amount. After that, phosphorus, pesticides, zinc, rice seed and electricity got ranked next, respectively (Fig. 3). In terms of renewable CED, rice

Table 4 Life cycle assessment (LCA) of cover crop-rice rotations for local and improved rice cultivars by cumulative renewable and non-renewable energies demand (CED) method

Cover crop-rice rotation	Non-renewable, fossil (MJ)	Non-renewable, nuclear (MJ)	Non-renewable, biomass (MJ)	Total non-renewable energy (MJ)	Renewable, biomass (MJ)	Renewable, wind, solar, geothe (MJ)	Renewable, water (MJ)	Total renewable energy (MJ)
Local cultivar ('Tarom Hashemi')								
Fallow-rice	5501 a	343.96 a	1.57 a	5847 a	314.45 abc	21.07 a	123.10 a	458.62 ab
Clover-rice	3510 d	189.83 e	0.90 c	3701 d	256.94 c	11.28 d	75.51 c	343.73 d
Rape seed-rice	5409 ab	317.10 b	1.44 ab	5727 ab	344.80 a	19.21 ab	118.44 ab	482.46 a
Wheat-rice	4653 bc	257.61 cd	1.23 b	4912 bc	282.08 bc	15.21 bc	96.95 bc	394.24 cd
Barley-rice	4424 cd	248.34 cd	1.29 b	4673 cd	294.75 bc	14.68 c	92.17 bc	401.60 cd
Faba bean-rice	4519 bcd	237.86 cde	1.01 bc	4757 bcd	331.93 ab	14.13 cd	95.24 bc	441.30 abc
Garlic-rice	4583 bcd	248.65 cd	1.25 b	4833 bc	286.72 bc	14.73 c	95.25 bc	396.69 cd
Lettuce-rice	4749 b	270.22 c	1.24 b	5020 b	304.00 abc	16.28 b	100.13 b	420.40 bc
Cabbage-rice	4671 bc	253.54 cd	1.26 b	4926 bc	295.95 bc	15.03 bc	98.06 bc	409.04 bcd
Mean	4665	262.46	1.24	4929	304.10	15.70	99.42	416.22
SE	192.93	14.94	0.07	207.54	8.84	0.96	4.70	13.55
CV (%)	12.41	17.08	16.16	12.63	8.81	18.32	14.18	9.77
Improved cultivar ('Shiroodi')								
Fallow-rice	4943 a	299.74 a	1.24 a	5244 a	253.59 a	18.28 a	106.44 a	378.31 a
Clover-rice	3213 e	171.80 c	0.75 c	3385 e	192.82 c	10.16 d	66.31 d	269.30 d
Rape seed-rice	4180 b	223.84 b	1.01 ab	4405 b	243.78 ab	13.22 b	83.55 b	340.56 b
Wheat-rice	4028 bc	228.58 b	0.98 ab	4258 bc	223.98 abc	13.80 b	84.18 b	321.96 bc
Barley-rice	3770 cd	199.25 bc	0.89 ab	3970 cd	209.99 bc	11.76 c	73.93 cd	295.67 cd
Faba bean-rice	3828 bcd	202.37 bc	0.81 abc	4031 bcd	240.49 ab	11.98 c	79.18 bc	331.65 bc
Garlic-rice	3716 cd	199.96 bc	0.92 ab	3917 cd	215.09 abc	11.82 c	74.97 cd	301.88 bcd
Lettuce-rice	3628 cde	198.00 bc	0.96 ab	3827 d	219.13 abc	11.69 c	72.74 cd	303.56 bcd
Cabbage-rice	3784 cd	207.52 bc	0.88 ab	3992 cd	216.11 abc	12.44 bc	77.65 bcd	306.19 bcd
Mean	3885	213.52	0.93	4099	223.38	12.73	79.50	315.61
SE	158.02	11.95	0.05	169.81	6.32	0.77	3.80	10.41
CV (%)	12.20	16.79	14.86	12.43	8.48	18.06	14.33	9.90
*pr > F**			Analysis of variance (ANOVA)					
Cultivar	**	**	*	**	**	*	**	**
Crop rotation	**	**	*	**	**	**	**	**

