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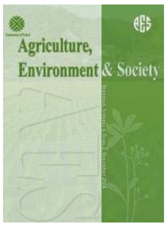

Energy flow analysis and environmental impacts of quinoa production systems in the Baluchestan region

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ABSTRACT

Energy flow and environmental impacts are two critical metrics for evaluating the sustainability of agricultural production systems. This study investigates the energy consumption of quinoa production in the Baluchestan region by analyzing various inputs and energy sources. Furthermore, it assesses the environmental impacts of quinoa cultivation using a life cycle assessment (LCA) approach. Data were collected from local farmers and agricultural professionals in the region, supplemented by information from the Ecoinvent® 3.0 databaseThe LCA was conducted using the cradle-to-farm-gate approach, as outlined in the ISO 14044 standard. This involved four main phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation of results. Energy indices, including net energy gain, energy use efficiency, specific energy, and energy productivity, were calculated for both the main product and by-product (straw) of the quinoa production system. The environmental impact categories evaluated were global warming potential, Abiotic depletion, ozone layer depletion, acidification, and eutrophication. The energy analysis, which revealed a positive net energy and a high energy use efficiency, demonstrated that quinoa cultivation is an efficient process. The results indicate that a significant portion of the total energy input is expended on the production of the by-product (straw). Additionally, machinery, fuel, and chemical fertilizers were identified as the primary contributors to environmental degradation. Based on these findings, it is recommended to adopt modern machinery and implement conservation agriculture practices, such as residue management and reduced tillage, to minimize the use of chemical fertilizers and fossil fuels.

Highlights

- Quinoa production in Baluchestan is energy-efficient with a high net energy gain.
- The by-product (straw) accounts for a significant portion of the total energy input.
- Machinery, fuel, and fertilizers are the main contributors to the environmental impact (LCA).
- Modern machinery and conservation agriculture are recommended to mitigate emissions.

1. Introduction

Continuous population growth and increasing demand for food production will lead to inevitable challenges for improving agriculture from the current situation and providing food for the growing population. Therefore, adoption of sustainable agricultural production methods for dealing with global challenges, such as food security, population explosion, and environmental pressures (Tilman et al., 2011), and producing sufficient and sustainable food for 9.2 billion people in the world in 2050 seems necessary (Connor et al., 2011).

One of the approaches that help mankind to achieve the goals of sustainable agriculture is planting plants that are resistant to drought and salinity. Quinoa (*Chenopodium quinoa*), which is a dicotyledonous plant belonging to the Amaranthaceae family and is classified as a pseudocereal plant, can grow in harsh conditions (Amiryousefi et al., 2021). The high tolerance of this plant to all kinds of

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environmental stresses, including salinity and drought stress, has made it widely adaptable to different climatic conditions (Soltanzadeh and Aahmadpour Borazjani, 2022). Besides having a high nutritional value, it can be cultivated well to produce a suitable product even in limited conditions like low fertility. Therefore, it can be used as a suitable plant to achieve sustainable agriculture, proper nutrition, and industrial production (Soltanzadeh et al., 2023).

Based on the FAO report, energy consumption in agricultural ecosystems has led to increased production efficiency and economic growth in rural areas (Li et al., 2016). However, due to the development of technology and increased consumption of chemical inputs in agricultural ecosystems (Skowroñska and Filipek, 2014), agricultural systems intensify a wide range of environmental effects, such as climate change, acidification, Eutrophication, etc. (Roy et al., 2009). In general, the agricultural sector consumes about 5% of the world's energy and accounts for an 11% share of greenhouse gas emissions. Evaluating energy flow and analyzing environmental impacts in agricultural production systems can be a useful step towards increasing energy efficiency and mitigating the negative environmental effects of the system, as it provides insight into the impacts of product and production system (Marzban et al., 2020; Roer et al., 2012).

In recent years, LCA has been used to evaluate the environmental impacts caused by a process or activity by identifying and determining the amount of energy consumption and inputs (Prasad et al., 2020). Compared to other tools, the LCA approach has received more attention from researchers. It seems that its superiority over other tools lies in its ability to simultaneously examine several groups of environmental impacts in a system (Ashworth et al., 2015; Bacenetti et al., 2014).

