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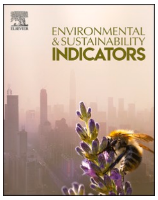

To what extent cultivar selection can affect the environmental impact of rapeseed production?

Seyedeh Samira HabibTabar Shiadeh [a], Yaser Feizabadi [b,*], Armaghan Kosari-Moghaddam [1]

[a] Department of Agricultural Economics, Qaemshahr Branch, Islamic Azad University, Qaemshahr, Mazandaran, Iran
[b] Johann Heinrich von Thuenen Institute - Institute of Farm Economics, Germany

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ABSTRACT

Rapeseed (*Brassica napus* L.), ranked as the second most crucial oil crop globally, holds a prominent position in world agriculture, playing a pivotal role in meeting the increasing demand for edible oil and biodiesel. Pursuing sustainable goals in rapeseed production systems becomes paramount to addressing this growing demand. This study focuses on cultivar selection, a key factor for decision-makers striving to establish sustainable production systems. The investigation, conducted in Mazandaran province, Iran, the country's third-largest rapeseed producer, examines five commonly used cultivars: Zafar, Hyola, Traper, RGS003, and Neptune. Employing Life Cycle Assessment (LCA) with the IMPACT2002+ method, the study reveals varying environmental impacts among cultivars, contingent on the selected functional unit. Accordingly, based on one ton of harvested mass, RGS003 emerges as the most pollutant cultivar, while considering 1 ha of rapeseed farms, Traper exhibits the highest environmental impacts. nitrogen-based fertilizers stand out as major hotspots, contributing to over half of the negative effects across various categories. In conclusion, while factors like drought tolerance and disease resistance are crucial in cultivar selection, the environmental performance of cultivars also significantly influences the decision-making process.

Nomenclature

LCA	Life Cycle Assessment	TE	Terrestrial Ecotoxicity
Car	Carcinogens	TA	Terrestrial Acid/Nutri
N-Car	Non-Carcinogens	LO	Land Occupation
RI	Respiratory Inorganics	AA	Aquatic Acidification
IR	Ionizing Radiation	AEU	Aquatic Eutrophication
OLD	Ozone Layer Depletion	GW	Global Warming
RO	Respiratory Organics	NRE	Non-Renewable Energies
AE	Aquatic Ecotoxicity	ME	Mineral Extraction

1. Introduction

Environmental factors play an important role in the establishment, development, and production of any crop and regulate the decomposition processes as well as ecosystem functioning (Bargali et al., 2019; Karki et al., 2021; Pandey et al., 2024). Rapeseed production holds global significance due to its pivotal role in meeting the rising demand for edible oils, animal feed, and biofuels (Kirkegaard et al., 2021). Rapeseed, scientifically known as Brassica napus, is a versatile crop cultivated worldwide for its oil-rich seeds (Zhang et al., 2022). Rapeseed meal, a byproduct of oil extraction, is widely used as a protein-rich component in animal feed, contributing to the livestock and poultry industries (Negawoldes, 2018). Moreover, rapeseed oil serves as an important feedstock for biodiesel production, aligning with global efforts to promote sustainable and renewable energy sources (Bessah et al., 2023). Rapeseed, at 84.79-million-ton ranks as the second most cultivated oilseed worldwide, trailing behind soybeans by 388.01 million tons in 2022/2023 (Statista, 2023b). European Union, Canada, China, and India are the main rapeseed-producing countries in the world with a total of 72.88% of total rapeseed production (Statista, 2023a). In Iran, approximately 153,536 ha of both irrigated and rainfed arable land were allocated for rapeseed cultivation as the primary oil crop, resulting in a total production of around 290,840 tons during the 2021/2022 period (Iran Ministry of Agriculture, 2023).

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* Corresponding author.

E-mail addresses: samiraahabibtabar999@yahoo.com (S.S. HabibTabar Shiadeh), yaser.feizabadi@thuenen.de (Y. Feizabadi), a.kosarimoghaddam@gmail.com (A. Kosari-Moghaddam).

[1] Independent Researcher.

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The substantial role of rapeseed production globally particularly in Iran has prompted concerted efforts to monitor and enhance the conditions of its cultivation. Accordingly, stakeholders have initiated measures to ensure sustainable and efficient cultivation practices. Monitoring efforts encompass various aspects, including crop growth (Khan et al., 2020; Raza, 2021), crop health (Pineda and Barón, 2022; Soomro et al., 2020), and yield optimization (Zheng et al., 2022; Rajković et al., 2021). One of the other important characteristics of a crop that can affect significantly on determining crop yield, oil quality, and overall adaptability to varying environmental conditions is crop cultivar selection. Choosing the right cultivars is essential for optimizing productivity and ensuring resilience against biotic and abiotic stress factors (Rane et al., 2021). Selecting rapeseed cultivars with high oil content, improved disease resistance, and enhanced agronomic traits contributes directly to the economic success of farmers and the sustainability of the crop.

In recent years, the role of rapeseed cultivar selection on various factors has been investigated. Most of the previous publications have focused on the performance of various rapeseed cultivars under drought stress. Accordingly, in a study, the response of different rapeseed cultivars to vermicompost under drought stress in terms of crop growth, physiology, and fatty acid content was studied (Feizabadi et al., 2021). Shafighi et al. (2021) reported the effect of planting dates and drought stress at the rapeseed flowering stage on the grain yield and physiological conditions of different cultivars. In another study, 17 rapeseed cultivars were compared based on drought tolerance indices (Eyni Nargeseh et al., 2020). Khan et al. (2019) also studied the morph-physiological and biochemical responses of different kinds of rapeseed cultivars to drought stress. The susceptibility of rapeseed cultivars to various factors has been also investigated such as peach potato aphids (Kordan et al., 2021), and the salinity stress during the early seedling stage (El-badri et al., 2021). Moreover, the role of the application of different kinds of fertilizers in the production of rapeseed cultivars was determined. Accordingly, Sikorska et al. (2021) investigated the impact of foliar application of nitrogen, sulfur, and boron on various rapeseed cultivars. Moradi et al. (2023) also determined how nitrogen fertilizer, biochar, and salicylic acid would affect rapeseed yield, and fatty acid profile in six different cultivars. Despite the extensive studies on the role of rapeseed cultivar selection on various aspects of crop production conditions, a few limited studies were focused on the role of cultivar selection on environmental performance indicators. To be more precise, Groth et al. (2020) evaluated the effectiveness of nitrogen and sulfur fertilization in various rapeseed cultivars in terms of crop productivity, and economic and energy balance. Sokólski et al. (2020) also investigated the performance of different rapeseed cultivars in terms of crop productivity, energy, and economic aspects in Poland.