*The $pr > F^*$ is the probability of significant F-test to compare different treatments

ns, * and **: non-significant and significant in 5% and 1% probability level, respectively

*Values within a column followed by same letter are not significantly different at LSD test ($P \leq 0.05$)

seed, machinery, nitrogen, phosphorus and pesticides got rank first to fifth, respectively. The lowest utilization of input for renewable CED recorded for electricity, potassium and zinc (Fig. 4).

Cumulative Exergy Demand (CExD)

The results of ANOVA of cumulative exergy demand (CExD) are shown in the electronic supplemental material (Tables S1, S2).

Greenhouse Gas Protocol (GGP) Method

Findings of ANOVA (Table 5) for GGP method demonstrated that all impact categories (fossil CO_2 eq, biogenic CO_2 eq, CO_2 eq from land transformation and CO_2 uptake) were statistically significant at $P \leq 0.05$ and $P \leq 0.01$ on cultivar and crop rotation treatment. The results of GGP method showed that fossil CO_2 eq, biogenic CO_2 eq, CO_2 eq from land transformation and CO_2 uptake of local cultivar were 11.79%, 34.76%, 29.98% and 34.63% greater than improved cultivar. Mean comparison of this impact category for crop

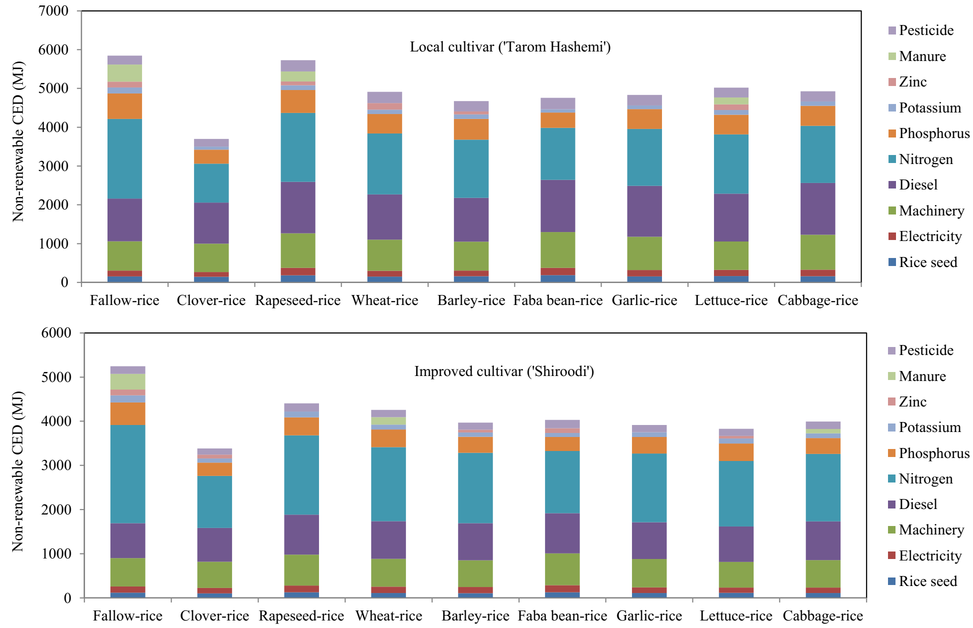


Fig. 3 Contribution of non-renewable cumulative energy demand (CED) of cover crops-rice rotation for local and improved rice cultivars by CED method

