

## Life cycle assessment of major crops in the lenjanat watershed, Isfahan province

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### ABSTRACT

Agriculture is a cornerstone of societal production, playing a pivotal role in food security, economic development, and environmental sustainability. However, the escalating use of chemical inputs and fossil fuels in agricultural systems has raised significant concerns about their environmental sustainability. This study applies the life cycle assessment methodology—specifically the CML 2001 baseline method developed by Leiden University and in accordance with ISO 14044 standards—to evaluate the environmental impacts of four major crops: wheat, barley, alfalfa, and rice, cultivated in the Lenjanat watershed of Isfahan Province, Iran. The functional unit was defined as the production of one ton of each crop, with the system boundary encompassing all farm activities from land preparation to harvest. Data were collected for the agricultural year 2020–2021 and analyzed using SimaPro 9.2 software and the Ecoinvent database. The results indicated that rice had the highest global warming potential at 4137.85 kg CO<sub>2</sub>-eq ton<sup>-1</sup>, primarily due to its high water demand and diesel fuel consumption. Wheat exhibited the highest acidification potential at 28.11 kg SO<sub>2</sub>-eq ton<sup>-1</sup> and the highest eutrophication potential at 11.79 kg PO<sub>4</sub><sup>3-</sup>-eq ton<sup>-1</sup>, driven by excessive nitrogen and phosphate fertilizer use. Alfalfa, while showing the lowest global warming potential and eutrophication potential, had the highest photochemical oxidant formation potential at 0.392 kg C<sub>2</sub>H<sub>4</sub>-eq ton<sup>-1</sup> due to frequent harvesting operations. The study underscores the critical role of nitrogen fertilizers, diesel fuel, and phosphate fertilizers in environmental impacts. To mitigate these effects, adopting organic inputs, modern irrigation technologies, reduced tillage, and optimized fuel use are recommended. These strategies can significantly enhance agricultural sustainability in the Lenjanat region.

### Highlights

- The study assessed the environmental impacts of four crops using Life Cycle Assessment.
- Rice had the highest global warming potential due to water use and diesel fuel.
- Wheat showed the highest acidification and eutrophication potential from fertilizer use.
- Alfalfa's frequent harvesting led to high photochemical oxidant formation.
- The study suggests improving irrigation, fertilizer use, and machinery efficiency.

### 1. Introduction

Agriculture is one of the most fundamental production sectors in any society, playing a vital role in ensuring food security, economic development, and environmental sustainability. However, several challenges have emerged, including increasing population, climate change, limited natural resources, and growing competition over land and water use. These challenges have placed immense pressure on agricultural systems, particularly in terms of resource

management and environmental impact. The growing reliance on external inputs, such as chemical fertilizers, pesticides, and fossil fuels, has led to significant environmental consequences, including soil and water contamination, greenhouse gas emissions, reduced biodiversity, and the degradation of ecosystems (Hoekstra et al., 2012; Dekamin et al., 2024). Approximately 20% of global greenhouse gas emissions originate from agricultural activities, with a large share attributed to

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nitrogen fertilizers and fossil fuels used in sowing, cultivation, and harvesting operations (Hoekstra et al., 2012; Nemecek et al., 2024). These realities underline the urgent need for accurate, cost-effective, and data-driven methods to assess and mitigate the environmental impacts of agricultural production.

One of the most internationally recognized approaches for environmental impact assessment is Life Cycle Assessment (LCA). Defined under ISO 14040 and ISO 14044 standards, LCA evaluates all inputs and outputs of a product or process from raw material extraction to final disposal. In the agricultural sector, LCA is commonly applied with a “cradle-to-farm-gate” system boundary, which encompasses input consumption, energy use, farming operations, and the associated emissions and outputs (Roy et al., 2009; Dekamin et al., 2018; Dekamin et al., 2022). Over recent years, the application of LCA in agricultural studies has expanded significantly. This method provides a systematic tool for quantifying environmental impacts at every stage of crop production, from input procurement to on-farm use (ISO, 2006).

Numerous studies worldwide, including in Europe, Australia, and beyond, have assessed the environmental impacts of crop production using LCA. In Iran, research by Mirhaji and Khojastehpour (2011) in South Khorasan, Koochehi et al. (2018) in Khorasan Razavi, and Aliqolinya (2015) in the Urmia Lake basin, all emphasized the essential role of LCA in assessing agricultural sustainability. In the field of agriculture, LCA is mainly employed to identify environmental hotspots in cropping and horticultural systems (Afshar et al., 2022). Several studies have applied LCA in horticultural production, including Nikkhah et al. (2017), who evaluated peach production in Mazandaran and Golestan provinces, and Mohseni et al. (2019), who assessed the energy use and environmental impacts of grape production. Similarly, Ghasempour and Ahmadi (2018) employed LCA to evaluate corn, wheat, and soybean production systems.

International studies in China (Zhu et al., 2018), Spain (Martin-Gorriz et al., 2020), and Italy (Pergola et al., 2022) have used LCA to evaluate the environmental performance of various agricultural crops. Across all these studies, nitrogen fertilizers, diesel fuel, and pesticides have been identified as the major contributors to environmental degradation. In the study by Zamani et al. (2024), the IMPACT 2002+ method was employed to assess environmental effects, revealing that walnut production caused the highest negative impacts across multiple categories, including human health, ecosystem quality, resource use, and climate change.

The Lenjanat region in Isfahan Province—one of the central agricultural hubs of Iran—faces intensive water consumption, a high dependency on chemical inputs, and traditional farming structures. These characteristics highlight the need for comprehensive environmental assessments. The region's four major crops—wheat, barley, alfalfa, and rice—differ significantly in their input requirements and productivity, making them suitable candidates for Life Cycle Assessment aimed at informing sustainable agricultural management.