On the other hand, regarding the importance of rapeseed production in the world, the various environmental performance aspects of this crop have been investigated widely. From an exergy viewpoint, various studies claimed the importance of chemical fertilizers in rapeseed production (Esmaeilpour-Troujeni et al., 2020, 2021; Esmaeilpour-Troujeni et al., 2021b; Amiri et al., 2020a). However, in another study in Iran on rapeseed production, diesel fuel consumption was reported as the exergetic hotspot (Hosseinzadeh Samani et al., 2020). From the energy point of view, the energy efficiency of rapeseed production in Poland under various farming systems was determined between 3.46 and 4.22 for seeds only, and 8.61 to 9.43 for seeds and straws (Budzyński et al., 2015). In another study in Poland, also, the energy efficiency of winter rapeseed production was reported to be 4.92 in terms of seeds only (Jankowski et al., 2015). This index for rapeseed production in Iran was varied between 2.79 and 3.83 for different levels of nitrogen fertilizers (Rabiee et al., 2021).In some other studies, the emergy criteria were considered to evaluate the environmental performance of rapeseed production. Accordingly, Amiri et al. (2019) compared two rapeseed farming systems in Iran in terms of emergy and economic indicators. They reported that commercial systems had lower sustainability than subsistence systems due to higher rates of soil organic matter loss (Amiri et al., 2019). In another study, they showed that the excess use of water, human labor, chemical fertilizers, and pesticides affects the sustainability of the traditional rapeseed production systems in Iran (Amiri et al., 2020b).

Following the environmental analysis methods, life cycle assessment (LCA) has been widely used in recent years to measure the environmental performance of various agricultural systems. This method offers a comprehensive approach to investigating the environmental impacts associated with the entire life cycle of agricultural products (Alhashim et al., 2021). LCA's core principle is to track a product across its life cycle, delineating a boundary between its 'product system' and the surrounding environment, with energy and material flows across this boundary linked to the system's inputs and outputs, which are subsequently aggregated into impact indicators (van der Werf et al., 2020). By quantifying energy consumption, resource use, and emissions across the entire life cycle, LCA facilitates the identification of hotspots and helps guide decision-makers toward more sustainable practices (Corominas et al., 2020). Ultimately, integrating LCA into the assessment of agricultural practices is imperative for promoting sustainable food production and ensuring that the global agricultural sector aligns with broader environmental goals. Accordingly, the LCA methodology has also been applied to study the environmental performance of rapeseed production systems. In a study in Argentina, the comparison between the environmental impacts of soybean and rapeseed production systems indicated that from the area-based viewpoint, rapeseed production was attended to higher environmental impacts, while from the energy-based viewpoint, the higher environmental impacts belonged to soybean production due to lower oil content (Fernández-Tirado et al., 2017). In another research in Latvia, the results approved that spring rapeseed had higher environmental consequences than winter rapeseed due to higher input consumption rates. In this study, mineral fertilizers as well as agricultural machinery were the environmental hotspots (Fridrihsone et al., 2020). In rapeseed production systems in China, it is reported that the rate of GHG emissions from these agricultural systems has increased from 2004 to 2018 due to higher consumption of agricultural inputs, particularly, diesel fuel (Guo et al., 2022). Moreover, in Iran, chemical fertilizers were identified as the most-pollutant input in the rapeseed production systems (Choobin et al., 2016).

According to the literature review, given the vital role of rapeseed worldwide, extensive efforts have been made to improve the production of this crop in numerous aspects. However, there are still significant gaps in assessing the environmental impact of rapeseed production systems. In this regard, cultivar selection can be a potential solution for mitigating the environmental impacts of rapeseed production by potentially reducing resource use, increasing resilience to environmental stressors, and enhancing yield. Specifically, the question of how cultivar selection affects the environmental impacts of rapeseed production systems remains unanswered. In this regard, using the LCA methodology, the present study focused on the role of cultivar selection on the environmental impacts arising from rapeseed production systems in Iran.

2. Materials and methods

Current research has been done to assess the effect of cultivar selection on the environmental performance of rapeseed production systems. Therefore, the LCA was applied for this purpose. Accordingly, this study follows the instruction proposed by ISO14040 to conduct an LCA based on four following steps.

2.1. Goal and scope definition

The *goal* of this study is to find how cultivar selection can affect the environmental load in the rapeseed production systems in Iran. Accordingly, five common rapeseed cultivars in the studied region, Mazandaran, Iran, were chosen including Zafar, Hyola, Traper, RGS003, and Neptune. Besides other important differences between these rapeseed cultivars, environmental performance can also be a vital factor for decision-makers and farm managers. Therefore, as a “cradle-to-gate” assessment, the *scope* of this study comprises all crop cultivation practices on the farm from land preparation before planting to the crop harvest. To accurately measure the environmental impact, two *functional units (FU)* were chosen: harvested mass (one ton of rapeseed seed) and cultivated area (1 ha of farm). These specific functional units were considered in a wide range of previous studies on the environmental impacts of the agricultural sector (Kosari-Moghaddam et al., 2025; AliGhaleh et al., 2024; Alijani et al., 2024), as they provide a comprehensive view of the environmental impacts, reflecting both production efficiency (mass) and resource use (area). The *system boundary* also contains background and foreground environmental impacts, including inputs extraction and production (i.e., chemical fertilizers, biocides, diesel fuel, and electricity), rapeseed production in the farm (i.e., emissions of fertilizers applications to soil, water, and air, as well as emissions from diesel combustion in tractors and combine harvesters) (Fig. 1).

2.2. *Life cycle inventory (LCI)*

2.2.1. *Studied location and cultivars*

The case study area in this research was Mazandaran province, located in the north of Iran ($53^\circ6'$ E, $36^\circ23'$N). This province is known as the third primary producer of rapeseed in Iran after Khuzestan and Golestan provinces with around 16,256 tons and 9476 ha contributing to around 6% of total rapeseed production and associated area in Iran. The data related to the farms were collected through personal interviews with farmers contributing to rapeseed production in the studied area. The collected data included farm size and crop yield, used cultivar, total crop harvested, and input consumption values including chemical fertilizers, biocides, diesel fuel, water, and electricity. Five common rapeseed cultivars were selected in this study including Zafar, Hyoal, Traper, RGS003, and Neptune. Some main characteristics of studied cultivars are shown in Table 2.