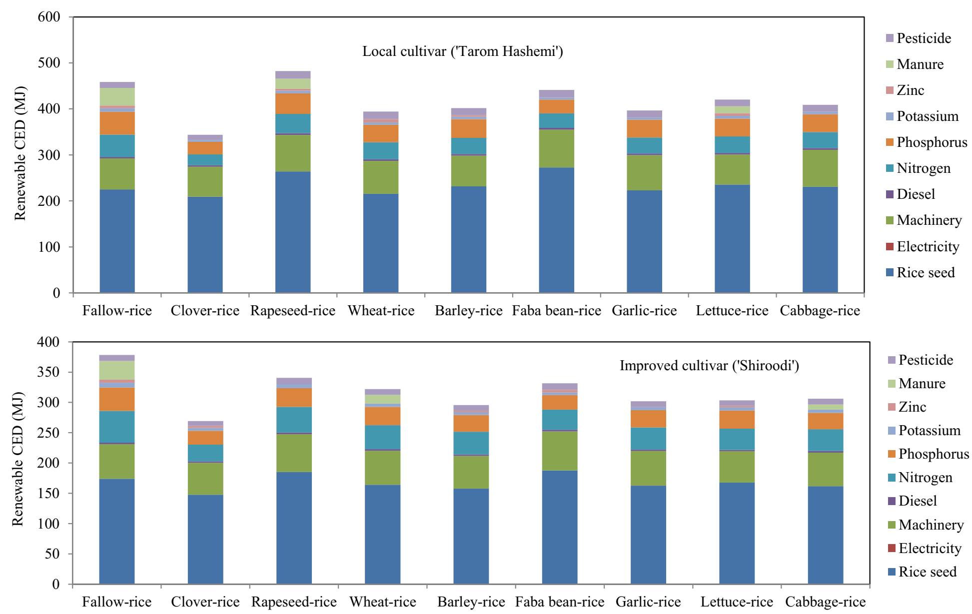


Fig. 4 Contribution of renewable cumulative energy demand (CED) of cover crops-rice rotation for local and improved rice cultivars by CED method

rotation revealed that the most emission of fossil CO_2 eq, CO_2 eq from land transformation and CO_2 uptake for both cultivars were calculated for fallow-rice rotation. But, the highest emission of biogenic CO_2 for local (23.39 kg CO_2 eq) and improved (17.42 kg CO_2 eq) cultivar was observed in rape seed-rice and fallow-rice rotations, respectively. The lowest emission of all impact categories of GGP method for both cultivars was calculated in clover-rice rotation and faba bean-rice rotation stood rank previous (Table 5). The share of different inputs for emission of fossil CO_2 eq revealed that in both cultivars, utilization of nitrogen and machinery have a highest amount and phosphorus, rice seed, electricity and pesticides got ranks next, respectively (Fig. 5). In contrast, the share of inputs on emission of biogenic CO_2 revealed that rice seed had a maximum share on emission of biogenic CO_2, after that, machinery, nitrogen and phosphorus stood ranks next, respectively (Fig. 6).

IPCC 2013 GWP 100a

The ANOVA of GWP 100a was significantly ($P \leq 0.01$) affected by cultivar and crop rotation (Table 5). GWP 100a of local cultivar (339.20 kg CO_2 eq) was 13.35% greater than improved cultivar (299.24 kg CO_2 eq). Mean

Table 5 Life cycle assessment (LCA) of cover crop-rice rotations for local and improved rice cultivars by greenhouse gas protocol (GGP) and IPCC 2013 GWP100a methods