Agriculture in Lenjanat, located in Isfahan Province, is vital to the local economy. However, the region faces challenges due to its semi-arid climate, characterized by low annual rainfall (ranging from 200 to 250 mm) and high summer temperatures exceeding 35°C. These climatic conditions significantly increase the demand for irrigation, which relies primarily on surface water from the Zayanderud River and groundwater. Due to limited water availability, farming practices in Lenjanat heavily depend on chemical inputs, such as nitrogen fertilizers and pesticides, to enhance crop yields. The region grows crops like wheat, barley, alfalfa, and rice, each requiring specific water and input management strategies. This, combined with traditional farming practices, underscores the need for sustainable approaches to ensure long-term agricultural productivity and environmental balance in the region.

Despite a growing body of global research applying LCA in agriculture, there is a significant gap in localized data, particularly in arid and semi-arid regions like Lenjanat. Existing studies often rely on generalized data that may not fully capture the unique environmental conditions and farming practices of these regions. Additionally, there is a lack of comprehensive supply chain analysis that accounts for the full range of inputs and outputs in agricultural production. This study aims to address these gaps by providing detailed, localized LCA data for four major crops in Lenjanat. By offering a more context-specific assessment of environmental impacts, this research is crucial for developing sustainable agricultural management strategies in the region.

The primary objective of this analysis is to identify key processes and inputs contributing to environmental impact categories, offering strategies for optimizing resource use and mitigating environmental damage. The findings of this study are expected to highlight critical hotspots in input and energy consumption, which will provide a foundation for management strategies aimed at reducing environmental impacts and enhancing sustainability in crop production systems. Additionally, the insights gained from this study may help agricultural policymakers optimize cropping patterns and input use in areas with similar ecological and climatic conditions.

## 2. Materials and Methods

### 2.1. Study Area

The Lenjanat region consists of three main counties: Lenjan, Mobarakeh, and Dehaghan. Lenjan County is located in the western part of Isfahan Province and covers an area of 1,172 km<sup>2</sup>, which represents approximately 1.1% of the total area of Isfahan Province. Lenjan is situated 35 km southwest of Isfahan city, with an average elevation of 1,700 meters above sea level. Lenjanat County, with its center in Zarinsahr, is located in the southwestern part of Isfahan Province and lies within the Central Plateau of Iran. Climatically, this area falls under the semi-arid and arid regions of the country. Geographically, it is positioned at approximately 51° longitude and 32° latitude. The average annual rainfall in this county ranges from 200 to 250 mm, which is below the national average of Iran, and its

distribution is uneven, mainly occurring in winter. Additionally, the summer temperatures in this area exceed 35°C, and the high evaporation rates further increase the water demand for crops.

Due to the limited availability of water resources, agriculture in this region is primarily irrigated using water from the Zayanderud River and underground water resources. The significant reduction in the Zayanderud River flow in recent years, along with the declining groundwater levels, has posed major challenges to the sustainability of agricultural production. The region has a long history of cultivating crops such as wheat, barley, forage corn, alfalfa, potatoes, and vegetables, which constitute a substantial part of the local economy.

Given that Lenjanat shares the characteristic features of dry regions, including low rainfall, high temperatures, limited water resources, and high dependence on chemical agricultural inputs, it can serve as a representative area for studying the environmental impacts of crop production in arid climates of Iran. Evaluating the consequences of input consumption, pollutant emissions, and water resource use in such regions can significantly contribute to sustainable agricultural management strategies under similar ecological conditions.

## 2.2. Study Objective and Scope

The primary objective of this research is to assess the environmental impacts of producing four major crops, namely wheat, barley, alfalfa, and rice, in the Lenjanat watershed in Isfahan Province using the LCA method. The scope of this assessment includes all environmental inputs and outputs related to farm operations, from land preparation to crop harvest. The selection of these crops was based on their significant cultivation area, economic importance in the region, and differences in their water and input requirements.

## 2.3. LCA Theoretical Framework

The LCA method is based on international standards ISO 14040 and ISO 14044 and includes four main stages: (1) goal and scope definition, (2) life cycle inventory analysis (LCI), (3) life cycle impact assessment (LCIA),

and (4) interpretation of results (ISO, 2006a; ISO, 2006b). This approach is highly suitable for analyzing the cumulative environmental impacts of a production system throughout its life cycle, especially in agricultural systems where the diversity and interdependence of inputs are high (Guinée, 2002).

## 2.4. Functional Unit

For this study, the functional unit was defined as the production of one ton of each agricultural crop. This unit serves as the basis for comparing the environmental impacts of different products and helps evaluate the efficient consumption of resources and the generation of pollution across various crops (Roy et al., 2009).

## 2.5. System Boundaries

The system boundary of this study is “cradle-to-farm-gate,” which includes all activities occurring within the farm, such as land preparation, sowing, input consumption (seeds, fertilizers, pesticides, fuel, and labor), farm operations, irrigation, and harvest. Post-harvest processes such as packaging, transportation, and processing are not included in this study’s scope (Nemecek & Schnetzer, 2010).

## 2.6. Data Collection

Isfahan Province, a comprehensive and structured data collection approach was adopted. The primary source of data was field surveys conducted among local farmers, complemented by expert consultations and secondary data from reputable databases. The study focused on both traditional and modern agricultural practices across different irrigation methods and crop types. For this study, data were collected from farms across the Lenjanat watershed, Isfahan Province. These calculations were performed using Cochran’s formula, which considers a 95% confidence level and a 5% margin of error. The results of these calculations are presented in Table 1, which shows both the initial and final sample sizes for each crop.