Numerous studies have been conducted worldwide using the life cycle assessment (LCA) approach to evaluate the sustainability and environmental impacts of various agricultural products. Examples include olive (Espadas-Aldana et al., 2019), sugarcane (Kaab et al., 2019), onion (Esmaeilzadeh et al., 2020), wheat (Ghasemi-Mobtaker et al., 2020), maize (Hassani et al., 2022), forage maize (Esfahani et al., 2018), oilseeds (Dekamin et al., 2018), pulses (Vahidi et al., 2021), paddy rice (Mohammadi et al., 2020), strawberry (Mafakheri et al., 2017; Parajuli et al., 2022), peanut (Nikkhah et al., 2015), and quinoa (Lotfalian Dehkordi and Forootan, 2020).

Quinoa is well-suited for cultivation in the Baluchestan region, which is characterized by limited water resources, low soil fertility, and relatively high salinity, as it can produce a suitable yield under these challenging conditions.

Given this crop's adaptability and significant importance for food security, enhancing farmer income, and production stability in the Baluchestan region, this research aims to evaluate the energy indicators and environmental impacts of the quinoa production system in this area. The ultimate goal is to provide recommendations for its optimal and sustainable management.

2. Materials and Methods

2.1. Sampling and data collection

This research was conducted in the Baluchestan region (Bampour County), located in the southeastern part of Sistan and Baluchestan province. This region is situated at an elevation of 560 meters above sea level, with geographical coordinates of 60°46′ E longitude and 27°19′ N latitude. The data required for this study were collected from 35 farmers and other agricultural stakeholders in the region through face-to-face interviews and the administration of questionnaires. Given the small population size, there is no need for sampling; the sample size is equal to the population size. The full list of inputs compiled includes: seeds, chemical fertilizers, manure, pesticide and herbicide, farm machinery, fossil fuel, water for irrigation, and human labor. The corresponding outputs are the quinoa grain and straw.

2.2. Determining Energy Indicators

To determine the energy of the inputs and outputs, the amount of each consumed input was multiplied by its energy content. The inputs, outputs, and their energy coefficients are presented in Table 1. Also, the energy indicators were calculated based on formulas 1- 4. In these formulas, the input and output energy flows are expressed in megajoules per hectare (MJ ha^{-1}), while the yield represents the grain yield in kilograms per hectare (kg ha^{-1}).

$$\text{Net Energy gain} = \text{Output Energy} - \text{Input Energy} \tag{1}$$

$$\text{Energy use efficiency} = \frac{\text{Output Energy}}{\text{Input Energy}} \tag{2}$$

$$\text{Specific Energy} = \frac{\text{Input Energy}}{\text{Yield}} \tag{3}$$

$$\text{Energy Productivity} = \frac{\text{Yield}}{\text{Input Energy}} \tag{4}$$

Energy utilization in the agricultural sector is classified into direct and indirect or renewable and non-renewable energy resources. In the present study, inputs such as fossil fuel, irrigation water, and human labor were considered direct energy (DE) inputs, while seeds, chemical inputs, manure, and machinery were considered indirect energy (IDE) resources. Renewable energy (RE) consists of seeds, manure, irrigation water, and human labor, whereas non-renewable resources (NRE) include machinery, chemical inputs, and fossil fuel (Erdal et al., 2007).

2.3. Life cycle assessment

Life cycle assessment was carried out in four stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results (ISO-14040, 2006).

2.3.1. Goal and scope

In this stage, the study's objectives, the final product, the system boundaries, and the functional unit are defined (Cederberg and Mattsson, 2000). The primary goal of this study is to investigate the environmental impacts of quinoa production in the specified region. While LCA is a "cradle-to-grave" approach, system boundaries can be limited to a specific part of the process to better focus on particular stages. In this research, we focused exclusively on the farm-level emissions, assuming they are entirely related to the farm's energy inputs. Consequently, the study's scope included materials, energy, fuels, and heat. Transportation, post-harvest operations, and waste management were excluded. The system boundary was defined as "cradle-to-farm-gate," encompassing the materials and their associated emissions from the production stage up to the point of harvest. The functional unit serves as a reference for quantitatively expressing the system's function and environmental impacts (ISO-14040, 2006). For this research, the functional unit was defined based on the yield mass as one ton of quinoa grain.