2.2.2. *Determining emissions*

The emissions from the application of nitrogen-containing fertilizers were determined based on IPCC (2006) in terms of direct and indirect emissions to air, water, and soil. To be more precise, the N-related emissions were defined in terms of carbon dioxide (CO_2), ammonia (NH_3), dinitrogen monoxide (N_2O), and nitrogen oxides (NO_x). Also, the P-related emissions were calculated based on Agri-Footprint 5(2019) databases as PO_4^{3-} to water. Moreover, the emissions related to diesel combustion were determined based on the Ecoinvent database.

2.3. *Life cycle impact assessment (LCIA)*

The environmental impacts were determined in this study using the IMPACT2002+ method Jolliet et al. (2003). This LCIA method as a widely used method to determine the environmental consequences of the agricultural sector (Hu et al., 2019; Khanali et al., 2021; Motevali et al., 2023) assesses environmental impacts at both midpoint and damage levels. First, the impacts were evaluated under 15 midpoint categories. These categories were chosen to provide a comprehensive view of the environmental burdens associated with rapeseed production. They cover various aspects such as resource use, emissions, and ecological effects. These values were then aggregated into four damage categories: human health, ecosystem quality, climate change, and resources. These damage categories were selected as they represent the broader, long-term consequences of environmental impacts on crucial aspects of both human and ecological systems. Although normalization and weighting in LCA are not mandatory, these steps were applied in this study to derive single score values. This approach simplifies the comparison of the environmental performance of various rapeseed cultivars by providing a clear and easily interpreted metric. The proposed LCA was defined in SimaPro 9.4 software.

2.4. *Results interpretation*

In the last step of LCA, the results were explored in three levels, i.e., midpoint level, damage level, and final environmental load (single score). Next, to find how the results would be affected by the LCIA method, two other LCIA methods i.e., ReCiPe2016 (Huijbregts et al., 2017), and LC-IMPACT (Verones et al., 2020), all impacts, average values were also examined.

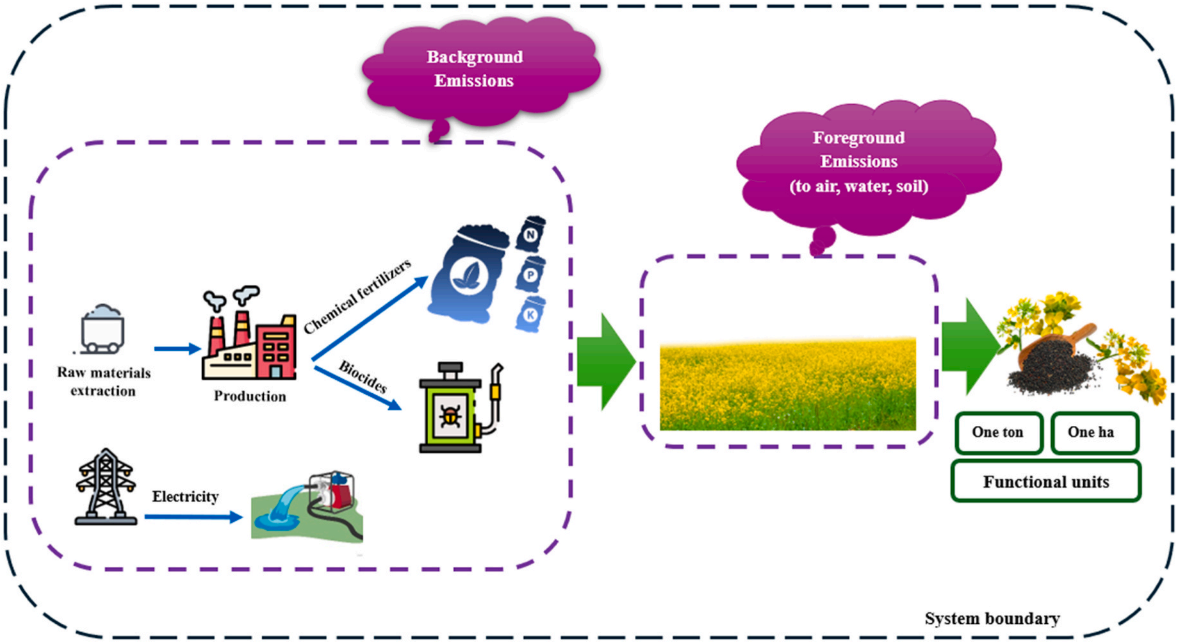


Fig. 1. The consumed inputs, system boundary, and functional units in rapeseed production.

Table 1
Life cycle inventory of the studied rapeseed production systems.

Cultivar	Diesel	N	P	K	Sulfur	Herbicide	Insecticide	Fungicide	Water	Electricity	Yield
	L	kg	kg	kg	kg	kg	kg	kg	m3	kWh	kg
Per one ton of harvested rapeseed											
Zafar	64.35	65.22	21.74	21.74	21.74	1.52	1.74	0.43	95.65	51.87	1000
Hyola	38.91	65.00	23.35	17.91	18.33	0.37	0.35	0.11	86.80	47.82	1000
Traper	40.54	86.14	24.80	24.74	24.80	0.30	0.10	0.10	94.01	61.43	1000
RGS003	46.56	80.19	33.02	23.58	26.42	0.09	0.47	0.09	105.66	76.42	1000
Neptune	45.20	78.04	28.89	23.11	21.68	0.52	0.14	0.09	78.90	71.39	1000
Per 1 ha											
Zafar	148	150	50	50	50	3.50	4.00	1.00	220.0	119.3	2300
Hyola	112.3	187.6	67.4	51.7	52.9	1.08	1.02	0.31	250.5	138.0	2886
Traper	136.5	290	83.5	83.3	83.5	1.00	0.34	0.34	316.5	206.8	3366.7
RGS003	98.7	170	70	50.0	56.0	0.20	1.00	0.20	224.0	162.0	2120
Neptune	120.3	207.7	76.9	61.5	57.7	1.38	0.38	0.23	210.0	190.0	2661.5

3. Results and discussion

3.1. Inputs contribution to the environmental pollution

Fig. 2 shows how the consumed inputs impact the environment when producing one ton of harvested rapeseed. Accordingly, nitrogen-based fertilizers were the main contributors to negative environmental impacts in most impact categories, accounting for more than 50% of total impacts. However, in some other indicators, such as RI, RO, OLD, and GW, on-farm emissions and diesel fuel were identified as other primary pollutants.