Cover crop-rice rotation	GGP method				IPCC 2013 method
	Fossil CO_2 eq (kg CO_2 eq)	Biogenic CO_2 eq (kg CO_2 eq)	CO_2 eq from land transformation (kg CO_2 eq)	CO_2 uptake (kg CO_2 eq)	GWP100a (kg CO_2 eq)
Local cultivar ('Tarom Hashemi')					
Fallow-rice	414.80 a	21.58 b	0.6311 a	28.30 b	424.62 a
Clover-rice	236.40 d	17.08 d	0.3609 c	23.05d	248.08 c
Rape seed-rice	387.84 ab	23.39 a	0.5829 ab	31.00 a	401.19 ab
Wheat-rice	327.33 bc	18.78 cd	0.4873 b	25.36 cd	337.60 b
Barley-rice	310.37 cd	19.49 bc	0.4935 b	26.48 bcd	321.83 bc
Faba bean-rice	308.06 cd	22.13 ab	0.4242 bc	29.79 ab	322.99 bc
Garlic-rice	314.28 cd	19.19 bcd	0.4876 b	25.79 cd	325.45 bc
Lettuce-rice	331.96 b	20.44 bc	0.4991 b	27.32 bc	343.94 b
Cabbage-rice	320.25 bcd	19.80 bc	0.4942 b	26.61 bcd	331.99 b
Mean	327.35	20.20	0.4943	27.06	339.20
SE	16.86	0.64	0.0262	0.80	16.80
CV (%)	15.46	9.48	15.89	8.83	14.84
Improved cultivar ('Shiroodi')					
Fallow-rice	395.19 a	17.42 a	0.5137 a	22.84 a	400.29 a
Clover-rice	233.93 d	12.90 c	0.3082 c	17.35 c	240.50 d
Rape seed-rice	316.60 b	16.23 ab	0.4050 ab	21.93 ab	323.37 b
Wheat-rice	307.55 bc	15.25 b	0.4033 ab	20.17 b	313.61 bc
Barley-rice	282.10 c	14.00 bc	0.3584 b	18.90 bc	287.69 c
Faba bean-rice	280.29 c	16.08 ab	0.3447 b	21.62 ab	288.87 c
Garlic-rice	278.67 c	14.33 bc	0.3665 b	19.35 bc	284.76 c
Lettuce-rice	269.28 cd	14.50 bc	0.3745 b	19.70 b	275.98 cd
Cabbage-rice	282.31 c	14.57 bc	0.3639 b	19.44 bc	288.62 c
Mean	292.82	14.99	0.3803	20.10	299.24
SE	14.84	0.45	0.0191	0.57	14.69
CV (%)	15.20	9.10	15.09	8.50	14.73
*pr > F**	Analysis of Variance (ANOVA)				
Cultivar	*	**	*	**	**
Crop rotation	**	**	*	**	**

*The $pr > F^*$ is the probability of significant F-test to compare different treatments

ns, * and **: non-significant and significant in 5% and 1% probability level, respectively

*Values within a column followed by same letter are not significantly different at LSD test ($P \leq 0.05$)

comparison of crop rotation demonstrated that fallow-rice rotation for local (424.62 kg CO_2 eq) and improved (400.29 kg CO_2 eq) cultivars emitted the highest GWP 100a and rape seed-rice rotation stood rank next, respectively. But, the lowest amount of GWP 100a was calculated in clover-rice rotation for both cultivars (248.08 and 240.5 kg CO_2 eq), respectively (Table 5). The findings of different input shares for GWP 100a shows that nitrogen application have a highest share and machinery stood rank next. After that, rice seed, phosphorus, electricity and pesticides got ranks next, respectively. The lowest shares of GWP 100a was belonged to application of zinc and potassium (Fig. 7).

CML Non-baseline Method

Findings of ANOVA of CML non-baseline method are demonstrated in the electronic supplemental material (Tables S3).

Ecopoints 97 (CH) Method

Findings of ANOVA of Ecopoints 97 (CH) method are presented in the Electronic Supplemental Material (Table S4; Fig. S2).

