Agriculture, Environment & Society

Journal homepage: www.aes.uoz.ac.ir

Life cycle assessment of wheat production systems in Southwest Iran: Comparison of farmer practices and experimental low, medium, and high-input agroecosystems

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ARTICLE INFO

Article history:
Received: 18 October 2025
Accepted: 12 May 2026
Available online: 5 June 2026

Keywords:
Ecological agriculture
Eutrophication
Freshwater toxicity
High-input agroecosystem

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ABSTRACT

Over the past few decades, wheat (*Triticum aestivum* L.) production in Iran has significantly increased due to reliance on chemical inputs. However, the environmental consequences of these inputs on human health and natural resources remain poorly understood. To evaluate the environmental impacts of wheat production using the Life Cycle Assessment (LCA) approach, this study was conducted in two parts: experimental field research and a field survey. In the experimental field section, three agroecosystems low-input, high-input, and medium-input were established at the Shahid Chamran University research farm in Ahvaz, with three replications in a randomized complete block design. In the field survey, data were collected from Karun and Hamidieh counties through face-to-face interviews with 50 farmers, based on four scenarios: the average of 50 farms, high-input, medium-input, and low-input agroecosystems in 2018. Input and output data for wheat production were gathered using questionnaires and field cultivation information, with input data sourced from the Ecoinvent database in SimaPro 9.0 software. Environmental impact assessments, conducted using the CML 2 Baseline 2000 V2.05 method, revealed that field survey agroecosystems exhibited significantly higher environmental impacts than experimental field cultivation due to excessive use of agricultural inputs. Among the seven scenarios, the high-input agroecosystem in the field survey had the greatest environmental impacts across seven impact categories: High-input agroecosystems exhibited severe environmental burdens, dominated by abiotic resource depletion (5.43 kg Sb eq.) and global warming potential (1003 kg CO_2 eq.), compounded by atmospheric impacts including soil acidification (15.62 kg SO_2 eq.) and ozone layer depletion (99 mg CFC-11 eq.). Emerging aquatic threats manifested through marine ecotoxicity (97,272 kg 1,4-DB eq.) and nutrient enrichment (7.36 kg PO_4 eq.), with photochemical oxidation (0.17 kg C_2H_4 eq.) completing the critical seven-impact profile. The low-input agroecosystem in the experimental field, due to the use of animal manure, showed the highest pollution in three impact categories: human toxicity (398 kg 1,4-DB eq.), freshwater aquatic ecotoxicity (346 kg 1,4-DB eq.), and terrestrial ecotoxicity (40 kg 1,4-DB eq.). Consequently, these strategies demonstrate dual efficacy: precision agriculture reduces input overuse by 30-40% through targeted application, while ecological substitution with manure lowers toxicity risks by 18-25%, both maintaining yields at 3.2-3.5 t/ha comparable to conventional systems.

Highlights

- Field-survey wheat systems showed greater environmental impacts than experimental systems.
- High-input farming had the highest global warming potential (1,003 kg CO_2 eq. t^{-1}).
- Farmer education and improved management practices may help reduce the environmental footprint of wheat cultivation.

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https://doi.org/10.22034/aes.2026.554201.1117

- Energy policy improvements could contribute to more sustainable wheat production systems.
- Optimizing agricultural inputs can improve the environmental sustainability of wheat production.

1. Introduction

Evaluating resource and energy efficiency through Life Cycle Assessment (LCA) has emerged as a critical tool for identifying sustainable pathways in agroecosystems (Rahimizadeh et al., 2007; Risoud, 2000). While previous studies have applied LCA to wheat production globally, this research introduces three novel dimensions to the field: first, a comprehensive LCA of wheat systems in Khuzestan, Iran, a region contributing ~18% of national wheat output but facing unique environmental stressors (water scarcity, soil salinity) unaddressed in prior studies. Innovative integration of region-specific agro-climatic factors into impact assessment, including localized irrigation practices and nitrogen volatilization rates under high temperatures. Direct comparison of traditional vs. intensive systems in a developing agricultural economy context, providing actionable insights for similar arid regions globally (Bennett et al., 2004). Current LCA frameworks often overlook critical regional variables that dominate environmental impacts in semi-arid climates. While earlier work quantified energy inputs (Meisterling et al., 2009) and acidification potentials (Brentrup et al., 2001(a and b); Ghasempour and Ahmadi, 2018b) in temperate zones, this study advances methodology by: Incorporating dust emission factors from frequent wind erosion events in Khuzestan, Analyzing water footprint through the region's unique "double cropping" irrigation regime, and benchmarking against both European LCA databases and localized emission coefficients. Our approach addresses a critical gap in sustainable wheat intensification – previous Iranian studies focused narrowly on energy balances (Pishgar-Komleh et al., 2011) or single impact categories (Nasiri Mahallati and Koocheki, 2017a).

Life Cycle Assessment (LCA) is a sustainability evaluation method developed based on production processes (Ness et al., 2007). LCA quantifies the environmental impacts of a product, process, or activity by identifying and measuring energy and material use, as well as waste and emissions released into the environment. LCA studies on agricultural product systems began in North America in the late 20th century, followed by Europe. Wheat, a critical global food crop, has been subject to LCA studies covering various stages, including grain production, flour processing, baking, packaging, and distribution (Bare et al., 2003).

Research comparing organic and conventional wheat production systems in the United States showed higher energy inputs in conventional systems, with fuel and electricity being the largest contributors (Meisterling et al., 2009). Energy efficiency assessments of rice production in Gilan, Iran, indicated higher energy efficiency in semi-mechanized methods compared to traditional ones (Pishgar-Komleh et al., 2011). Brentrup et al. (2001b) reported that the highest acidification potential for one ton of wheat grain in a high-input field system was 15.62 kg SO_2 eq., while the lowest was 4.51 kg SO_2 eq. in a low-input experimental field system also showed that nitrogen fertilizer use below 150 kg/ha resulted in abiotic resource depletion ranging from 0.22 to 0.26 kg Sb eq. per ton of wheat grain, increasing with higher nitrogen inputs. Soltani et al. (2010) reported an acidification potential of 6.7 kg SO_2 eq. for one ton of wheat in Gorgan, Iran. Huerta et al. (2012) found acidification potentials of 15.28 kg and 1.01 kg SO_2 eq. for conventional and organic wheat production, respectively. Ghasempour and Ahmadi (2018a) assessed the environmental impacts of corn, wheat, and soybean production, reporting acidification potentials of 16.7, 14.9, and 6.6 kg SO_2 eq., respectively, for one ton of wheat grain.

Nasiri Mahallati and Koocheki (2017a) reported that abiotic resource depletion was higher in high-input systems compared to medium- and low-input systems in Iranian wheat production. Huerta et al. (2012) found abiotic resource depletion of 3.01 kg and 0.89 kg Sb eq. for conventional and organic wheat systems, respectively. In Iran, limited studies have applied LCA to agricultural products, with most research focusing on energy balances in agroecosystems rather than comprehensively assessing environmental impacts.

Given the lack of comprehensive data on the environmental impacts of wheat production in Khuzestan (specifically Karun and Hamidieh counties), this study aims to (1) quantify and compare the environmental impacts of wheat production in experimental vs. actual farm settings under different input regimes, and (2) identify the primary sources of impact to inform mitigation strategies for the Karun and Hamidieh regions.