The midpoint categories related to human toxicity, including Car, N-Car, RI, RO, IR, and OLD, are considered indicators of toxicological risk and potential human health impacts. In the Car and N-Car indicators, nitrogen fertilizers contribute approximately 70% of the total environmental impacts associated with their production. Although the contribution of nitrogen fertilizers decreases to around 35–40% in other midpoint indicators, they remain the main pollutant in categories related to human health. The production process of chemical fertilizers, especially nitrogen-based ones, relies heavily on consuming mineral and fossil resources, leading to airborne emissions (Walling and Vaneeckhaute, 2020) that exacerbate human health challenges. Furthermore, in respiratory-related impacts such as RI and RO, on-farm emissions have the highest contribution to environmental impacts, at about 29% and 32%, respectively, following nitrogen fertilizers. This can be attributed to the emission of hazardous air pollutants causing respiratory health issues. Additionally, in IR and OLD indicators, diesel fuel is identified as the second most significant pollutant input, contributing around 20% and 38%, respectively. Currently, exposure to emissions from diesel exhaust from tractors and agricultural machinery makes farmers and agricultural workers vulnerable to a wide range of diseases, including lung cancer (Sauvé et al., 2020).

The investigation of factors influencing ecosystem pollution, including AE, TE, TA, LO, AA, and AEU, revealed that chemical fertilizers, particularly nitrogen-based fertilizers, were the most significant contributors. In these categories, 50%–65% of the total contribution was attributed to nitrogen-based fertilizers, with phosphorous-based fertilizers ranking second, accounting for 10%–30% of the total contribution. Potassium-based fertilizers, contributing around 10% on average, were the next significant factor in the total environmental impacts. The

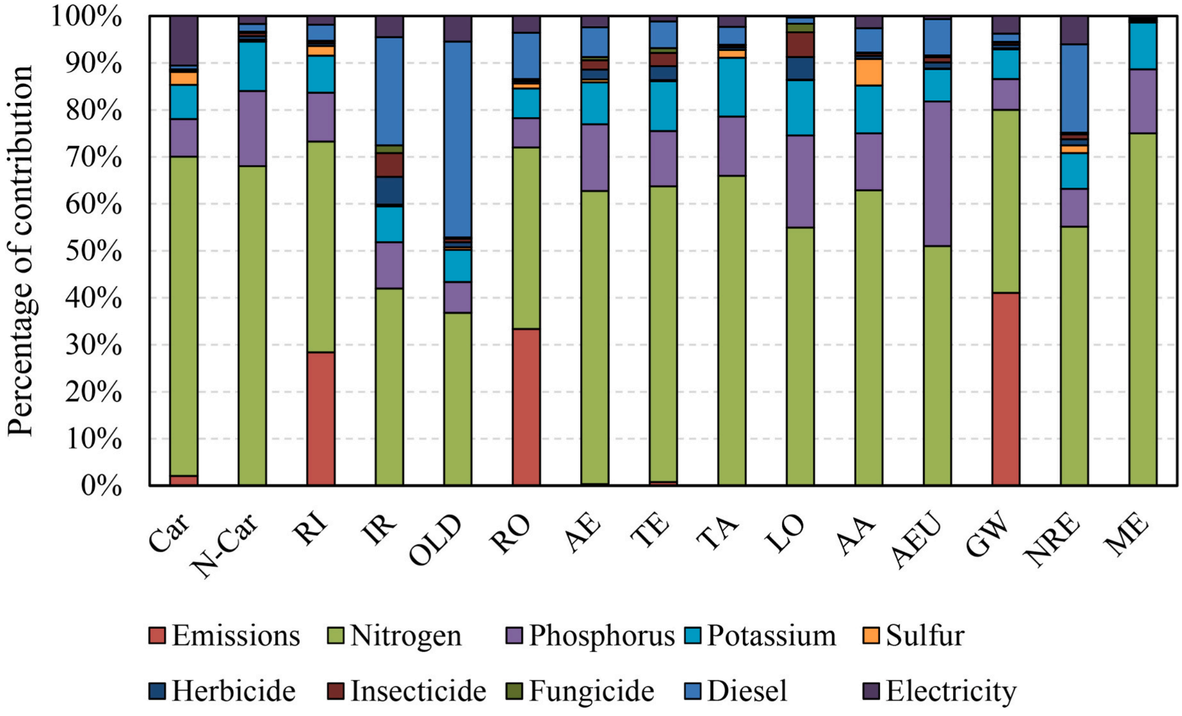


Fig. 2. Average percentage of contribution of various inputs in the studied impact categories.

negative impacts associated with applying mineral fertilizers on farms include the addition of heavy metals to soils, deterioration of the physical and biological characteristics of agricultural soils, entry of metals into the food chain, water eutrophication, and pollution of underground water resources (Khan et al., 2018). Accordingly, precision agricultural techniques, such as applying variable rates of fertilizers based on farm monitoring, can be an effective solution to control such pollution.

In the GW midpoint indicator, the primary environmental pollution sources were on-farm emissions and nitrogen-based fertilizers, accounting for 41% and 39%, respectively. The application of chemical fertilizers on farms results in emissions, with nitrous oxide (N_2O) being a major contributor (Walling and Vaneeckhaute, 2020). The 100-year global warming potential of nitrous oxide is approximately 298 times that of carbon dioxide according to IPCC (Ming et al., 2016). Consequently, in agricultural systems relying on inorganic nitrogen fertilizers, on-farm emissions become primary contributors to global warming. Additionally, the combustion of diesel fuel in tractors and combine harvesters releases considerable amounts of carbon dioxide, another significant factor in global warming potential. In this regard, replacing traditional fuels with biofuels in agricultural practices can reduce these negative impacts. Accordingly, previous studies demonstrated the superior environmental performance of biodiesel in tractors (Hosseinzadeh-Bandbafha et al., 2021; Akbari et al., 2024).

In the midpoint categories related to resource consumption, such as NRE and ME, nitrogen fertilizers were the predominant contributors. According to Fig. 2, nitrogen-based fertilizers accounted for approximately 55% and 75% of the total environmental impacts in these indicators. In the NRE category, diesel fuel was the second most significant pollutant, contributing 17% of the total impact, whereas in the ME category, other chemical fertilizers, including phosphorous and potassium-based fertilizers, ranked second and third, accounting for about 15% and 10%, respectively. The production of chemical fertilizers requires the extraction of various mineral resources (Walling and Vaneeckhaute, 2020). Similarly, diesel fuel is derived from crude oil and other mineral resources. Additionally, the production processes for both inputs are energy-intensive, necessitating the use of additional resources.