**Table 1. initial and final sample sizes for each crop**

Crop	Initial Sample Size (n <sub>0</sub> )	Final Sample Size (n)
Wheat	101	47
Barley	82	41
Alfalfa	68	36
Rice	59	33

A detailed questionnaire was designed to gather essential information on farming operations, energy inputs, and resource use. The questionnaire was divided into several sections, including (1) demographic information of farmers (e.g., age, education, years of experience), (2) farm characteristics such as total area, cultivated area, and crop variety, (3) input quantities used during the production cycle (e.g., seeds, fertilizers, manure, pesticides, fuel, water, electricity), and (4) operation-specific details for land preparation, sowing, crop maintenance, and harvesting

activities. Additional questions addressed labor inputs (e.g., type and number of workers) and transportation logistics for both inputs and harvested products.

In order to enhance the accuracy and reliability of the data, face-to-face interviews were conducted with selected farmers across the Lenjanat watershed. These interviews were complemented by consultations with agricultural experts, including extension officers, researchers, and faculty members from regional universities. The dual approach of farmer interviews and expert validation

ensured that the collected data reflected actual field practices while compensating for potential gaps in farmer recall or knowledge.

To capture upstream environmental impacts associated with the production and use of agricultural inputs (e.g., fuel combustion, fertilizer manufacturing), secondary data were sourced from well-established life cycle inventory databases. These databases were accessed via the SimaPro software platform, which was used to model and assess the full life cycle of each crop under study.

## 2.7. Software and Database

For process modeling and impact assessment, SimaPro 9.2 software was used. This software is one of the most powerful LCA tools, allowing the incorporation of local data and the use of standard global databases such as EcoInvent (Pré Consultants, 2020). Processes related to fertilizer production, diesel fuel, energy consumption, and other inputs were modeled through connections to the EcoInvent database.

## 2.8. Environmental Impact Assessment (LCIA) Method

For environmental impact analysis, the CML 2001 – baseline method, developed by Leiden University, was employed. This is one of the most widely used LCIA approaches recommended for evaluating agricultural products (Guinée et al., 2002).

In this study, four key environmental impact categories were evaluated:

- Global Warming Potential (GWP) in kg CO<sub>2</sub>eq ton<sup>-1</sup>
- Acidification Potential (AP) in kg SO<sub>2</sub>eq ton<sup>-1</sup>
- Eutrophication Potential (EP) in kg PO<sub>4</sub><sup>3-</sup>eq ton<sup>-1</sup>
- Photochemical Oxidant Formation Potential (POFP) in kg C<sub>2</sub>H<sub>4</sub>eq ton<sup>-1</sup>

These indicators represent the most significant negative environmental consequences in agricultural systems and have been commonly used in similar studies (Brenttrup et al., 2004; Nemecek et al., 2011).

## 2.9. Model Assumptions

Some of the key assumptions for the modeling are as follows:

- The production of inputs (fertilizers, pesticides, seeds) occurs outside the farm, and their data are sourced from the EcoInvent database.
- Irrigation operations are conducted via gravity-fed systems, with the primary water source being surface water from the Zayanderud River or local wells.
- Farm machinery is diesel-powered and commonly used.
- Post-harvest operations (such as storage, transportation, and processing) are not included within the system boundary.

## 2.10. Uncertainty and Data Accuracy Analysis

To assess the accuracy of the data, quality control methods proposed by ISO standards were applied, and farm data were cross-checked with official sources such as the Agricultural Planning and Economics Bureau of Isfahan Province and agricultural statistics reports. Additionally, some sensitive data (such as fertilizer and fuel consumption) were modeled with a  $\pm 20\%$  variation to assess the impact of fluctuations on the environmental impact categories (Notarnicola et al., 2017). Monte Carlo simulations (1,000 iterations) were conducted in SimaPro 9.2 to evaluate the effect of  $\pm 20\%$  variation on fertilizer and fuel inputs.

## 3. Results

### 3.1. Life Cycle Inventory Analysis

All raw materials, chemical and organic fertilizers, and pesticides used, as well as the fuel for farm machinery, are considered as input findings, or in other words, all the operations from sowing to harvest are included in the life cycle assessment process. Table 2 provides the inputs and outputs for crop production in the Lenjanat watershed.

**Table 2. inputs and outputs for crop production per ha in Lenjanat watershed**

	Wheat	Barley	Alfalfa	Rice
Machinery (kg)	300.8	340.8	20	40.2
Nitrogen (kg)	160.6	220.8	50	10.1
Phosphorus (kg)	120.1	90	0	112
Potassium (kg)	3	3.2	0	0.6
Herbicide (l)	6.5	1.1	2	0.3
Fungicide (l)	1.5	2.4	0.5	0.6
Insecticide (l)	5.2	4.4	2	1
Organic Fertilizer (kg)	5200	4375	2000	1000
Irrigation Water (m <sup>3</sup> )	5757	5175	10000	14180
Electricity (kWh)	1950	1660	4860	1738
Seed (kg)	300	300	30	300
Irrigation Wastewater (m <sup>3</sup> )	4029	3556	3556	3556
Nitrous Oxide (kg)	62	68	48.4	48.4
Ammonia (kg)	56	50	90.4	90.4
Nitrate (kg)	1.22	3	1.22	1.22
Phosphorus (kg)	0.81	0.5	0.5	0.5
Herbicide (l)	3.51	0	0	0
Fungicide (l)	1.62	1.24	1.24	1.24
Insecticide (l)	0.62	0.24	0.24	0.24
Crop Yield (kg)	4300	4500	10000	5500

### 3.2. Life Cycle Impact Assessment (LCIA) Results

The results from the LCA for the four crops—wheat, barley, alfalfa, and rice—were analyzed across various environmental impact categories. This analysis helps identify which products exert the most pressure on the

environment and highlights the key inputs and processes contributing to each impact category. The results for the four major environmental impact indicators—GWP, AP, EP, and POFP—are reported below in Table 3.