2. Materials and methods

To assess the environmental impacts of wheat production systems, an experiment was conducted in the 2018 agricultural year at the research farm of the Plant Production and Genetics Engineering Department, Faculty of Agriculture, Shahid Chamran University, Ahvaz, with three replications. Additionally, data were collected via questionnaires from 50 wheat farmers in Hamidieh and Karun counties. Geographically, the research farm is located at 31°19' N latitude and 48°41' E longitude, on the western bank of the Karun River, at an elevation of 20 meters above sea level.

Hamidieh is situated 25 km northwest of Ahvaz, at 48°43'36" E longitude, 31°48'8" N latitude, and 22 meters above sea level. Karun County, in southwestern Iran, borders the Karun River to the west and the Persian Gulf Freeway to the east, located at 48°64'79" E longitude and 31°22'79" N latitude.

For land preparation in the experimental field, two perpendicular plow passes, two disc harrow passes, a leveler, and a furrower were used, with chemical herbicides (2 L/ha of 2,4-D and 1 L/ha of Topic) applied for weed control. Planting was done manually on November 11, 2018, with each plot consisting of eight rows, approximately 3 meters long and 2 meters wide, with 20 cm row spacing and 2 cm plant spacing within rows. Agronomic practices, such as irrigation and weed control

(manual weeding for low- and medium-input systems), were conducted regularly per a predetermined schedule. At maturity, two outer rows and plants at the ends of each plot were excluded to eliminate border effects, and a 0.5 m² area was harvested. Harvesting occurred on April 18, 2019. Wheat yield was measured by separating seeds from spikes in the physiology laboratory, with grain yield calculated in grams per square meter and converted to kilograms per hectare.

The low-input agroecosystem used only organic inputs, with no chemical inputs, and soil fertility was maintained using 5 tons/ha of vermicompost. Tillage involved one disc, one leveler, and one furrower, with manual weed control. The medium-input (integrated) agroecosystem used 50% organic (vermicompost) and 50% chemical inputs (nitrogen from urea, phosphorus from triple superphosphate, and potassium from potassium sulfate), with tillage involving one plow, one disc, one leveler, and one furrower. Weed control was performed manually with a mower, using 0.5 L/ha Topic and 1 L/ha 2,4-D. The high-input (conventional) agroecosystem used only chemical fertilizers (nitrogen, phosphorus, and potassium) based on soil test results and wheat nutrient requirements (Kamaie et al., 2021).

In the field survey, wheat production agroecosystems were evaluated and compared using LCA, identifying the system with the least environmental impact. Four scenarios were defined: the average of 50 farms, 25 low-input farms, 15 medium-input farms, and 10 high-input farms in Karun and Hamidieh counties (via questionnaires). These were compared with three experimental field scenarios (low-, medium-, and high-input agroecosystems) using LCA and SimaPro 9.0 software. The functional unit was one ton of wheat grain.

Life Cycle Assessment Method: The LCA was conducted following the ISO 14040 framework, comprising four stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation of results (Guinee et al., 2001).

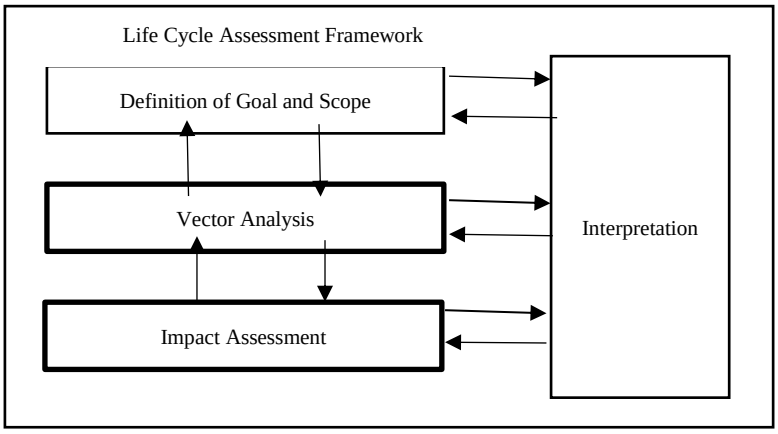


Figure 1. Stages of life cycle assessment (ISO, 1997)

3. Results and discussion

3.1. Acidification impact category

In this study, the acidification potential for the four field survey scenarios namely, the average of 50 farms, high-input, medium-input (integrated), and low-input agroecosystems and the three experimental field scenarios high-input, medium-input (integrated), and low-input agroecosystems was calculated as 14.36, 15.62, 13.15, 12.34, 7.45, 6.28, and 4.51 kg SO_2 equivalent per ton of wheat grain produced, respectively.

Analysis of farm inputs (Figure 2) indicated that acidification potential increased with higher input levels. In all field survey agroecosystems and the high-input and medium-input (integrated) experimental field agroecosystems, the primary contributors to acidification were, in order: direct farm emissions, electricity production, and fertilizer production (both chemical and organic). In the low-input agroecosystems of both the field survey and experimental field, direct farm emissions were followed by fertilizer production (chemical and organic) and electricity production as the main factors contributing to acidification.

The results (Figure 3) demonstrated that ammonia had the greatest impact on acidification across all agroecosystems, followed by NO_x and SO_2. Huerta et al. (2012) in Chile, using life cycle assessment, estimated acidification potentials of 19 and 23 kg SO_2 equivalent per ton for rapeseed and sunflower oil production, respectively. Soltani et al. (2010) reported an acidification potential of 6.7 kg SO_2 equivalent per ton of wheat grain in Gorgan, Iran. Iriarte et al. (2010) evaluated conventional and organic wheat production systems in Chile, reporting acidification potentials of 15.28 and 1.01 kg SO_2 equivalent per ton of wheat grain, respectively. Ghasempour and Ahmadi (2018b), in their assessment of the environmental impacts of three main crops (corn, wheat, and soybean) using life cycle assessment in Alborz Province, reported acidification potentials of 16.7, 14.9, and 6.6 kg SO_2 equivalent per ton of wheat grain for wheat, corn, and soybean, respectively.

3.2. Eutrophication impact category

In this study, the eutrophication potential for the average of 50 farms, high-input, medium-input (integrated), and low-input agroecosystems in the field survey, as well as the high-input, medium-input (integrated), and low-input agroecosystems in the

experimental field, was calculated as 7.04, 7.36, 6.36, 7.21, 2.96, 2.72, and 2.43 kg PO_4 equivalent per ton of wheat grain, respectively.

The study revealed that, among farm inputs across all agroecosystems, direct farm emissions, followed by fertilizer production (both chemical and organic) and seed production, had the greatest impact on the eutrophication category (Figure 4). The results indicated that nitrate (NO_3) leaching, ammonia (NH_3) emissions to the air, and phosphorus (P) leaching were the primary contributors to eutrophication across the seven scenarios. Nitrate leaching was higher in the low-input field survey agroecosystem compared to all other agroecosystems, despite the use of 150 kg/ha of urea, due to the low yield (2.5 t/ha), which increased nitrate leaching in this system (Figure 5).

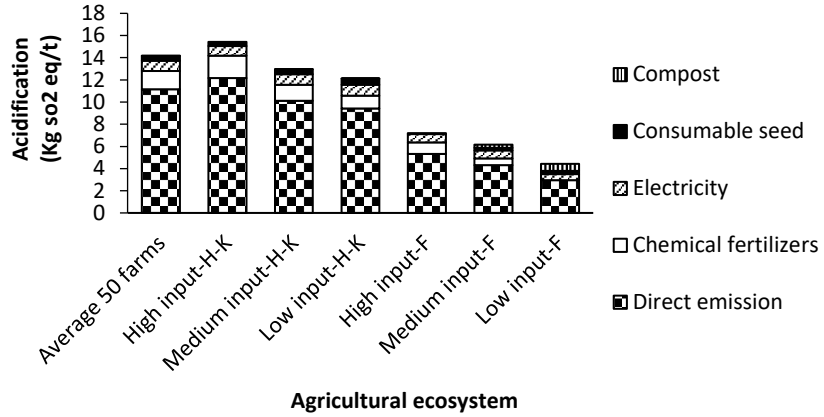


Figure 2. Acidification potential by inputs
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively.