3.2. Effect of rapeseed cultivars on midpoints indicators

Fig. 3 compares the environmental impacts of the five investigated rapeseed cultivars at the midpoints level. In most midpoint categories, Traper and RGS003 exhibited the highest negative impacts. However, in some categories, such as IR, OLD, RO, and LO, Zafar was the most pollutant cultivar. RGS003 and Traper showed higher consumption rates of chemical fertilizers, while Zafar was the highest consumer of diesel fuel. In contrast, the Hayola cultivar had significantly lower environmental impacts than other studied cultivars in all midpoint categories, with a difference of more than 20% compared to the most pollutant cultivar in each midpoint category. Producing one ton of Hyola cultivar required the least amount of agricultural inputs and as a result lowest environmental impact.

The results of environmental impacts related to the Car and N-Car indicators highlighted that Traper had the highest effects on the environment, with RGS003 and Neptune following closely at 99.89% and 95.51% of the maximum determined impacts, respectively. However, despite the close consumption rates of inputs in these three cultivars, the main reason for this difference can be attributed to the higher usage of nitrogen and potassium fertilizers per one ton of produced crops. Moreover, Zafar and Hyola exhibited the lowest impacts in these indicators, with 81.64% and 77.39% of the maximum determined impacts, respectively, owing to their significantly lower consumption of chemical fertilizers and diesel fuel compared to Traper (Table 1).

In the RO and RI indicators, the trends were different. In the RI indicator, the RGS003 cultivar was associated with the highest environmental impacts. Following RGS003, Zafar held the second rank with 99.40% of the maximum determined impacts. Subsequently, Traper and Neptune were ranked third and fourth, respectively, with 96.24% and 95.83% of the maximum determined impacts. Finally, the Hyola cultivar contributed to 79.91% of the total maximum determined impacts. This difference may stem from the higher rates of phosphorus and sulfur-

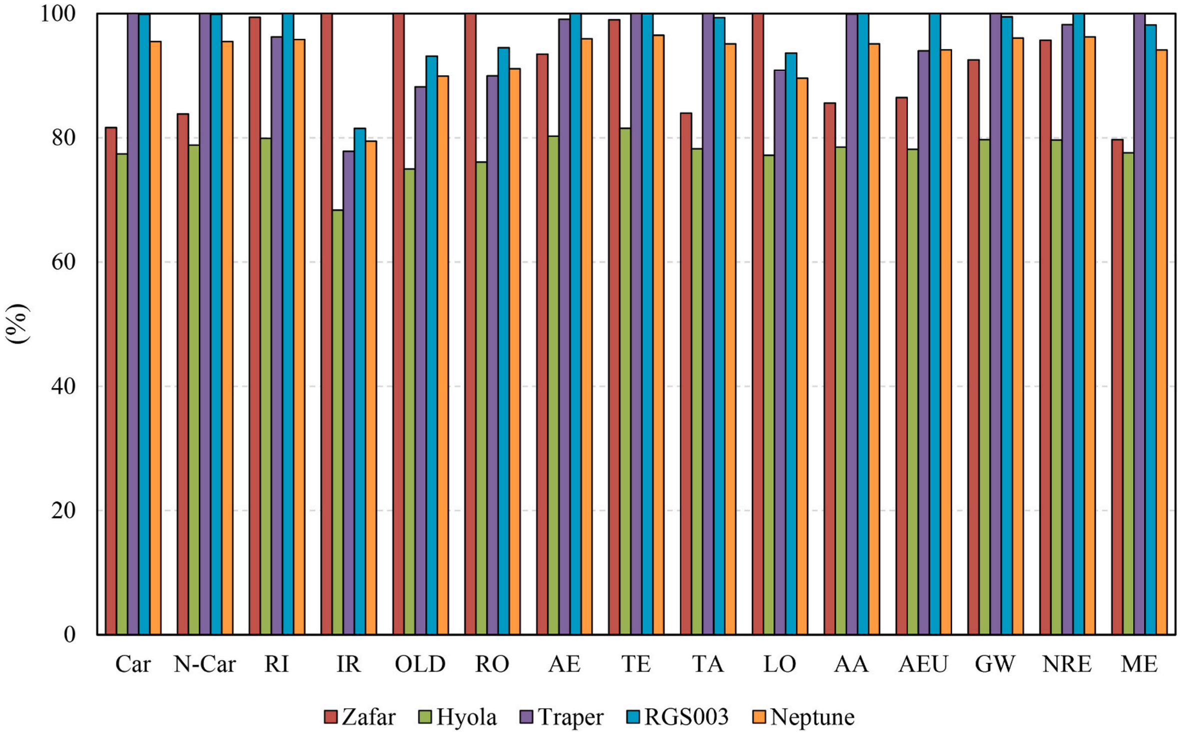


Fig. 3. Comparison between the environmental impacts of five investigated rapeseed cultivars at the midpoints level.

Table 2
Characteristics of rapeseed cultivars in this study.

Cultivar	Characteristics	References
Zafar	Hybrid, Spring, medium-maturity, mild, cold-resistance, disease-resistant, origin of Iran	Seed and Plant Improvement Institute SPII (2017)
Hyola[a]	Hybrid, Spring, early-maturity, warm-wet, Warm-dry, origin of Canada	Alizadeh et al. (2021)
Traper	Hybrid, Spring, very-early-maturity, Warm-wet, Warm-dry, grain losses resistant, origin of Germany	Alizadeh et al. (2021)
RGS003	Hybrid, Spring, early-maturity, origin of Germany	Rameeh et al. (2013)
Neptune	Hybrid, winter, early- maturity, cold and mild-cold, grain loss resistant, cold tolerant, origin of France	Zareei Siahbidi et al. (2021)

[a] Hyola cultivar has different cultivars such as Hyola 401, and Hyola 4815.

based fertilizers in the RGS003 cultivar compared to other cultivars.

On the other hand, in the RO, IR, and OLD indicators, the highest negative impacts belonged to the Zafar cultivar. According to Table 1, the Zafar cultivar was responsible for the highest consumption rate of diesel fuel among the studied rapeseed cultivars, stemming from a higher needfor biocides. Therefore, the higher consumption of diesel fuel resulted in higher on-farm emissions and background negative impacts from diesel production as well as biocide production.