Table 1. Inputs and outputs of the quinoa production system and their energy coefficients

Items (unit)	Magnitude	Energy Coefficient (MJ unit^{-1})	Refrences for Energy Coefficients
Inputs			
1. Seeds (kg)	7	17.21	(Lotfalian Dehkordi and Forootan, 2020)
2. Chemical fertilizer (kg)			
Nitrogen	105	66.14	(Rafiee et al., 2010)
Phosphorus	60	12.44	(Rafiee et al., 2010)
Potassium	55	9.28	(Rafiee et al., 2010)
3. Manure (kg)	3000	0.3	(Elhami et al., 2019)
4. Pesticide and Herbicide (kg)	1.50	199	(Kitani, 1999)
5. Machinery (h)			
Tractor	8	93.61	(Canakci et al., 2005)
Implements	8	62.70	(Kitani, 1999)
Combine	2	87.63	(Rafiee et al., 2010)
6. Fossil fuel (L)	193	47.8	(Mohseni et al., 2018)
7. Water for irrigation (m^3)	7500	1.02	(Mohammadi and Omid, 2010)
8. Human labor (h)	130	1.96	(Mohseni et al., 2018)
Outputs			
1. Quinoa grain (kg)	2000	17.21	(Lotfalian Dehkordi and Forootan, 2020)
2. Straw (kg)	5200	12.13	(Soltanzadeh and Aahmadpour Borazjani, 2022)

2.3.2. Life Cycle Inventory

At this stage, all system inputs, wastes, and pollutants released during product production are determined and calculated in terms of the functional unit (Brentrup et al., 2001).

According to ISO guidelines, the inventory includes emissions of greenhouse gases, heavy metals, and pesticides to the atmosphere, soil, and water (Finkbeiner et al., 2006). The data required for this step is divided into two main categories: the direct on-farm inputs and materials, and the data related to the manufacturing process of each input (Rafiee et al., 2016).

The first set of data was previously described as being collected from farmers using a questionnaire. The second set of data was gathered from the Ecoinvent® 3.0 database. To quantify the direct emissions to air, water, and soil resulting from the utilization of agricultural inputs, the Tier 1 methodology outlined in the IPCC guidance gocuments (Eggleston et al., 2006) and methods reported by other researchers (Nemecek et al., 2014; Nemecek et al., 2007) were employed.

2.3.3. Life Cycle Impact Assessment (LCIA)

This stage is the quantitative analysis of the results from the life cycle inventory, divided into three sub-sections: classification, normalization, and weighting (Brentrup et al., 2004). Since the normalization and weighting steps are optional, no calculations were performed for these phases. To estimate the environmental emissions from the inputs, data from other studies were used (Gasol et al., 2007).

The collected information was then entered into SimaPro® 9.1 software for analysis of the impact categories. The CML 2 baseline V3.04/EU25 method was selected within the SimaPro software to calculate the life cycle environmental impacts.

2.3.4. Interpretation of Results

In this stage, the results from the inventory and impact assessment are evaluated to identify the stages or points in the production and consumption process that have the most significant negative environmental impacts. Finally, conclusions are drawn, and the LCA report is prepared (Brentrup et al., 2004).

3. Results and Discussion

3.1. Energy Consumption Pattern

The energy consumption values for each input in the quinoa production system are presented in Table 2. The results show that the total energy input for the system is 28,076 MJ per hectare. The largest share of this energy input, at 32.86%, belongs to fossil fuels, primarily the diesel consumed by tractors and combine harvesters. Following fossil fuels, the next largest share of energy consumption in quinoa production is from chemical fertilizers, at 29.22%, with the majority of this being attributed to nitrogen fertilizer (24.74%). Among the other inputs, irrigation water ranks third with a 27.25% share, agricultural machinery is fourth with 5.08%, and manure is fifth with 3.21%. The results also indicate that seeds and labor have the lowest energy consumption.

Energy analyses of wheat production systems have shown that chemical fertilizers and irrigation water had the largest share of energy input (Khoshnevisan et al., 2013). Similarly, some researchers highlighted the significant impact of chemical fertilizers and irrigation water in their analysis of sugar beet production systems (Asgharipour et al., 2012).