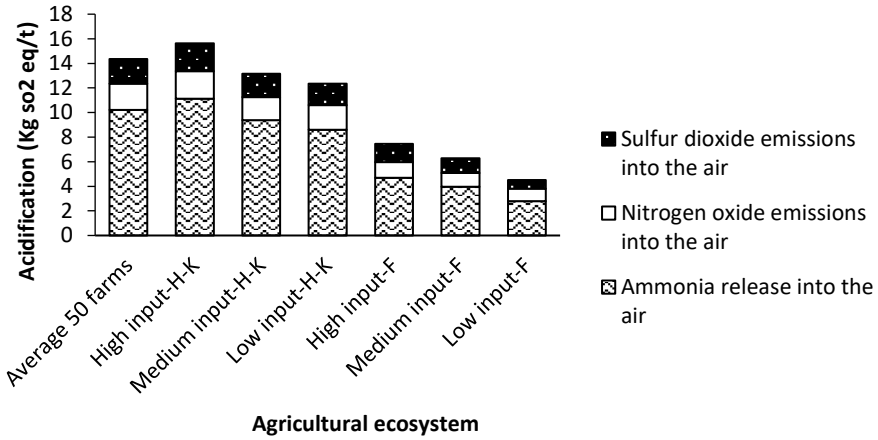


Figure 3. Acidification potential by emitted substances (cut-off = 1%)
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively.

Nasiri Mahallati and Koocheki (2017a) assessed the life cycle of wheat production in Iran and considered the contribution of phosphorus emissions to the environment in this impact category to be minor, estimating it to account for 8% to 13% of the total nutrient potential in low- and high-input systems, respectively. Across all agroecosystems, nitrate leaching, followed by ammonia emissions to the air and phosphorus leaching, contributed the most to emissions. Soltani et al. (2010), in their evaluation of the environmental impacts of crop production using the LCA method and comparison with Europe, reported eutrophication potentials of 2.99 kg PO_4 equivalent per ton of wheat grain for Gorgan conditions and 6.17 kg PO_4 equivalent per ton of wheat grain for Barrois, France.

3.3. Global warming impact category due to greenhouse gases

In this study, the global warming potential for the average of 50 farms, high-input, medium-input (integrated), and low-input agroecosystems in the field survey, as well as the high-input, medium-input (integrated), and low-input agroecosystems in the experimental field, was calculated as 960, 1003, 920, 907, 579, 501, and 362 kg CO_2 equivalent per ton of wheat grain, respectively.

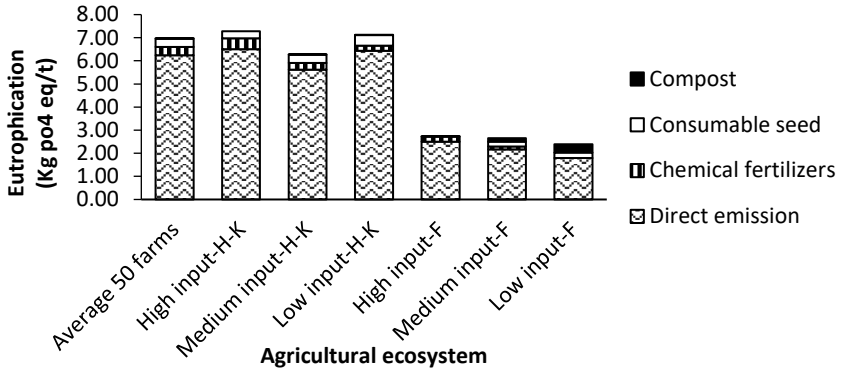


Figure 4. Eutrophication potential by input
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively.

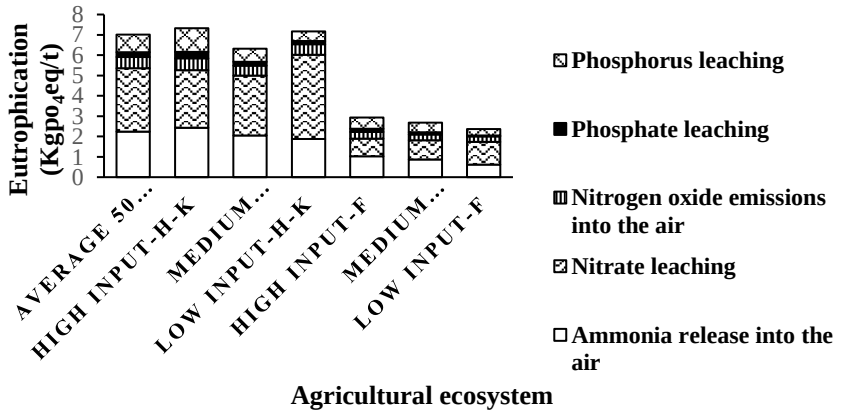


Figure 5. Eutrophication potential by emitted substances (cut-off = 1%)
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively.

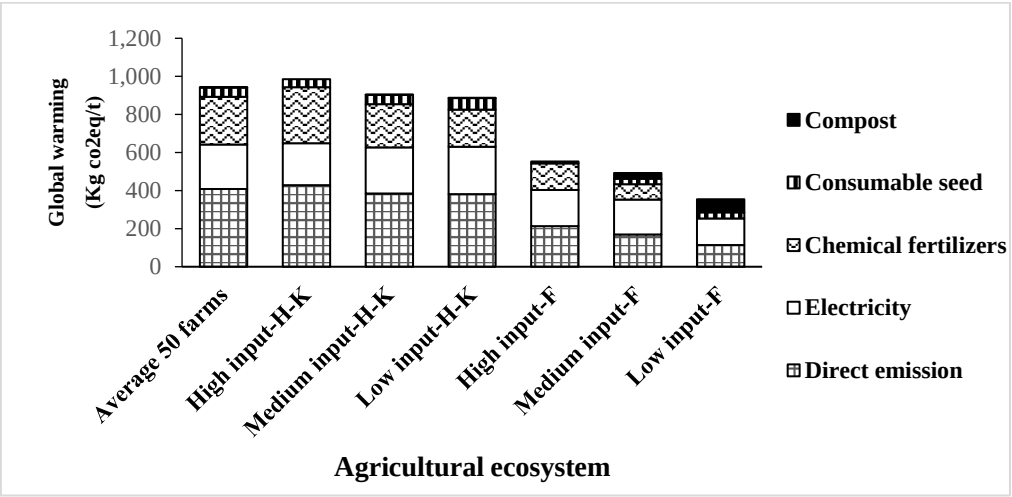


Figure 6. Global warming potential by inputs
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively.