**Table 3. environmental impact categories for 1 ton of each crop produced in Lenjanat**

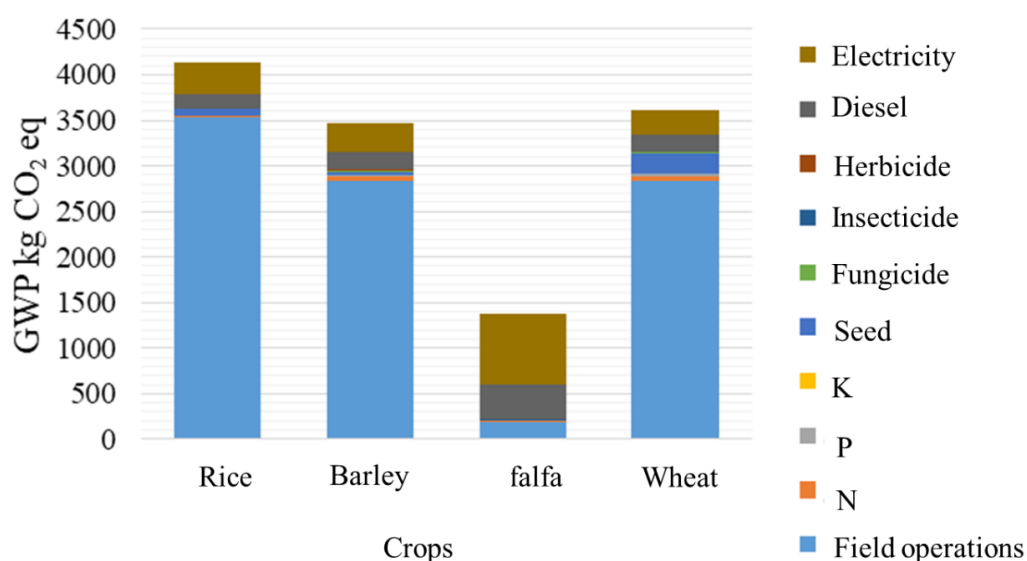
Impact Category	Rice	Barley	Alfalfa	Wheat
Global Warming Potential (kg CO <sub>2</sub> -eq)	4137.8	3469.3	1381.1	3616.9
Photochemical Oxidant Formation (kg C <sub>2</sub> H <sub>4</sub> -eq)	0.182	0.186	0.392	0.162
Acidification Potential (kg SO <sub>2</sub> -eq)	7.34	21.705	11.356	28.113
Eutrophication Potential (kg PO <sub>4</sub> <sup>3-</sup> -eq)	6.02	11.24	1.86	11.79

### 3.3. Global Warming Potential (GWP)

GWP is an indicator used to measure the environmental impact of greenhouse gases emitted due to human activities. According to Table 4 and Figure 1, rice exhibited the highest GWP among the four crops studied, with a value of 4137.8 kg CO<sub>2</sub>-eq ton<sup>-1</sup>. This is primarily due to its very high water requirements, frequent irrigation, and consequently, the large amount of diesel fuel used for pumping irrigation water, along with the heavy application of nitrogen fertilizers.

In contrast, alfalfa showed the lowest GWP at 1381.1 kg CO<sub>2</sub>-eq ton<sup>-1</sup>, due to its multi-year growth cycle, nitrogen fixation, and lower need for tillage and frequent mechanized operations. Over 70% of the impact in this

category is attributed to electricity use, manure, and mineral fertilizers. Other inputs have a relatively minor effect on this category. This aligns with findings from Zhu et al. (2018), which also reported high GWP for rice due to methane emissions and irrigation energy use. The comparison suggests that water management strategies and alternative irrigation methods could significantly reduce rice's environmental impact. Pishgar-Komleh et al. (2020), which also reported that rice has a significant carbon footprint, primarily due to methane emissions from flooded fields and fossil fuel use in irrigation. However, Ahmad et al. (2023) presents a slightly lower GWP for rice, suggesting that variations in irrigation methods and fertilizer application can influence emissions.



**Figure 1. Global Warming Potential (GWP) for wheat, barley, alfalfa and rice produced in the Lenjanat watershed (units: kg CO<sub>2</sub>-eq ton<sup>-1</sup> product)**

### 3.4. Acidification Potential (AP)

AP results from the release of gases such as SO<sub>2</sub>, NH<sub>3</sub>, and NO<sub>x</sub>, which can cause acid rain and degrade soil and water resources. As shown in Table 4 and Figure 2, wheat has the highest AP value, with 28.113 kg SO<sub>2</sub>-eq ton<sup>-1</sup>. This high value is mainly due to the heavy application of urea fertilizers and ammonia emissions from its evaporation from soil surfaces. The ammonia released is converted to nitrates in the atmosphere and falls as nitric acid during rainfall, contaminating both soil and water. In comparison, rice and alfalfa showed much lower AP values, with 7.34

and 1.86 kg SO<sub>2</sub>-eq ton<sup>-1</sup>, respectively, due to their lower fertilizer consumption and reduced ammonia evaporation. This is consistent with findings from Koocheki et al. (2018), which also highlighted the role of nitrogen fertilizers in acidification and eutrophication. The comparison underscores the need for optimized fertilizer application techniques to mitigate these environmental effects. Pishgar-Komleh et al. (2020) stating that wheat production leads to high ammonia volatilization and nitrate leaching, which contribute to acidification.