Fig. 5 Contribution of fossil CO_2 emission of cover crops-rice rotation for local and improved rice cultivars by greenhouse gas protocol (GGP) method

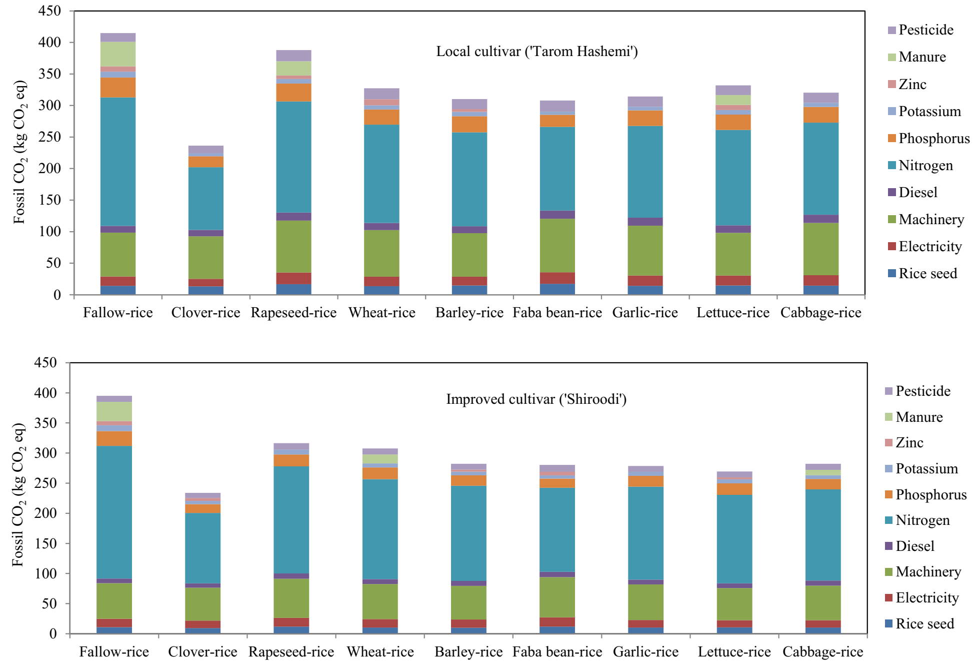
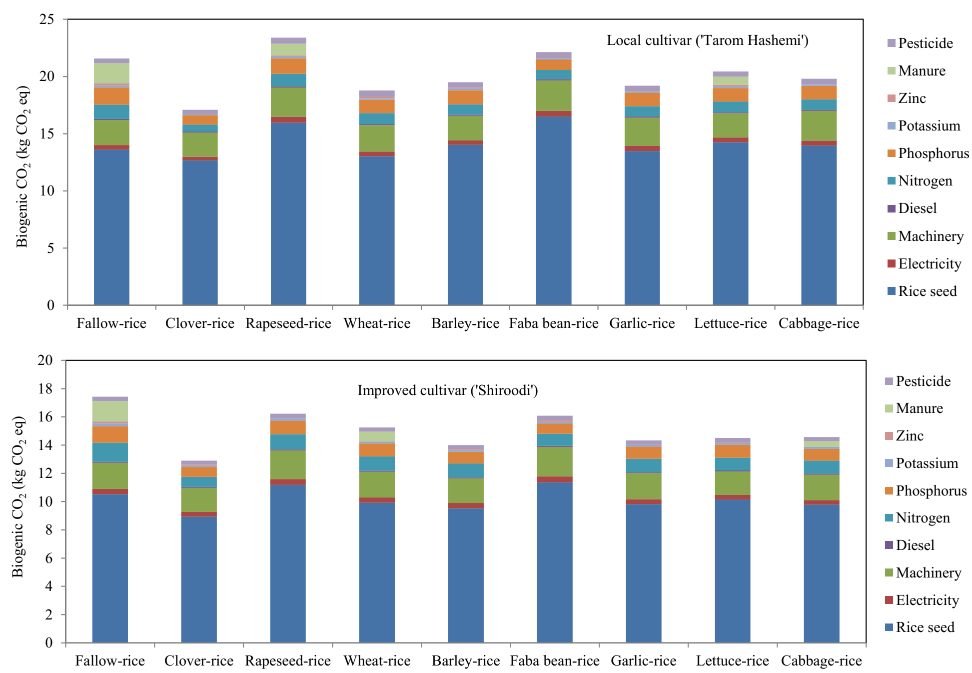