The study (Figure 6) showed that among farm inputs, direct farm emissions, followed by chemical fertilizer production and electricity production, were the primary contributors to global warming in the field survey agroecosystems (average of 50 farms, high-input, and medium-input (integrated)). In the low-input field survey agroecosystem and the high-input, medium-input (integrated), and low-input experimental field agroecosystems, the main contributors, in order, were direct farm emissions, electricity production, and

production of chemical and organic fertilizers. Data analysis (Figure 7) indicated that CO_2, followed by N_2O and CH_4, were the primary contributors to global warming across the seven scenarios. CO_2 emissions to the atmosphere were calculated as 683, 712, 658, 647, 439, 369, and 246 kg per ton of wheat grain for the average of 50 farms, high-input, medium-input (integrated), low-input field survey, and high-input, medium-input (integrated), and low-input experimental field agroecosystems, respectively. N_2O emissions to the atmosphere were calculated as 245, 256, 231, 229, 119, 109, and 89 kg per ton of wheat grain for the same respective agroecosystems. Nasiri Mahallati and Koocheki (2017b), in their life cycle assessment of wheat production systems in Iran (spatial comparison), estimated the highest global warming potential for Khuzestan Province at 993 kg CO_2 equivalent per ton of wheat grain and the lowest for Hamedan Province at 557 kg CO_2 equivalent per ton of wheat grain. Ghasempour and Ahmadi (2018), in their assessment of the environmental impacts of three main crops (corn, wheat, and soybean) using life cycle assessment, reported global warming potentials of 1008, 993, and 1481 kg CO_2 equivalent per ton for wheat, corn, and soybean, respectively.

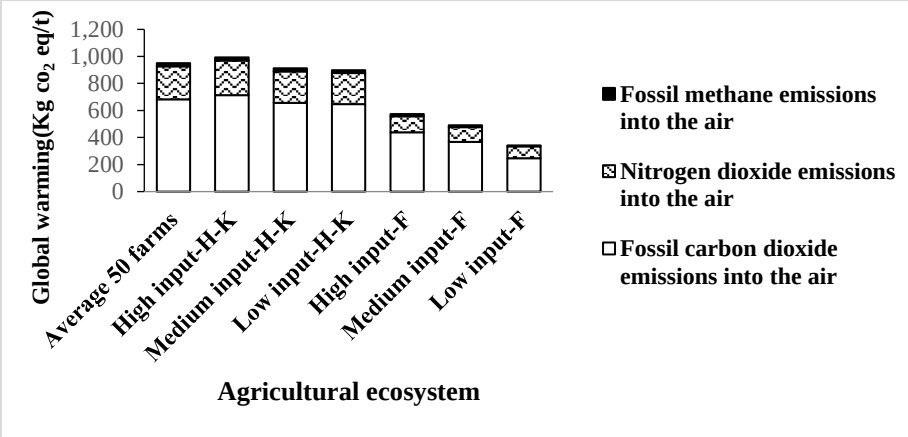


Figure 7. Global warming potential by emitted substances (cut-off = 1%)
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively.

3.4. Impact on ozone layer depletion

In this study, the ozone layer depletion potential for the average of 50 farms, high-input, medium-input (integrated), and low-input agroecosystems in the field survey, as well as the high-input, medium-input (integrated), and low-input agroecosystems in the experimental field, was calculated as 95, 100, 95, 94, 63, 54, and 35 mg CFC-11 equivalent per ton of wheat grain, respectively.

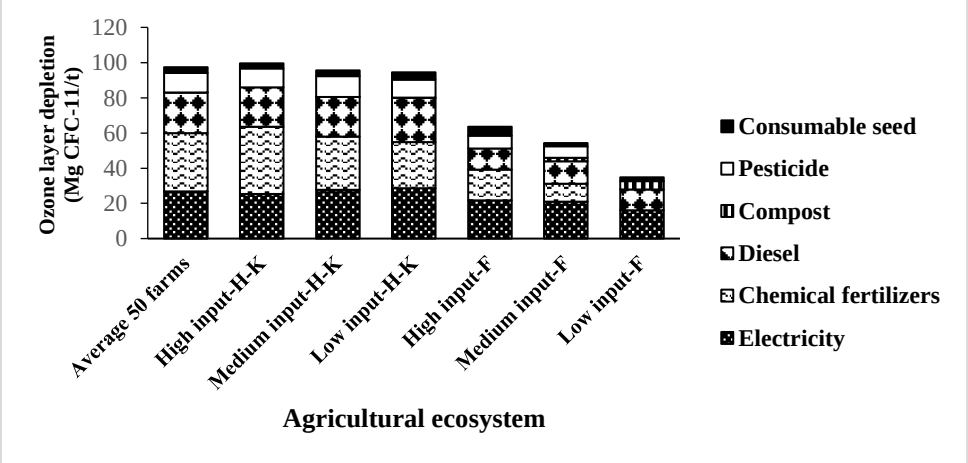


Figure 8. Ozone layer depletion potential by input
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively

Analysis of farm inputs (Figure 8) indicated that in wheat production, direct farm emissions had no impact on ozone layer depletion (indirect emissions from input production were the primary contributors to ozone depletion). In the field survey of agroecosystems, including the average of 50 farms, high-input and medium-input (integrated) systems, the primary contributors to ozone depletion, in order, were chemical fertilizer production, followed by electricity production and diesel production. Similarly, in the low-input field survey agroecosystem and

the high-input and medium-input (integrated) experimental field agroecosystems, electricity production, followed by chemical fertilizer production and diesel production, were the main factors contributing to ozone depletion in wheat production. In the low-input experimental field agroecosystem, electricity production, followed by organic fertilizer (manure) production and diesel production, were the primary contributors to ozone depletion. The ozone depletion potential for wheat production in Gorgan's climatic conditions was reported as 46.6 mg CFC-11 equivalent per ton of wheat grain (Soltani et al., 2010).

3.5. Human toxicity (human poisoning)

In the present study, the human toxicity impact category for the average of 50 farms, high-input, medium-input (integrated), and low-input agroecosystems in the field survey, as well as the high-input, medium-input (integrated), and low-input agroecosystems in the experimental field, was calculated as 229.3, 251.1, 207.3, 195.6, 125.4, 255.9, and 397.9 kg 1,4-dichlorobenzene (1,4-DB) equivalent per ton of wheat grain, respectively. The highest human toxicity impact (Figure 9) was observed in the low-input agroecosystem, followed by the medium-input (integrated) agroecosystem in the experimental field. Generally, an increase in input levels leads to higher human toxicity; however, in the low-input and medium-input (integrated) agroecosystems, the opposite occurred due to the use of compost (animal manure), which is rich in micronutrients and heavy metals. Analysis of farm inputs (Figure 9) showed that for wheat production, in the field survey agroecosystems (average of 50 farms, medium-input (integrated), and low-input) and the high-input experimental field agroecosystem, the primary contributors to human toxicity, in order, were chemical fertilizer production, followed by electricity production and direct farm emissions.

In the high-input field survey agroecosystem, chemical fertilizer production, followed by direct farm emissions and electricity production, were the main factors contributing to human toxicity.

In the low-input and medium-input (integrated) experimental field agroecosystems, direct farm emissions, followed by compost production and electricity production, were the primary contributors to human toxicity. Ghasempour and Ahmadi (2018b), in their assessment of the environmental impacts of three main crops (corn, wheat, and soybean) using life cycle assessment in Alborz Province, reported human toxicity values of 203, 170, and 305 kg 1,4-dichlorobenzene equivalent per ton of grain for wheat, corn, and soybean, respectively.