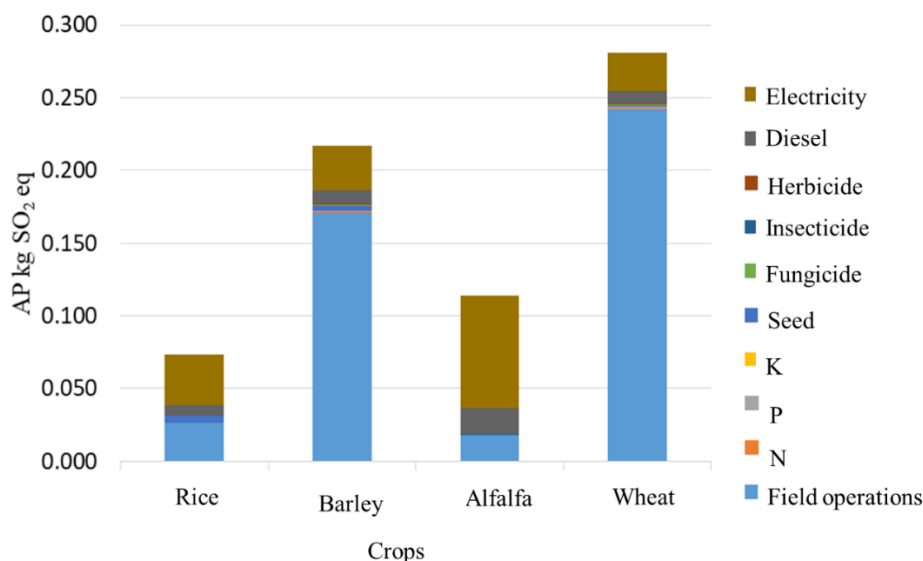


Figure 2. Acidification Potential (AP) for wheat, barley, alfalfa and rice produced in the Lenjanat watershed (units: kg SO<sub>2</sub>-eq ton<sup>-1</sup> product)

### 3.5. Eutrophication Potential (EP)

EP refers to the enrichment of surface and groundwater resources with nutrients, often caused by the leaching of nitrates and phosphates from fertilizers. As seen in Table 4 and Figure 3, wheat exhibited the highest EP at 11.79 kg PO<sub>4</sub><sup>3-</sup>-eq ton<sup>-1</sup>, mainly due to the excessive use of phosphate fertilizers and their non-optimal distribution,

leading to surface runoff and leaching in the soils of the region. In contrast, alfalfa demonstrated a significantly lower EP value of 1.86 kg PO<sub>4</sub><sup>3-</sup>-eq ton<sup>-1</sup>, attributed to its natural nitrogen fixation and limited fertilizer requirements. Nuraeefar et al, (2024), also confirms that wheat has a significant eutrophication impact, but it attributes this more to irrigation runoff rather than direct fertilizer application.

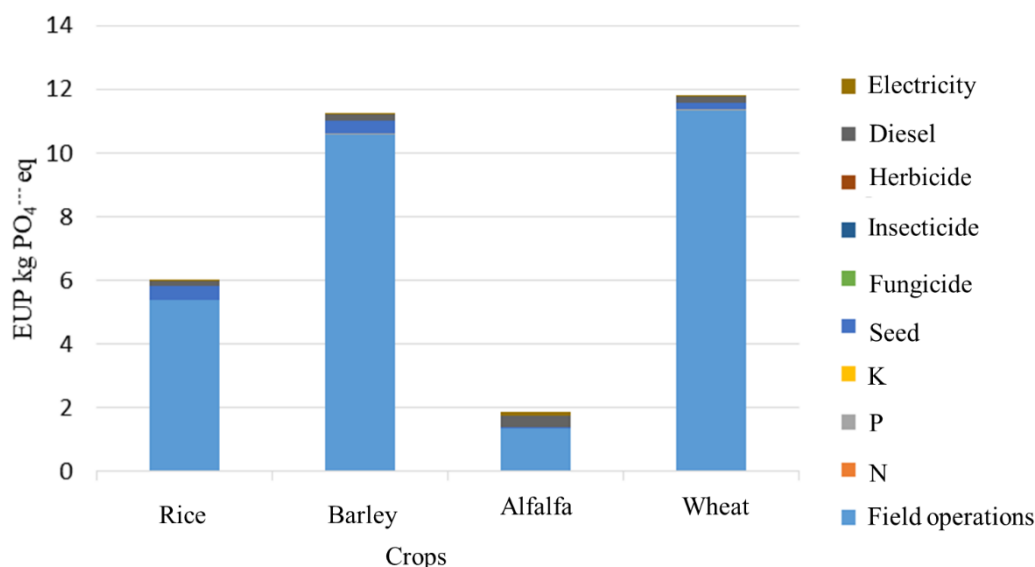


Figure 3. Eutrophication Potential (EP) for wheat, barley, alfalfa and rice produced in the Lenjanat watershed (units: kg PO<sub>4</sub><sup>3-</sup>-eq ton<sup>-1</sup> product)

### 3.6 Photochemical Oxidant Formation Potential (POFP)

POFP, also known as smog formation, is primarily influenced by the release of volatile organic compounds (VOCs) and nitrogen oxides from fuel consumption and fertilizers. Based on the data presented in Table 4 and Figure 4, alfalfa recorded the highest POFP at 0.392 kg C<sub>2</sub>H<sub>4</sub>-eq ton<sup>-1</sup>. This may seem unexpected initially, but it is

due to the repeated harvesting operations in alfalfa farms (more than four times per year), each of which requires the use of diesel-powered machinery and fueling.