Fig. 6 Contribution of biogenic CO_2 emission of cover crops-rice rotation for local and improved rice cultivars by greenhouse gas protocol (GGP) method



Discussion

Investigation of the impacts of different crop rotations for local ('Tarom Hashemi') and improved ('Shiroodi') rice cultivars on the environment and human health, both controversial and essential issues, was considered in the study. The findings of our study showed that local cultivar had once and/or twice as much harmful eco-impact than improved cultivar for several investigated impact categories including energy utilization and the emissions of GHG due to the more utilization of inputs compared to performances (paddy yield) along with other agricultural management practices. Since fossil fuel is utilized in the production of synthetic pesticides, it is essential for assessing the LCA method. The findings of crop rotations revealed that all rotations led to augmented pollutant emission and enhancing performances. Generally,

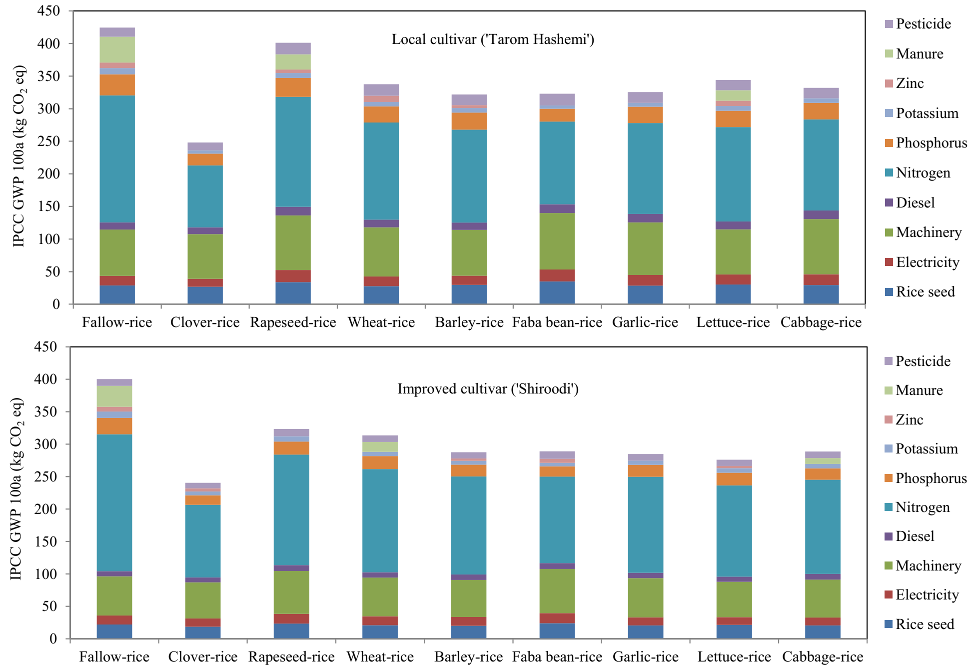


Fig. 7 Contribution of global warming potential (GWP) of cover crops-rice rotation for local and improved rice cultivars by IPCC GWP 100a method

the results demonstrated that in the case of legume-rice rotations, the effect of clover on reducing emission was significantly less as compared to faba bean. In addition, clover cultivation before rice emitted less pollutant than other cover crop before rice transplanting. The reason for less energy utilization and GWP in clover-rice and faba bean-rice rotations might be because of their lower inputs-dependence and less energy utilization that disregard environmental impacts. The results of the input energies and GWP showed a direct correlation between both aspects. As a matter of fact, in terms of ecological issues non-renewable energies are adverse which derived from fossil fuels. The inputs and paddy field practices were statistically significant under cultivar effect (Table 1). As a matter of fact, the main cause of varied input energies and emissions of GHG between cultivars and crop rotations was diverse application of fertilizers, management practices and chemical pesticides. Fallow-rice, rape seed-rice and wheat-rice rotations leading to an increase in the utilization of inputs (fertilizers) and the energy-related inputs and field management practices. These inputs utilized without pay attention to ecological indices for rice cultivation in these crop rotation systems. Different outputs in the nine crop rotations influenced the results of this study. In this regard, the emissions of GHG occurs during different agricultural practices directly via utilization of fossil fuel during field management practices (from transplanting to harvest), or indirectly during the production and input transportation which includes chemical fertilizers and synthetic herbicides and pesticides (Wood and Cowie 2004).