According to the midpoints related to the ecotoxicity and acidification of resources, i.e., AE, TE, and TA, it can be seen that the cultivars with higher consumption rates of chemical fertilizers attended to the higher negative impacts. Though these chemical fertilizers have an important role in increasing crop production they adversely affect the ecosystem environment (Padalia et al., 2017, 2018). To be more precise, in the AE indicator, the highest environmental impact was related to the RGS003, and then Traper and Neptune followed it with 99.06% and 95.96% of maximum determined impacts, respectively. RGS003 was responsible for higher consumption of phosphorus and sulfur fertilizers as well as electricity based on FU. Additionally, in the TE indicator, Traper was determined as the most pollutant input and after that, RGS003 and Zafar cultivars were in the second and third ranks with 99.98% and 98.99% of maximum determined impacts, respectively. The highest rates of nitrogen and potassium-based fertilizers were consumed in the production process of the Traper and RGS003 cultivars, respectively. However, the high negative impacts of the Zafar cultivar in this indicator can stem from the significant high consumption of diesel fuel in the production process that resulted in about two-fold on-farm emissions compared to the Traper and GRS cultivars in this midpoint category.

In the land occupation midpoint category (LO), the highest negative impact was related to the Zafar cultivar. After Zafar, RGS003 and Traper with 93.63% and 90.89% of maximum determined impacts, respectively had the highest negative effects. As described before, the Zafar cultivar was responsible for the highest consumption of biocides and diesel fuel consumption. However, in this midpoint indicator, the main reason for the higher contribution of the Zafar cultivar was the higher consumption of biocides compared to other cultivars.

From aquatic resource pollution viewpoints, i.e., AA and AEU, the results indicated that RGS003 had the highest impacts, and after that, Traper with 99.94% and 94.01%, respectively had the highest negative effects on the environment. In these indicators, Neptune had the third rank and after that, Zafar and Hyola had the lowest impacts on the aquatic resources. Chemical fertilizer consumption is known as a primary pollution resource in these indicators, therefore, two rapeseed cultivars with the highest consumption of chemical fertilizers, i.e., RGS003 and Traper, were found to have the highest negative impacts.

In the GW midpoint category, the highest GHG emissions were related to the Traper cultivar by 1112.82 kg CO2eq. It was followed by RGS003 with 1106.99 and Neptune with 1069.00 kg CO2eq. In the next ranks, Zafar and Hyola also had 1029.81 and 887.04 kg CO2 eq GHG emissions. In this indicator, however, the Zafar cultivar had the highest on-farm emissions stemming from a higher consumption rate of diesel fuel with 455.91 kg CO2eq, the higher emissions related to the chemical fertilizers production in the production systems of Traper, RGS003, and Neptune resulted in higher GWP in these cultivars.

From a non-renewable energy consumption (NRE) viewpoint, the RGS003 cultivar was responsible for the highest energy consumption with 11957.84 MJ. After GRS, Traper, Neptune and Zafar stood on the following ranks by 11745.01, 11509.78, and 11446.01 MJ, respectively. And finally, Hyola with 9524.61 MJ had the lowest energy consumption. In general, chemical fertilizers, diesel, and electricity are responsible for energy consumption in the agricultural sector. Therefore, in this midpoint category, cultivars with high rates of chemical fertilizers were found to have the highest energy consumption.

Finally, in the midpoint category of ME, the Traper cultivar was the most-pollutant cultivar. Then, RGS003 and Neptune followed Traper with 98.18% and 94.13% of maximum determined impacts, respectively. In this category, also, the main factor of pollution was chemical fertilizers, especially nitrogen fertilizers which had the highest consumption rate in the Traper cultivar.

3.3. Damage indicators

The environmental impacts of various rapeseed production systems in terms of four damage categories are shown in Fig. 4. For more details, each damage category is presented based on the effective midpoints. In general, the Traper and RGS003 cultivars had the highest environmental impacts, while the Hyola was the least-pollutant cultivar in all damage categories per one ton of harvested rapeseed.

Fig. 4(a) describes environmental impacts associated with human health issues in terms of Disability Adjusted Life Year (DALY). DALY quantifies damages to human health due to specific diseases resulting in the loss of life or normal ability (Gao et al., 2015). Six midpoint indicators that contribute to this damage category include Car, N-Car, RO, RI, IR, and OLD. In this damage category, the RGS003 cultivar was the most pollutant cultivar by around 0.000797 DALY, and three cultivars, Zafar, Traper, and Neptune, followed it. Finally, the Hyola cultivar caused the lowest human health-related challenges. Moreover, the role of RI was greater than other midpoints in this damage category, and after that, Car and N-Car factors contributed to the environmental impacts. RI pollution can result from the high rates of chemical fertilizers directly and indirectly, i.e., an increase in on-farm emissions (Fig. 2). Chemical fertilizer production releases a wide range of emissions into the air, influencing RI. Ammonia and nitrogen oxides are two primary emissions from nitrogen-based fertilizer production that affect respiratory challenges, and the combination of these emissions with other particulates can be another effective factor in the negative damages (Schlesinger and Lippmann, 2020) related to RI. Generally, chemical fertilizers containing nitrogen components can cause diseases related to polluted drinking water (de Vries, 2021), and air (Bittman et al., 2014). Therefore, improving the production process of chemical fertilizers as well as optimizing the consumption of these inputs in the farms can lessen the environmental impacts associated with human health.

The next damage category studied in this study was ecosystem quality (Fig. 4(b)). This category indicates the damage to the ecosystems and is defined based on the PDF.m^2.yr. The ecosystem quality in terms of PDF.m^2.yr quantifies the annual disappearance rate of organisms classified as surface species within a square meter. This damage category consists of four midpoint indicators including aquatic and terrestrial eutrophication, terrestrial acidification, and land occupation. In ecosystem quality, the RGS003 was the most-pollutant cultivar by 219.19 PDF.m^2.yr and Traper, Zafar, Neptune, and Hyola had the next ranks. Among the midpoint categories, TE was the primary pollutant in this damage category in all investigated systems. After that, LO and TA were the biggest contributors to the ecosystem's damage. According to