Despite its favorable performance in other impact categories, the frequent harvesting operations in alfalfa farms lead to increased emissions of compounds contributing to photochemical smog. Rice ranked second

with 0.182 kg C<sub>2</sub>H<sub>4</sub>-eq ton<sup>-1</sup>, followed by wheat with 0.162 kg C<sub>2</sub>H<sub>4</sub>-eq ton<sup>-1</sup>.

This aligns with Ghasempour and Ahmadi (2018), which also noted increased emissions from mechanized

harvesting in alfalfa production. The comparison suggests that improving mechanization efficiency and adopting alternative harvesting methods could reduce POFP.

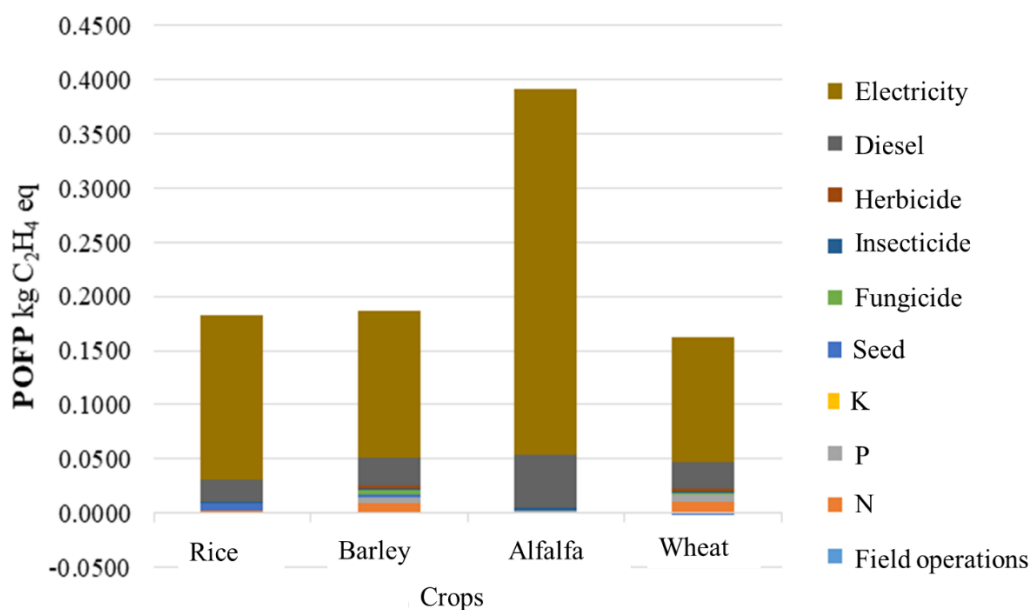


Figure 4. Photochemical Oxidant Formation Potential (POFP) for wheat, barley, alfalfa and rice produced in the Lenjanat watershed (units: kg C<sub>2</sub>H<sub>4</sub>-eq ton<sup>-1</sup> product)

### 3.7. Key Inputs Driving Environmental Impacts

The three main inputs contributing most significantly to environmental impacts were nitrogen fertilizers (urea), diesel fuel, and phosphate fertilizers. Specifically, nitrogen fertilizers accounted for 40-60% of the GWP and AP. Phosphate fertilizers were the main driver of EP, contributing between 60-80%, while diesel fuel played a significant role in both GWP and POFP. These findings are consistent with those reported in previous studies by Guinée (2002) and Notarnicola et al. (2017).

### 3.8. Environmental Performance of Crops

From an environmental perspective, alfalfa exhibited the best overall performance and could be recommended as a suitable option for sustainable agriculture in the region. Rice, despite its high nutritional value, contributed the most to GWP and requires a thorough reconsideration of input usage and irrigation methods. Wheat demonstrated the highest values for AP and EP, indicating that fertilizer management is crucial for this crop.

## 4. Discussion

The results from LCA of the four major crops—wheat, barley, alfalfa, and rice—cultivated in the Lenjanat region provide important insights into the environmental impacts of agricultural practices in semi-arid regions. The results revealed significant differences in the environmental performance of each crop, primarily due to variations in input consumption, water requirements, farming operations, and the intensity of mechanized activities. This section discusses these findings in detail, compares them

with previous studies, and offers recommendations for improving the sustainability of agricultural practices in Lenjanat and other similar regions.

Rice exhibited the highest GWP among the crops studied, with a value of 4137.8 kg CO<sub>2</sub>-eq ton<sup>-1</sup> produced. This high GWP can largely be attributed to two key factors: the high water demand for rice cultivation and the associated use of diesel fuel for irrigation, coupled with the significant nitrogen fertilizer application. The water-intensive nature of rice farming, particularly in the Lenjanat region, where irrigation is heavily reliant on surface water from the Zayanderud River and groundwater, exacerbates the GWP of this crop. Rice cultivation, especially under conventional irrigation systems, is a major source of greenhouse gas emissions, including methane and carbon dioxide. Studies such as those by Brentrup et al. (2004) and Singh et al. (2010) have similarly emphasized the contribution of flooded rice systems to global warming, mainly due to methane emissions and fossil fuel consumption.