According to findings of Pathak and Wassmann (2007) the reasons of global warming include in rice production are field management practices such as the production and transportation of synthetic pesticides (16–91 kg CO_2 eq ha^{-1}) and chemical fertilizers (80–98 kg CO_2 eq ha^{-1}). Another researcher reported that the main reason of global warming is increase in emissions of GHG resulted from human activities (Bare 2011). Pishgar-Komleh et al. (2011) proved that the utmost energy usage in rice field was belonged to fossil fuel including diesel, natural gas and electricity for irrigation. Soltani et al. (2013) explored the emissions with GWP to be 621 kg CO_2 eq for producing a ton of wheat in Gorgan, Iran. Impact category of GWP for field management of wheat production was 119.5 kg CO_2 eq in China (Wang et al. 2009), and 381 kg CO_2 eq for wheat production in Switzerland (Charles et al. 2006). The total energy usage which depended on production systems and farm management practices was 274–557 MJ t^{-1} in the UK (Tzilivakis et al. 2005), and 521 MJ t^{-1} for sugar beet in Japan (Koga 2008). Pazouki et al. (2017) found that the difference in fuel usage, fertilizer, and machinery performance was the reason for the high or low share of non-renewable energy in different wheat production scenarios.

Our findings indicated that clover-rice rotation emitted fewer heavy metals into water, air and soil than other crop rotations for both cultivars because of lower input utilization especially chemical fertilizers (nitrogen, phosphorus, potassium and zinc) and pesticides. In fact, emissions of heavy metal estimated by the annual measurement of the deposit and entrance of these metals into soil through application of chemical fertilizers, synthetic pesticides, seeds and leaching, erosion and harvesting of these metals from soil by. In terms of energy demand, GGP, GWP 20a, GWP 100a and GWP 500a, fallow-rice rotation ranked first followed by rape seed-rice rotation. The main reason for these results were greater application of chemical fertilizers (nitrogen, phosphorus, potassium and zinc) and pesticides in these crop rotations. The share of NH_3 in acidification potential is statistically greater than that of N_2O and SO_2 (Engstrom et al. 2007). In fact, resource of NH_3 emission is urea fertilizer (Engstrom et al. 2007).

Diverse amounts of chemical fertilizers and field management practices of crop plant rotations are the main reasons of these kinds of findings. Application of extreme amount of nutrients is one of the most important cause of eutrophication which modified the species in ecosystems and enhance the biomass production (Pishgar-Komleh et al. 2017). Nemecek and Kagi (2007) verified that in the impact category of eutrophication the amount of leaching was 0.59 kg N t^{-1} for production of sugar beet in Switzerland. In Chile, eutrophication for producing sunflower and canola was 9 and 7.2 kg PO_4 eq, respectively (Iriarte et al. 2010).

Using LCA for rice cultivation by Wang et al. (2010) in China revealed that utilization of resources of fossil fuel was 106 MJ t^{-1} and the final eco-index was 0.008 (Wang et al. 2010). Unakitan et al. (2010) using LCA in Turkey announced that to produce one ton of crops, the following amount of diesel fuel needs to be consumed: 25.63 L for rape seed, others reported 87.78 L for soybean in Iran (Ramedani et al. 2011), and 25.08 L for paddy field in Iran (Pishgar-Komleh et al. 2011). The water utilization during rice growing season in China was 379 cm t^{-1} (Wang et al. 2010). To produce 1-ton of wheat crop in Germany, impact categories of global warming and acidification were the main environmental issues (Brentrup et al. 2004). To produce sunflower and rape seed, the greatest environmental issues were global warming and eutrophication (Iriarte et al. 2010).