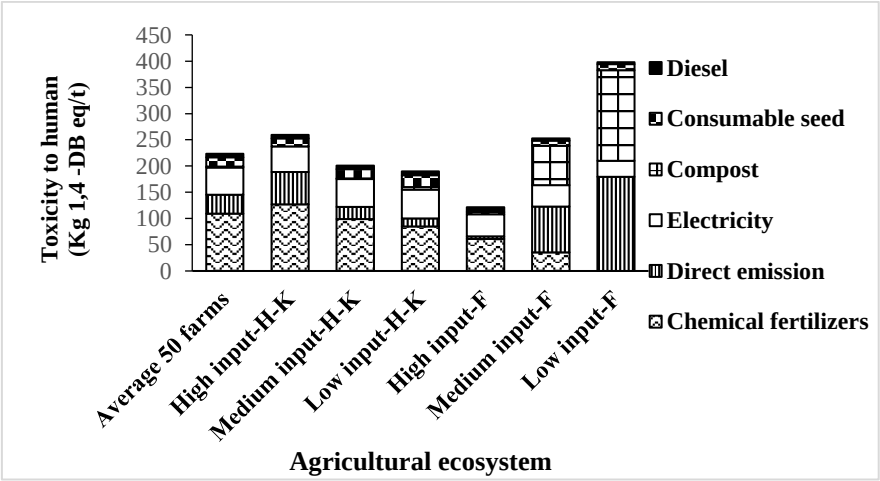


Figure 9. Human toxicity potential by inputs
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively.

3.6. Freshwater aquatic ecotoxicity

The results indicated that the freshwater aquatic ecotoxicity impact category for the average of 50 farms, high-input, medium-input (integrated), and low-input agroecosystems in the field survey, as well as the high-input, medium-input (integrated), and low-input agroecosystems in the experimental field, was calculated as 171.3, 155.88, 166.99, 213.68, 84.63, 231.83, and 345.52 kg 1,4-dichlorobenzene (1,4-DB) equivalent per ton of wheat grain, respectively.

For wheat production in the field survey agroecosystems (average of 50 farms, high-input, and medium-input (integrated)) and the high-input experimental field agroecosystem, the primary contributors to freshwater aquatic ecotoxicity, in order, were direct farm emissions, followed by chemical fertilizer production and electricity production (Figure 10). In the low-input field survey agroecosystem, direct farm emissions, followed by chemical fertilizer production and seed production, were the main factors contributing to freshwater aquatic ecotoxicity. In the low-input and medium-input (integrated) experimental field agroecosystems, direct farm emissions, followed by compost production and electricity production, were the primary contributors to freshwater aquatic ecotoxicity in wheat production. The high ecotoxicity in the low-input and medium-input (integrated) experimental field agroecosystems was attributed to the use of compost (animal manure), which is rich in micronutrients and heavy metals, particularly copper and zinc. The model accounts for both direct emissions and system-level resource demands through element emissions (vanadium, barium) and Metal depletion effects (copper,

zinc) quantified via the database's characterization factors. This dual approach reflects the database's methodology for capturing both Acute toxicity from direct emissions and Chronic impacts from gradual resource depletion. The low-input field survey agroecosystem exhibited higher ecotoxicity due to low yields and high pesticide use (the amount of fungicide-treated seeds relative to the yield was higher compared to other agroecosystems) (Figure 11).

In all field survey agroecosystems and the high-input experimental field agroecosystem, the primary cause of freshwater aquatic ecotoxicity was direct pesticide emissions from the farm (fungicides and herbicides). Additionally, emissions of vanadium and barium, as well as deficiencies in copper and zinc, contributed to ecotoxicity in the high-input experimental and field survey agroecosystems and the medium-input field survey agroecosystem (Figure 11). In the low-input and medium-input (integrated) experimental field agroecosystems, excessive emissions of copper, followed by pesticide emissions and zinc, were the main factors contributing to freshwater aquatic ecotoxicity. Ghasempour and Ahmadi (2018b), in their assessment of the environmental impacts of three main crops (corn, wheat, and soybean) using life cycle assessment in Alborz Province, reported freshwater aquatic ecotoxicity values of 144.3, 122.2, and 196.4 kg 1,4-dichlorobenzene equivalent per ton of grain for wheat, corn, and soybean, respectively.

3.7. Marine aquatic ecotoxicity

The results of this study indicated that the marine aquatic ecotoxicity impact category for the average of 50 farms, high-input, medium-input (integrated), and low-input agroecosystems in the field survey, as well as the high-input, medium-input (integrated), and low-input agroecosystems in the experimental field, was calculated as 90,795, 97,272, 86,339, 83,186, 54,191, 64,658, and 87,942 kg 1,4-dichlorobenzene (1,4-DB) equivalent per ton of wheat grain, respectively. Analysis of farm inputs (Figure 12) showed that for wheat production, chemical fertilizer production, followed by electricity production, were the primary contributors to marine aquatic ecotoxicity in all field survey agroecosystems and the high-input experimental field agroecosystem. In these agroecosystems, direct emissions had a negligible or negative impact (in the case of the high-input experimental field agroecosystem) on this impact category.

In the medium-input (integrated) experimental field agroecosystem, direct farm emissions, followed by electricity production and chemical fertilizer production, were the main contributors to marine aquatic ecotoxicity. In the low-input experimental field agroecosystem, direct farm emissions, followed by electricity production, were the primary factors contributing to marine aquatic ecotoxicity in wheat production (Figure 12). The contributions of diesel production, seed production, pesticide production, and compost production to this impact category were minimal (less than 4%) across all agroecosystems. The results showed that in all field survey agroecosystems and the high-input experimental field agroecosystem, vanadium, followed by barium and nickel, were the primary metals causing marine aquatic ecotoxicity. In these agroecosystems (except the low-input field survey agroecosystem), deficiencies in copper and zinc for marine organisms were also observed.

These elements are present in minimal amounts in chemical fertilizer formulations, necessitating their extraction from water or soil in these agroecosystems to meet wheat production needs, which contributes to toxicity for marine organisms. To mitigate this toxicity, the use of micronutrients or organic and animal-based fertilizers is recommended in these agroecosystems (Figure 13). Marine aquatic ecotoxicity in the low-input and medium-input (integrated) agroecosystems was attributed to emissions of metals such as vanadium, copper, and zinc. Substances such as barite, hydrogen fluoride, and others contributed minimally (less than 5%) to ecotoxicity across the seven scenarios (Figure 13). Iriarte et al. (2010), using life cycle assessment for rapeseed and sunflower oil production, determined that chemical fertilizers had the greatest impact on the marine aquatic ecotoxicity category.

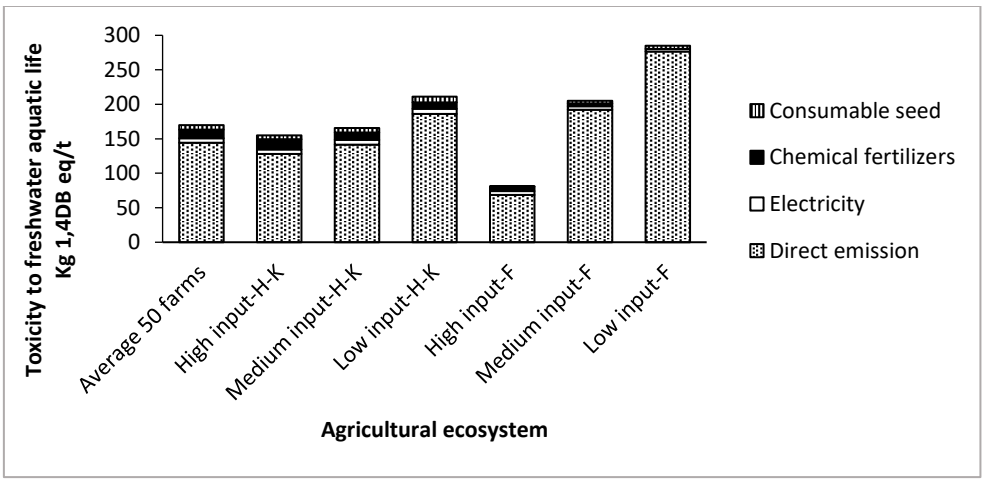


Figure 10. Freshwater aquatic ecotoxicity potential by input
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively

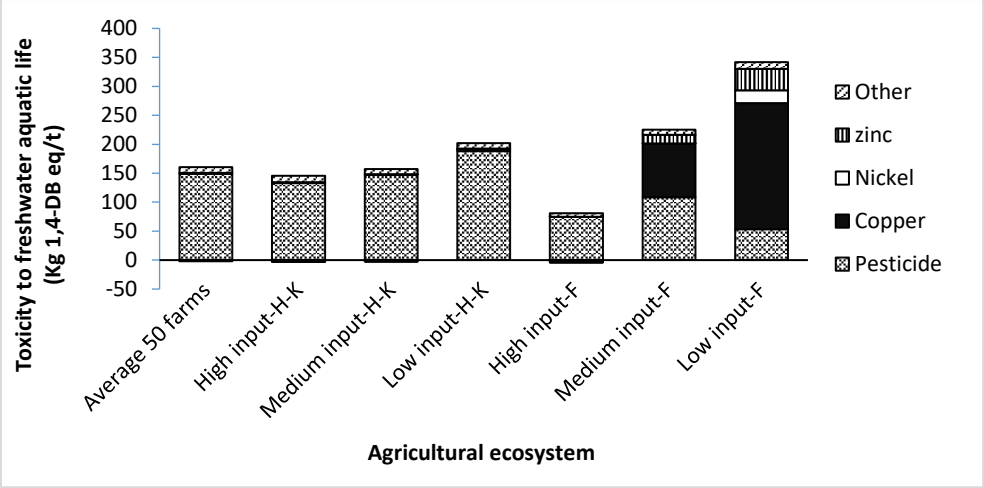


Figure 11. Freshwater aquatic ecotoxicity potential by emitted substances (cut off =1%)
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively

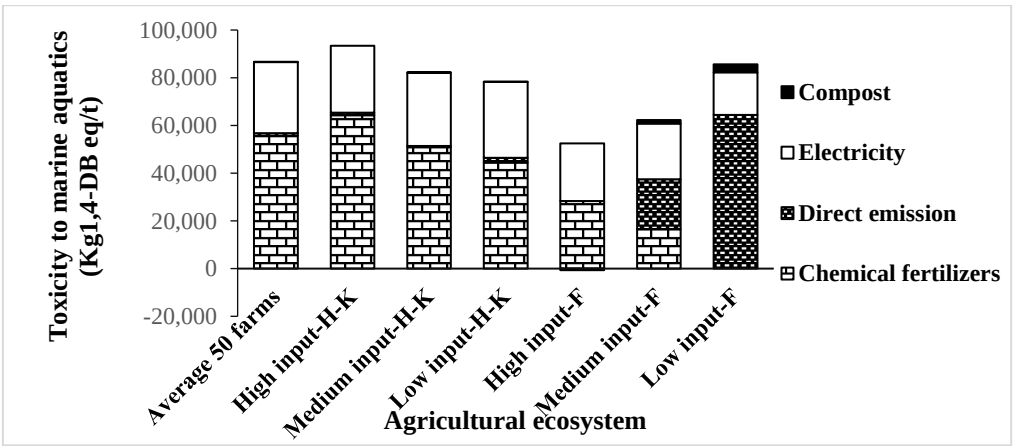


Figure 12. Marine aquatic ecotoxicity potential by input
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation respectively

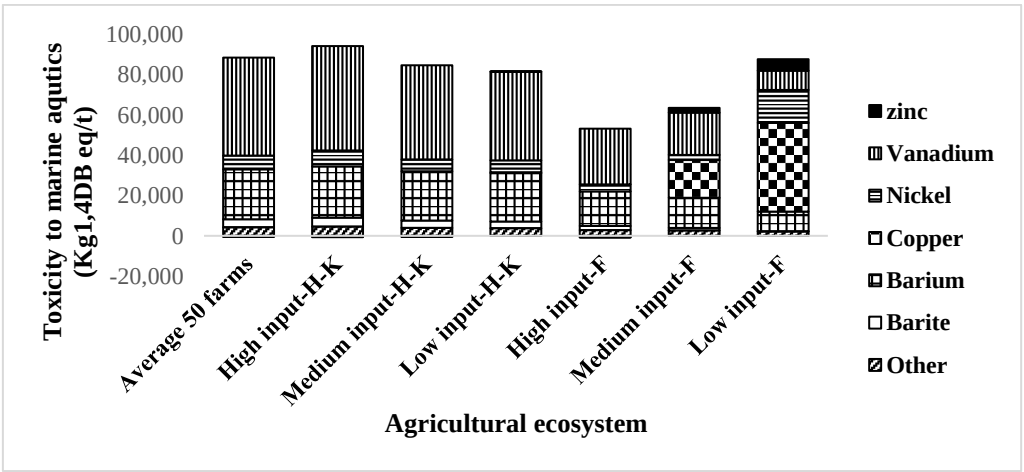


Figure 13. Marine aquatic ecotoxicity potential by emitted substances (cut off =1%)
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively

3.8. Terrestrial ecotoxicity (soil organisms)

The results indicated that the terrestrial ecotoxicity per ton of wheat grain, as a functional unit, for the average of 50 farms, high-input, medium-input (integrated), and low-input agroecosystems in the field survey, as well as the high-input, medium-input, and low-input agroecosystems in the experimental field, was calculated as 9.18, 8.81, 8.8, 10.8, 4.2, 19.15, and 40.35 kg 1,4-dichlorobenzene (1,4-

DB) equivalent, respectively. In the three agroecosystems—average of 50 farms, high-input, and medium-input (integrated)—terrestrial ecotoxicity increased with higher input levels. However, in the low-input agroecosystem, this trend was driven by higher direct emissions and greater seed use relative to the yield of this agroecosystem (Figure 14).

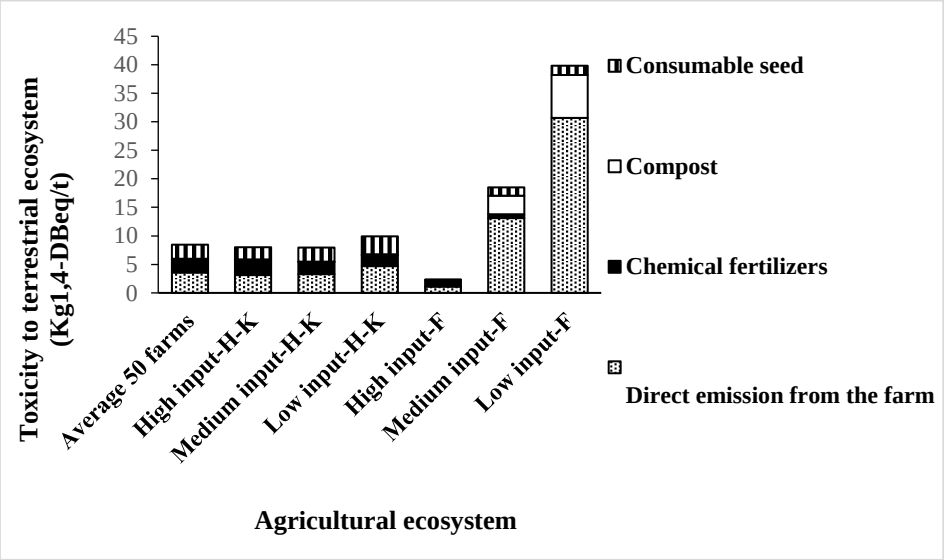


Figure 14. Terrestrial ecotoxicity potential by input
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively

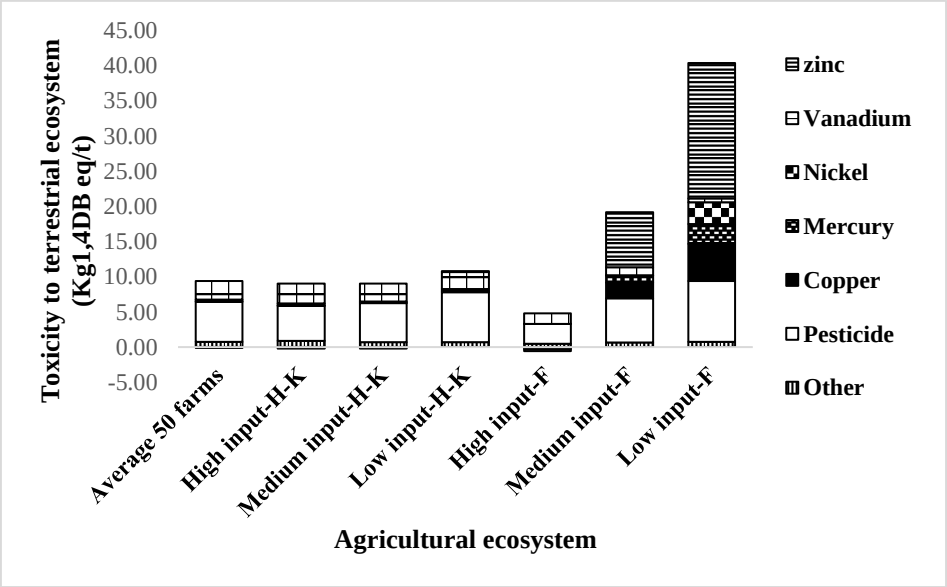


Figure 15. Terrestrial ecotoxicity potential by emitted substances (cut off =1%)
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively

Analysis of farm inputs (Figure 15) showed that for wheat production, direct farm emissions, followed by chemical fertilizer production and electricity production, were the primary contributors to terrestrial ecotoxicity in the average of 50 farms, high-input, and medium-input (integrated) field survey agroecosystems. In the low-input field survey agroecosystem, direct farm emissions, followed by seed production and chemical fertilizer production, were the main factors contributing to terrestrial ecotoxicity. In the high-input experimental field agroecosystem, diesel production, followed by chemical fertilizer production and direct farm emissions, were the primary contributors to terrestrial ecotoxicity. In the medium-input and low-input experimental field agroecosystems, direct farm emissions, followed by compost production and seed production, were the main factors contributing to terrestrial ecotoxicity in this impact category. Emissions from pesticide production had a negligible impact in this category and were not significant.

For all field survey agroecosystems and the high-input experimental field agroecosystem, pesticides, followed by vanadium, were the primary contributors to terrestrial

ecotoxicity among emitted substances. In the high-input field survey and high-input experimental field agroecosystems, ecotoxicity was also caused by deficiencies in copper and zinc for terrestrial ecosystems. These elements are present in minimal amounts in chemical fertilizer formulations, necessitating their extraction from water or soil in these agroecosystems to meet wheat production needs, which contributes to toxicity for soil organisms. To mitigate this toxicity, the use of micronutrients or organic and animal-based fertilizers is recommended in these agroecosystems (Figure 15). In the low-input and medium-input (integrated) experimental field agroecosystems, zinc from animal manure, followed by pesticides, were the two primary factors contributing to soil organism ecotoxicity (Figure 15).

3.9. Photochemical oxidation (smog)

The results indicated that the photochemical oxidation potential for the average of 50 farms, high-input, medium-input (integrated), and low-input agroecosystems in the field survey, as well as the high-input, medium-input (integrated), and low-input agroecosystems in the experimental field, was calculated as 0.16, 0.17, 0.15, 0.15, 0.11, 0.1, and 0.09 kg ethylene (C_2H_4) equivalent per ton of wheat grain as a functional unit, respectively. In all field survey and experimental field agroecosystems, the photochemical oxidation potential decreased as input levels increased. The results showed that for wheat production in all field survey agroecosystems and the high-input and medium-input (integrated) experimental field agroecosystems, the primary contributors to photochemical oxidation, in order, were chemical fertilizer production, followed by electricity production and direct farm emissions. In the low-input experimental field agroecosystem, compost production, followed by electricity production and direct farm emissions, were the primary contributors to photochemical oxidation (Figure 16). For wheat production in all field survey agroecosystems and the high-input and medium-input (integrated) experimental field agroecosystems, among emitted substances, SO_2 and fossil CO were the primary contributors to photochemical oxidation. In the low-input experimental field agroecosystem, fossil CO, followed by SO_2, were the primary contributors to photochemical oxidation among emitted substances (Figure 17). The photochemical oxidation potential was reported as 0.5 kg C_2H_4 equivalent per ton of wheat grain (Soltani et al., 2010). Some researchers, including Ghasempour and Ahmadi (2018b), reported photochemical oxidation potentials for wheat, corn, and soybean as 0.7, 0.6, and 0.36 kg ethylene equivalent per ton of grain, respectively.

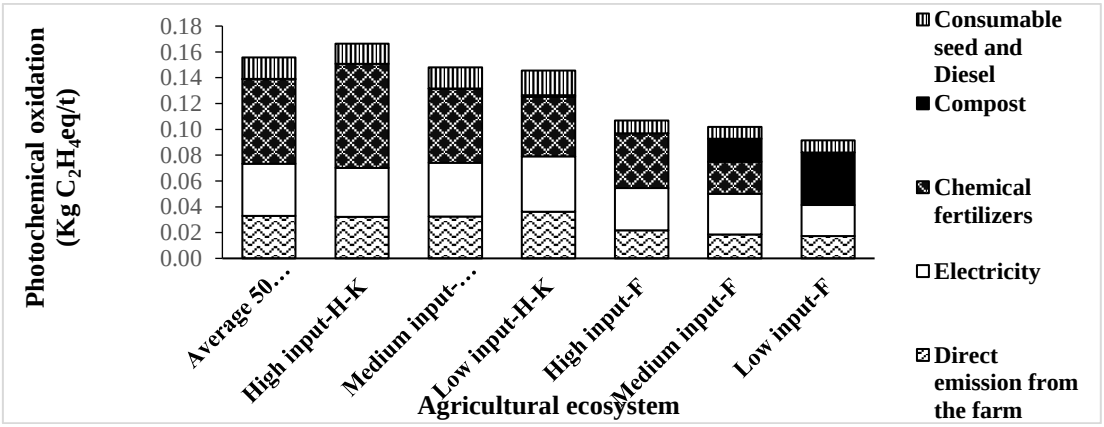


Figure 16. Photochemical oxidation potential by input
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively

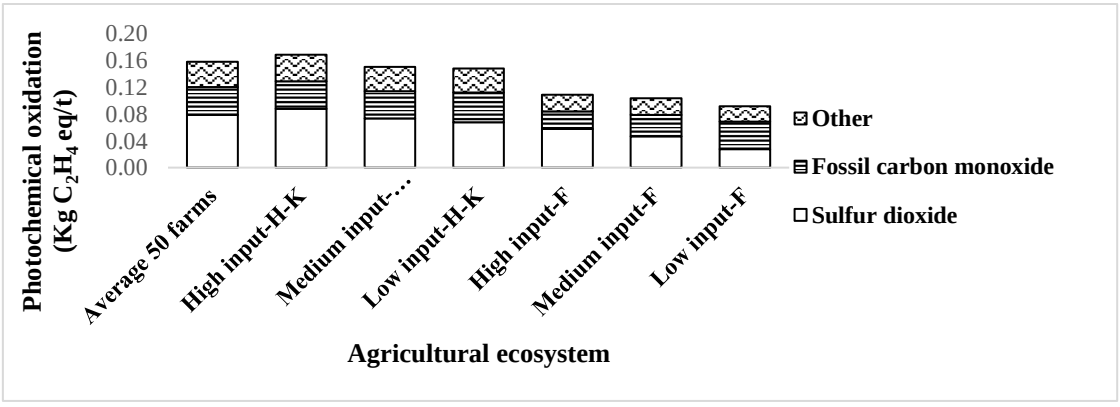


Figure 17. Photochemical oxidation potential by emitted substances (cut off =1%)
(H-K) and (F) mean Hamidiyeh and Karun counties and Field cultivation, respectively.

4. Conclusion

The overall results indicated that wheat production in the field survey (Karun and Hamidieh counties) had significant environmental impacts and lower yields compared to experimental field cultivation. The primary reasons for this disparity include excessive use of inputs on farms, limited awareness among farmers of the environmental consequences of pollutants, and poor wheat farm management practices in Karun and Hamidieh counties. Additionally, the electricity generation model used for irrigation in Iran (with over 95% of irrigation pumps in Karun and Hamidieh wheat farms being electric) relies heavily on fossil fuels, resulting in substantial differences in the environmental impacts of agricultural production compared to European models, which primarily utilize wind, hydroelectric, and nuclear power. Consequently, significant differences were observed between the seven scenarios and European countries in certain impact categories. Chemical fertilizer production had the greatest impact on five environmental impact categories: ozone layer depletion in the average of 50 farms, high-input, and medium-input field survey agroecosystems; abiotic resource depletion in all field survey and experimental field agroecosystems (except the low-input field survey and low-input experimental field agroecosystems); photochemical oxidation in all agroecosystems (except the low-input experimental field agroecosystem); marine aquatic ecotoxicity in all agroecosystems (except the medium-input and low-input experimental field agroecosystems); and human toxicity in all field survey agroecosystems and the high-input experimental field agroecosystem. Finally, these results underscore the need for context-specific mitigation strategies addressing both agricultural practices (input optimization, farmer education) and national energy policy reforms to reduce wheat production's environmental footprint.

References

Bare, J. C., Norris, G. A., Pennington, D. W., & McKone, T. (2003). TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. *Journal of Industrial Ecology*, *6*, 49–78. https://doi.org/10.1162/108819802766269539

Bennett, R., Phipps, R., Strange, A., & Grey, P. (2004). Environmental and human health impacts of growing genetically modified herbicide-tolerant sugar beet: A life cycle assessment. *Plant Biotechnology Journal*, *2*(4), 272–278. https://doi.org/10.1111/j.1467-7652.2004.00076.x

Brentrup, F., Küsters, J., Kuhlmann, H., & Lammel, J. (2001a). Application of the life cycle assessment methodology to agricultural production: An example of sugar beet production with different forms of nitrogen fertilizers. *European Journal of Agronomy*, *14*(3), 221–233. https://doi.org/10.1016/S1161-0301(00)00098-8

Brentrup, F., Kusters, J., Lammel, J., & Kuhlmann, H. (2001b). Application of the life cycle assessment methodology to agricultural production: An analysis of 143 case studies. *International Journal of Agricultural Sustainability*, *9*(3), 215–228. https://doi.org/10.1080/14735903.2011.583470

Ghasempour, A., & Ahmadi, E. (2018a). Comparative life cycle assessment of major crops in Iran: Environmental hotspots and improvement opportunities. *Journal of Cleaner Production*, *197*(1), 732–741. https://doi.org/10.1016/j.jclepro.2018.06.236

Ghasempour, A., & Ahmadi, E. (2018b). Evaluation of environmental effects in producing three main crops (corn, wheat, and soybean) using life cycle assessment. *CIGR Journal*, *20*(2), 126–137.

Huerta, J. H., Alvear, E. M., & Navarro, R. M. (2012). Evaluation of two production methods of Chilean wheat by life cycle assessment (LCA). *IDESIA (Chile)*, *30*(2), 101–110. https://doi.org/10.4067/S0718-34292012000200013

Guinee, J. (2001). Handbook on life cycle assessment operational guide to the ISO standards. The international *Journal of Life Cycle Assessment*, *6*(5), 255-255. https://doi.org/10.1007/BF02978784.

International Organization for Standardization. (1997). *ISO 14040: Environmental management Life cycle assessment Principles and framework.*

Iriarte, A., Rieradevall, J., & Gabarrell, X. (2010). Life cycle assessment of sunflower and rapeseed as energy crops under Chilean conditions. *Journal of Cleaner Production*, *18*(4), 336–345. https://doi.org/10.1016/j.jclepro.2009.11.004

Kamaie, S., Fateh, A., & Veisi, H. (2021). Impact of different agricultural management practices on quantitative and qualitative wheat yield. *Crop Production*, *14*(4), 47–62.

Meisterling, K., Samaras, C., & Schweizer, V. (2009). Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. *Journal of Environmental Management*, *90*(1), 23–30. https://doi.org/10.1016/j.jenvman.2008.03.023

Nasiri Mahallati, M., & Koocheki, A. (2017a). Energy efficiency and environmental sustainability in wheat systems of Iran: A case study from Khorasan Province. *Iranian Journal of Field Crops Research*, *15*(2), 243–256.

Nasiri Mahallati, M., & Koocheki, A. (2017b). Life cycle assessment of wheat production systems: Comparison of input levels. *Agricultural Ecology*, *9*(4), 972–992.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., & Olsson, L. (2007). Categorising tools for sustainability assessment. *Ecological Economics*, *107*(1), 1–19. https://doi.org/10.1016/j.ecolecon.2006.07.023

Pishgar-Komleh, S. H., Sefeedpari, P., & Rafiee, S. (2011). Energy and economic analysis of rice production under different farm levels in Guilan province of Iran. *Energy*, *36*, 5824–5831. https://doi.org/10.1016/j.energy.2011.08.044

Rahimizadeh, M., Madani, H., Rezadoust, S., Mehraban, A., & Marjani, A. (2007). Analysis of energy in agroecosystems and methods of increasing energy efficiency. *6th National Energy Congress*, Tehran, Iran, June 12–13.

Risoud, B. (2000). Energy efficiency of various French farming systems: questions and sustainability. *International Conference on Sustainable Energy: New Challenges for Agriculture and Implications for Land Use*, Wageningen University, Netherlands, May 18–20.

Soltani, A., Rajabi, M., Zeinali, A., & Soltani, A. (2010). Environmental impact assessment of crop production using LCA: Wheat in Gorgan. *Electronic Journal of Crop Production, 3*(3), 201–218.