Rice's high GWP in this study reflects a broader global trend where rice cultivation, especially in regions with inefficient irrigation systems, remains a significant source of greenhouse gas emissions. The dependence on diesel-powered irrigation systems, which are common in the Lenjanat region, further compounds this environmental burden. Therefore, addressing the inefficiencies in irrigation systems and transitioning to more sustainable methods, such as drip or sprinkler irrigation, could significantly reduce the GWP associated with rice farming.

In contrast, alfalfa showed the lowest GWP at 1381.1 kg CO<sub>2</sub>-eq ton<sup>-1</sup> produced. The lower GWP of alfalfa can be attributed to its ability to fix nitrogen naturally, reducing the need for synthetic nitrogen fertilizers. Additionally, alfalfa's multi-year growth cycle and lower mechanization requirements compared to annual crops like rice and wheat contribute to its relatively lower GWP. Alfalfa's lower GWP is a significant finding, as it suggests that leguminous crops, with their natural nitrogen fixation capabilities and lower water and energy requirements, could offer more sustainable alternatives to conventional cereal crops, particularly in regions like Lenjanat that face water scarcity and limited energy resources.

Wheat, which recorded the highest AP and EP values among the crops, shows a clear need for better nutrient management practices. The AP of wheat was 28.11 kg SO<sub>2</sub>-eq ton<sup>-1</sup>, primarily driven by the over-application of nitrogen fertilizers, particularly urea, and ammonia emissions from soil surfaces. Ammonia volatilization is a significant concern in wheat farming, as it contributes to the formation of acid rain, which leads to soil and water pollution. The excessive application of nitrogen fertilizers in wheat farming has been a recurring issue in many studies worldwide, including Mirhaji and Khojastehpour (2011), which also highlighted the negative effects of over-fertilization on both water quality and soil health. The high AP in wheat production reflects broader trends in conventional farming practices, where nutrient management is often suboptimal, leading to nutrient imbalances that harm the environment.

The high EP of wheat, recorded at 11.79 kg PO<sub>4</sub><sup>3-</sup>-eq ton<sup>-1</sup>, is similarly attributed to the excessive use of phosphate fertilizers. Phosphorus runoff from agricultural fields is a well-known environmental concern, as it can lead to nutrient pollution in rivers, lakes, and other water bodies, contributing to eutrophication and algal blooms. The overuse of phosphate fertilizers in wheat production, combined with inefficient fertilizer application techniques, leads to the leaching of phosphorus into the environment, where it contributes to water quality deterioration. These findings are consistent with the research of Roy et al. (2009), which identified phosphorus as a key driver of eutrophication in agricultural systems.

Rice, despite its high water usage, showed much lower AP (7.34 kg SO<sub>2</sub>-eq ton<sup>-1</sup>) and EP (0.81 kg PO<sub>4</sub><sup>3-</sup>-eq ton<sup>-1</sup>) values compared to wheat. The lower fertilizer requirements for rice, along with its relatively lower ammonia volatilization, contributed to its more favorable performance in these impact categories. However, it is important to note that rice still poses significant environmental challenges, particularly in terms of water management and fuel consumption. Therefore, improving fertilizer management, especially in the case of wheat, could significantly reduce the environmental impacts of crop production in Lenjanat.

Alfalfa exhibited the highest POFP value among the crops at 0.392 kg C<sub>2</sub>H<sub>4</sub>-eq ton<sup>-1</sup>, which is somewhat surprising given its relatively favorable performance in other environmental impact categories. The high POFP of alfalfa can be attributed to the frequent harvesting

operations required for this perennial crop. Alfalfa is typically harvested more than four times per year, which necessitates the use of diesel-powered machinery. The emissions from these mechanized operations contribute to the formation of photochemical oxidants, commonly known as smog. While alfalfa's lower GWP and EP make it a more sustainable crop compared to other alternatives, the environmental burden from frequent harvesting remains a concern. This finding underscores the importance of improving mechanization in alfalfa production, particularly by adopting more energy-efficient machinery and exploring alternative harvesting techniques.

In comparison, rice (0.182 kg C<sub>2</sub>H<sub>4</sub>-eq ton<sup>-1</sup>) and wheat (0.162 kg C<sub>2</sub>H<sub>4</sub>-eq ton<sup>-1</sup>) showed lower POFP values. The lower POFP values for these crops can be attributed to less frequent mechanized operations, particularly in the case of rice, where water management and irrigation are the primary environmental concerns. The findings suggest that while wheat and rice have lower POFP, they still pose significant environmental challenges in other categories, particularly GWP and AP.

The primary drivers of environmental impacts across all four crops were nitrogen fertilizers, diesel fuel, and phosphate fertilizers. Specifically, nitrogen fertilizers were responsible for 40-60% of the GWP and AP in wheat and rice production, highlighting the importance of optimizing nitrogen use. Diesel fuel, particularly for irrigation and mechanized operations, was a major contributor to both GWP and POFP, emphasizing the need to transition to more energy-efficient irrigation and mechanization practices. Phosphate fertilizers were the main contributor to EP, particularly in wheat production, where excessive use led to phosphorus runoff and leaching into water bodies.

These findings are consistent with previous research, which has identified these inputs as major environmental burdens in agricultural systems. The study by Notarnicola et al. (2017) also emphasized the importance of nitrogen and phosphorus management in reducing the environmental impacts of crop production. The results of this study suggest that improving fertilizer management, reducing fuel consumption, and transitioning to more efficient technologies can significantly reduce the environmental burden of crop production in the Lenjanat region.