The reason for greater energy utilization and GWP in fallow-rice rotation are their high dependence on inputs without any concern to environmental issues. As a matter of fact, an appropriate practice in rice fields for clover-rice rotation and greater utilization of input in other rotations were the causes of the results. The findings indicated that clover-rice rotation displayed more satisfactory influence for energy indices and environmental sustainability for rice field. Energy utilization with more efficiently is possible through enhancing shares of fertilizers and pesticides (Habibi et al. 2019). By analyzing the input in crop rotation system, utilization of energy and environmental emission will be measured and we can be supplying restricted resources which includes fields, water for irrigation and biological resources for future generations. Therefore, for enhancing input productivity, utilization of less chemical fertilizers (especially nitrogen) and fossil fuel as well as mechanization of agricultural crop by legume-rice rotation especially clover is recommended. It can be debated that farmers in fallow-rice, wheat-rice, barley-rice, rape seed-rice rotations do not consider environmental sustainability and economic efficiency. It appears that the gap created could be offset to increase productivity and environmental sustainability for transplanting of both rice cultivars in the region through less application of chemical fertilizers, synthetic pesticides and design of legume-based cropping systems. As a result, the level of emission of environmental pollutants is directly related to input application and crops species in rice rotation, which was based on the lowest level of these indices obtained when leguminous cultivated in rice rotation.

Conclusion

In this research, the environmental impacts related to the production of local ('Tarom Hashemi') and improved ('Shiroodi') rice cultivars in different crop rotations was estimated using the life cycle assessment method. All impact categories assessed by using several models in LCA. Our results demonstrated that decreased application of chemical fertilizers (nitrogen, phosphorus, potassium and zinc), pesticides and better agricultural management practices in clover-rice rotation led to less use of human force, machinery and fuel, resulting in a decrease in energy utilization, emission of GHGs and GWP. The highest amount of GWP, non-renewable and renewable CED, non-renewable and renewable CExD, CC, TA, FE, MEU, OD, WD, MD, FD, HT, POF, PMF, TE, FE, ME, IR, ALO, WD, MD, FD, fossil CO_2 eq, biogenic CO_2 eq, CO_2 eq from land transformation and CO_2 uptake were observed in clover-rice rotation. In contrast, the lowest share of investigated impact categories belonged to fallow-rice rotation followed by rape seed-rice and wheat-rice rotations. Fewer heavy metals were emitted in air (Pb, Cd, Zn and Hg), water (Cr, Zn, Cu, Cd, Hg, Pb and Ni) and soil (nitrate, metals and pesticides) by improved cultivar and clover-rice rotation followed by faba bean rotation. Therefore, the findings of this research suggested that application of chemical fertilizers (especially nitrogen), pesticides, and agricultural management practices are main cause of environmental hazards which is an ecologically important issue that needs to be considered if agrosystems are to be sustainably developed. As a result, emissions is directly related to application of inputs and method of field management. We concluded that the least amount of environmental emissions was obtained in the clover-rice rotation. In conclusion, clover-rice rotation showed the potential to save non-renewable energies (fuel, nitrogen, and etc.) with higher paddy yield which is considered to be environmentally friendly crop in rotation with respect to reducing GHG emissions. The most important finding(s) of this research versus current knowledge is that LCA has not been applied to specifically assess the environmental impact of crop rotation systems in paddy fields in Iran. We compared the results of different LCA methods to provide a better perspective for decision makers related to rice production, farming systems and human health.

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Compliance with Ethical Standards

Conflict of interest The authors do not have any conflicts of interest to declare.

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