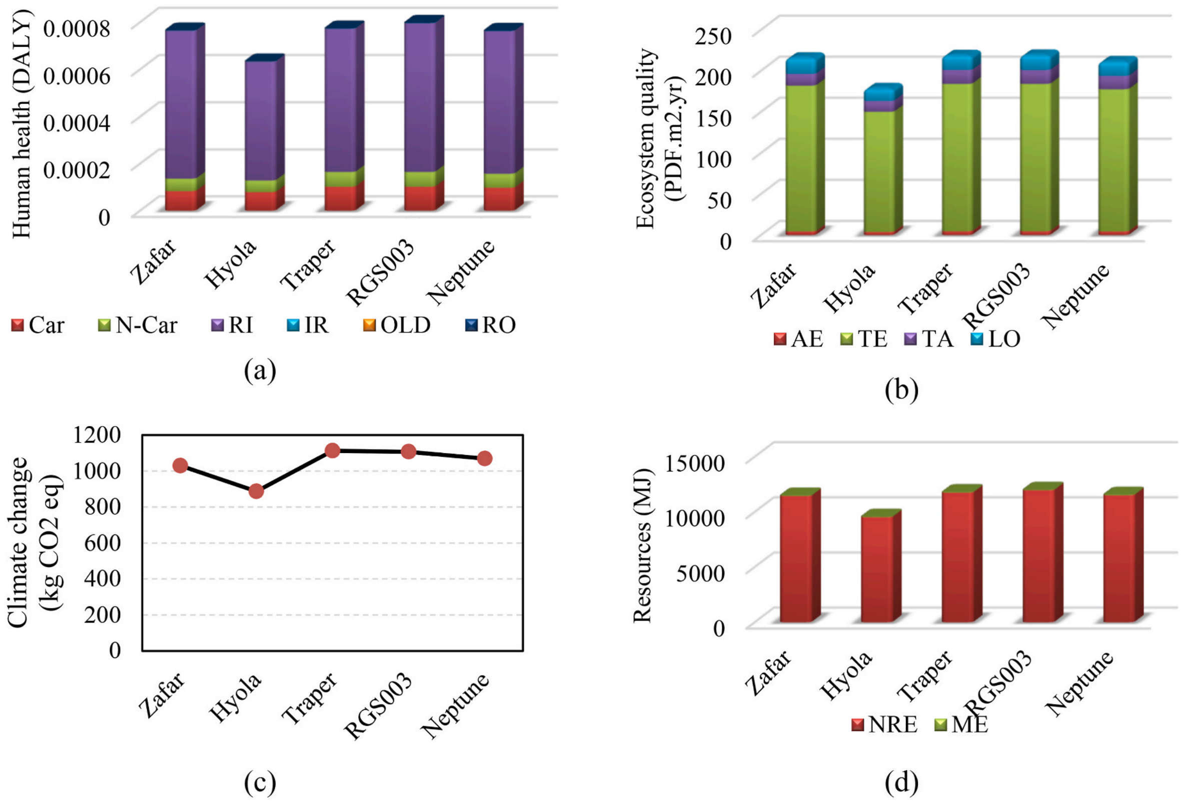


Fig. 4. The environmental impacts associated with five rapeseed cultivars in terms of four damage categories; (a) human health, (b) Ecosystem quality; (c) Climate Change; (d) Resources.

Fig. 2(b), the potential damage in TE belongs to the high consumption rates of chemical fertilizers, particularly nitrogen-containing fertilizers. Production of chemical fertilizers, particularly nitrogen-based fertilizers can lead to entering chemical compounds into the environment through runoff or leaching into groundwater. This results in enriching the environment with specific chemical components and consequently increases in eutrophication (Henderson, 2015). Additionally, Excessive use of chemical fertilizers causes soil pollution by increasing soil acidity (Cai et al., 2015), water pollution by eutrophication (Rathore et al., 2016) and leaching (Pahalvi et al., 2021), and as a result, disrupting biodiversity (Singh et al., 2021) and microbial activity (Bai et al., 2020). However, promising agricultural practices such as precision farming and replacing organic fertilizers can mitigate such potential impacts.

In the next step, the effective factors in the climate change damage category were investigated (Fig. 4(c)). This damage category in the IMPACT2002+ method shows the potential global warming of the investigated systems and is defined based on kg of equivalent carbon dioxide. In this damage category, the highest value was related to Traper. After Traper, RGS003, and Neptune were the second and third ranks in this damage category. The results indicated that, due to the high consumption rates of chemical fertilizers, Traper was the most-pollutant cultivar.

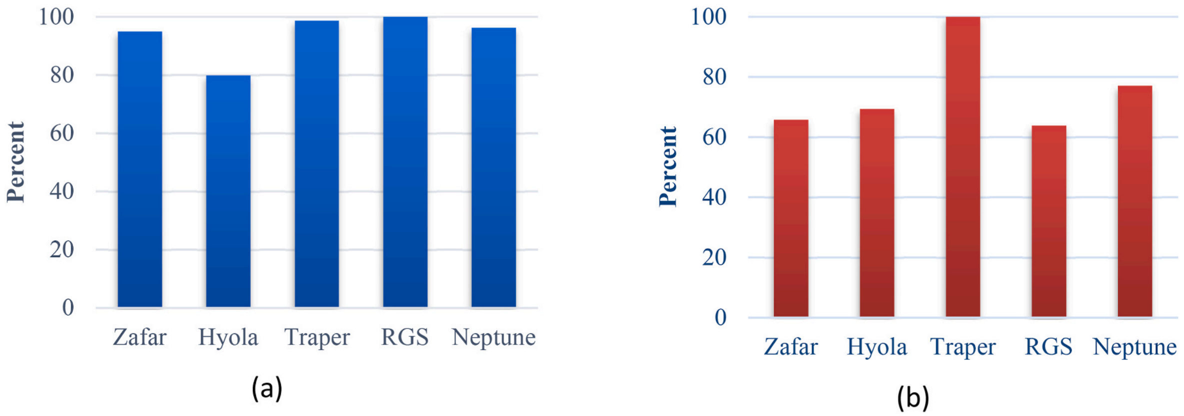
Finally, the fourth damage category was resources. This category indicates the associated impacts related to the use of non-renewable resources and is defined in terms of Mega Joule (MJ). Resources consist of two midpoint categories, i.e., non-renewable energy and extraction of mineral resources. According to Fig. 4(d), RGS003 had the highest pollution rate in this damage category by 12000 MJ, and Traper, Zaffar, and Neptune with a little difference followed it. In this category, almost all share of environmental impacts belongs to non-renewable energy. According to the results from midpoint categories, chemical fertilizers, diesel fuel, and electricity were the primary contributors to this midpoint category. Therefore, decreasing the role of non-renewable resources such as replacing renewable energy sources (Nikkhah et al., 2021), and organic fertilizers (Zhang et al., 2019) would improve the environmental performance of agricultural production systems.