Based on the findings of this study, several strategies can be implemented to reduce the environmental impacts of crop production in Lenjanat. First, improving water management practices, particularly for rice farming, is essential. Adopting efficient irrigation systems, such as drip or sprinkler irrigation, can reduce water consumption and diesel fuel use, significantly lowering the GWP of rice production. Additionally, improving the efficiency of fertilizer use, particularly nitrogen and phosphate fertilizers, can help reduce the AP and EP associated with wheat and other crops. Implementing precision farming techniques, such as variable rate application of fertilizers, can optimize input use and minimize environmental pollution.

In the case of alfalfa, improving mechanization is key to reducing POFP. The adoption of more energy-efficient machinery or exploring less mechanized harvesting methods could reduce the emissions associated with frequent harvesting. Moreover, the use of organic fertilizers and the promotion of crop rotation systems could further reduce the environmental burden of alfalfa production.

From a policy perspective, the results of this study highlight the need for sustainable agricultural policies in the Lenjanat region. Key recommendations include: Reforming cropping patterns to favor low-input and drought-resistant crops, such as legumes and other sustainable alternatives. Diversifying irrigation systems by replacing gravity-fed systems with more efficient methods such as drip or sprinkler irrigation. Providing financial incentives for farmers to adopt sustainable practices, such as the use of organic fertilizers and efficient irrigation technologies. Establishing local environmental databases to track LCA changes over time and support evidence-based decision-making in agricultural policy.

## 5. Conclusions

This study demonstrated that LCA can be a powerful tool for evaluating and improving the environmental sustainability of agricultural systems. The results indicate that the environmental impacts of crop production in the Lenjanat region vary significantly depending on the crop type, input structure, water consumption, and level of mechanization. These findings emphasize that sustainable agriculture in this region can only be achieved through optimizing input use, improving water management, adopting more efficient technologies, and implementing data-driven policies based on LCA results.

In terms of environmental impacts, rice was found to have the highest GWP, primarily due to high diesel fuel consumption for irrigation and extensive use of nitrogen fertilizers. This finding aligns with previous studies that have emphasized the need for improved irrigation practices and reduced fossil fuel consumption. The adoption of more efficient irrigation systems, such as drip or sprinkler irrigation, could significantly reduce the GWP associated with rice production. Additionally, improving irrigation practices in the Lenjanat region could help reduce water consumption and improve water use efficiency.

Wheat, which exhibited the highest AP and EP, highlighted the urgent need for better nutrient management and reduced reliance on chemical fertilizers. Specifically, excessive use of nitrogen and phosphate fertilizers has led to water and soil pollution in the region. In this context, adopting precision agriculture techniques, such as optimized fertilizer use and efficient irrigation systems, could significantly reduce the environmental impacts associated with wheat. Additionally, using organic fertilizers and slow-release fertilizers could help reduce chemical fertilizer use and mitigate environmental pollution.

Alfalfa, with the lowest GWP and EP, was considered a more sustainable option for agriculture in the region. This crop benefits from its natural nitrogen fixation ability, reducing the need for synthetic nitrogen fertilizers.

However, due to the frequent harvesting required for this perennial crop, diesel-powered machinery contributes to increase POFP. To address this, improving mechanization efficiency or exploring alternative harvesting methods could help reduce the emissions associated with frequent harvesting. Therefore, while alfalfa performs better in many environmental categories, attention must still be paid to improving mechanization and reducing fossil fuel consumption.

The analysis of key inputs revealed that nitrogen fertilizers (especially urea), diesel fuel, and phosphate fertilizers were the primary drivers of environmental impacts. Specifically, nitrogen fertilizers contributed the most to GWP and AP, while phosphate fertilizers were the main contributors to EP in wheat production. Diesel fuel played a significant role in both GWP and POFP, emphasizing the need for the modernization of irrigation systems and mechanization practices. These findings are consistent with previous research that has identified these inputs as major environmental burdens in agricultural systems. The study suggests that optimizing fertilizer use, reducing fuel consumption, and transitioning to more efficient technologies can significantly reduce the environmental burden of crop production in the Lenjanat region.

The results of this study emphasize the need for resource management strategies in Lenjanat that focus on reducing fuel consumption, improving irrigation methods, optimizing fertilizer use, and educating farmers on reducing environmental impacts. Given the environmental challenges faced by Lenjanat, such as reduced water resources, soil erosion, and water source pollution, it is crucial to adopt policies that specifically promote sustainable agricultural practices. The findings can serve as a basis for regional policy-making aimed at improving agricultural practices and enhancing environmental sustainability in this area.

Key policy recommendations that could be implemented based on this study include:

- Reforming cropping patterns to favor low-input and drought-resistant crops, such as legumes that require less nitrogen fertilizer.
- Diversifying irrigation systems by replacing gravity-fed systems with more efficient systems, such as drip or sprinkler irrigation, which would reduce water consumption and diesel fuel use.
- Providing financial incentives for the use of sustainable inputs and practices, such as organic fertilizers and efficient irrigation technologies.
- Establishing local environmental databases to track LCA changes over time and support data-driven decision-making in agricultural policy.

In conclusion, this study has demonstrated that LCA can be an effective tool for analyzing and improving the sustainability of agricultural systems. The findings show that the environmental impacts of crops in the Lenjanat region vary significantly due to differences in input structure, water consumption, and mechanization levels. Based on these findings, it can be concluded that sustainable agriculture in this region will only be

achievable through a combination of changes in cropping patterns, optimized input use, the adoption of efficient technologies, and data-driven policymaking. Implementing these recommendations could help reduce the environmental impacts of agriculture in Lenjanat and other regions with similar environmental conditions.

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