3.4. Total environmental load

After finding the environmental impacts associated with different rapeseed cultivars in terms of damage categories, these values were normalized and weighted to determine the total environmental load of the investigated production systems. These values are presented based on two different functional units, i.e., a one ton of harvested rapeseed, and 1 ha (Fig. 5). The final indicators are defined based on a single score, and the associated unit is Pt. Pt shows the weighted environmental points per equivalent inhabitant (Gonzalez-Garcia et al., 2018). According to the figure, per one ton of harvested crop, the RGS003 was the most pollutant cultivar and Traper, Neptune, and Zafar followed it. Hyola also had the lowest environmental impacts based on this functional unit. However, area-based functional unit present different results. According to Fig. 5(b), the highest environmental impacts belonged to the Traper cultivar, and after that, RGS003 had around 80% of the negative impacts of the Traper. In this functional unit, the RGS003 cultivar, which was the most pollutant cultivar based on the one ton of the harvested crop, had the lowest environmental impacts. It can be stemmed from the lower yield of RGS003 compared to the other cultivars (Table 1). Therefore, the lower yield per hectare resulted in lower environmental impacts.

3.5. Sensitivity analysis

Two different impact assessment models were applied to analyze the sensitivity of the results in this study. These models were ReCiPe2016 Endpoint (Huijbregts et al., 2017) and LC-IMPACT average preference, all impacts, 100 years (Verones et al., 2020). The results of three damage



(a)

(b)

Fig. 5. The total environmental load of different rapeseed cultivars in terms of (a) Single score per ton and (b) per unit area.

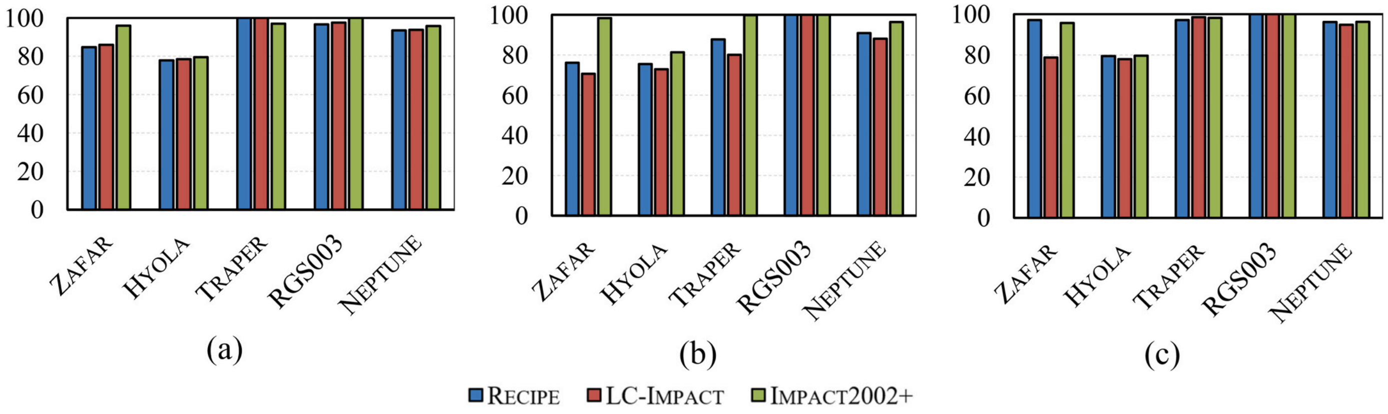
categories, including human health, ecosystem quality, and resources, were compared in terms of the percentage of maximum determined impacts (Fig. 6). The results indicated that, per ton of harvested crop, the most pollutant cultivar in all damage categories was RGS003, except for human health, where the Traper cultivar was selected by two examined models compared to IMPACT2002+. However, in all LCIA models, the Hyola cultivar had the lowest negative impacts. Generally, there were no significant differences between the two examined models and the IMPACT2002+ model at a 5% probability based on two-sample t-tests. The results confirmed the acceptable reliability of the proposed LCA model for assessing the environmental impacts of five rapeseed cultivars in Iran.

4. Conclusion

This study investigated the role of cultivar selection in the environmental performance of rapeseed production systems in Iran. Among the five common cultivars analyzed, i.e., Zafar, Hyola, Traper, RGS003, and Neptune, it was revealed that nitrogen-based fertilizers were critical contributors to environmental burdens, particularly in terms of human toxicity and global warming potential. Traper and RGS003 cultivars consistently ranked as the most pollutant, whereas Hyola exhibited the lowest potential impacts based on the defined functional units.

The findings have several important implications for farm managers and stakeholders to achieve sustainable crop production. First, the significant differences in environmental performance among cultivars highlighted the necessity for careful selection of cultivars, considering their yield potential and environmental footprint. This comprehensive approach can help mitigate the negative environmental impacts of rapeseed production and promote more sustainable agricultural practices. Second, the critical role of nitrogen-based fertilizers in contributing to environmental burdens confirms the importance of applying strategies to optimize fertilizer use, such as precision agriculture techniques or adopting more efficient fertilization practices to reduce environmental impacts. Alternatively cropping systems or organic fertilizers would be a potential solution to lessen dependency on synthetic fertilizers and decrease the overall environmental footprint. Third, the results presented that the choice of functional units, whether based on harvested mass (one ton of rapeseed seed) or cultivated area (1 ha of farm), can significantly influence the LCA results. This finding emphasizes the need for a multifaceted analysis approach incorporating multiple functional units to ensure the comprehensive assessment of environmental impacts. Such an approach can enhance the reliability and robustness of LCA studies, by providing a more detailed understanding of the trade-offs associated with different cultivars.

Furthermore, the implications of these findings extend beyond the scope of rapeseed production in Iran. Farm managers and policymakers in other regions with similar agricultural conditions can also benefit from these insights to make informed decisions on cultivar selection and farming practices, ultimately leading to global improvements in the sustainability of rapeseed production systems. In conclusion, this study demonstrates that the choice of rapeseed cultivar profoundly impacts environmental performance, driven by differences in input and output dynamics. Conducting detailed environmental performance analyses alongside yield assessments is crucial for introducing new cultivars in any region. Future research should focus on developing and implementing sustainable farming practices that optimize yield and environmental performance, ensuring long-term viability and sustainability



(a)

(b)

(c)

Fig. 6. Sensitivity analysis of LCIA model to determine the environmental load of rapeseed production systems based on three damage categories in terms of percentage of maximum determined impacts: (a) Human health, (b) Ecosystem quality, and (c) Resources.

in rapeseed production.

CRediT authorship contribution statement

Seyedeh Samira HabibTabar Shiadeh: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Yaser Feizabadi:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Armaghan Kosari-Moghaddam:** Writing – review & editing, Software, Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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