It appears that using more modern agricultural machinery, which can reduce field passes and increase field capacity, could have a beneficial effect on decreasing fossil fuel consumption. Additionally, replacing conventional flood irrigation with modern irrigation systems could reduce water consumption and, consequently, its associated energy use.

Table 2. Input and output energies of the quinoa production system

Items (unit)	Consumption energy (MJ ha^{-1})	Share of total Energy (%)
Inputs		
1. Seeds (kg)	120	0.43
2. Chemical fertilizer (kg)		29.22
Nitrogen	6945	24.74
Phosphorus	746	2.66
Potassium	510	1.82
3. Manure (kg)	9000	3.21
4. Insecticide (kg)	299	1.06
5. Machinery (h)		5.08
Tractor	749	2.67
Implements	502	1.79
Combine	175	0.62
6. Fossil fuel (L)	9225	32.86
7. Water for irrigation (m^3)	7650	27.25
8. Human labor (h)	255	0.91
Total inputs energy	28076	100
Outputs		
1. Quinoa grain (kg)	31718	36.91
2. Straw (kg)	54209	63.09
Total outputs energy	85927	100

In this study, quinoa grain was considered the main product and its residue (straw) as a by-product. The quinoa grain and straw accounted for 36.91% and 63.09% of the system's total energy output, respectively. Accordingly, the energy indices were calculated once for the main product and a second time for both the main and by-products, as shown in Table 3.

Table 3. Energy indices for quinoa production

Energy Indices	Unit	Value		
		Main Product (Grain)	Main and by-product (Grain and Straw)	Type of energy (Share %)
Net energy gain	MJ ha^{-1}	3642	57851	
Energy use efficiency	-	1.13	3.06	
Specific energy	MJ kg^{-1}	15.23	4.45	
Energy productivity	kg MJ^{-1}	0.07	0.22	
Direct energy (DE)	MJ ha^{-1}			17130 (61.01%)
Indirect energy (IDE)	MJ ha^{-1}			10946 (38.99%)
Renewable energy (RE)	MJ ha^{-1}			8925 (31.79%)
Non-renewable energy (NRE)	MJ ha^{-1}			19151 (68.21%)

The net energy gain for the main product (grain) and for both the main and by-products (grain and straw) were calculated to be 3,642 MJ ha^{-1} and 57,851 MJ ha^{-1}, respectively. Similarly, the energy use efficiency for these two scenarios was determined to be 1.13 and 3.06, while the specific energy was 15.23 MJ kg^{-1} and 4.45 MJ kg^{-1}, respectively.

The positive net energy gain and an energy use efficiency greater than one indicate the energy consumption efficiency of the quinoa production system. The energy use efficiency in this system was lower than that for rapeseed production (Choobin et al., 2016). The energy analysis for this system demonstrates that direct energy constitutes the predominant share of the total energy input (61.01%). Crucially, the system exhibits a high dependency on unsustainable sources, with non-renewable resources accounting for 68.21% of the total energy consumption

Comparing the energy indices for the main and by-products reveals that a significant portion of the energy is spent on producing the straw. In the study area, farmers sometimes burn this residue, which, according to the findings of this research, constitutes an energy loss. This residue should be managed either as animal fodder or through the implementation of conservation tillage policies.

3.2. LCA Results

In the current research, the environmental impact assessment was carried out using the LCA method based on ISO14040 standard. The environmental indicators were quantified per ton of quinoa grain produced in the Baluchestan region. The summarized results concerning the impact categories for quinoa production are presented in Table 5. Furthermore, the contribution of farm operations and consumed inputs to the various impact categories for producing one ton of quinoa is illustrated in Figure 1. This figure reveales that chemical fertilizers, diesel fuel, and machinery are the dominant contributors to the overall environmental impacts.

During the quinoa production life cycle, from raw material extraction to on-farm input application, over a thousand substances are emitted into the air, soil, and water, some of which are classified as toxic and hazardous. This study quantifies a selection of these emissions for the production of one ton of quinoa in the Baluchestan region.

A summary of these calculated emissions is presented in Table 4. The corresponding calculated environmental indicators for quinoa production, based on a functional unit of one ton, are summarized in Table 5.

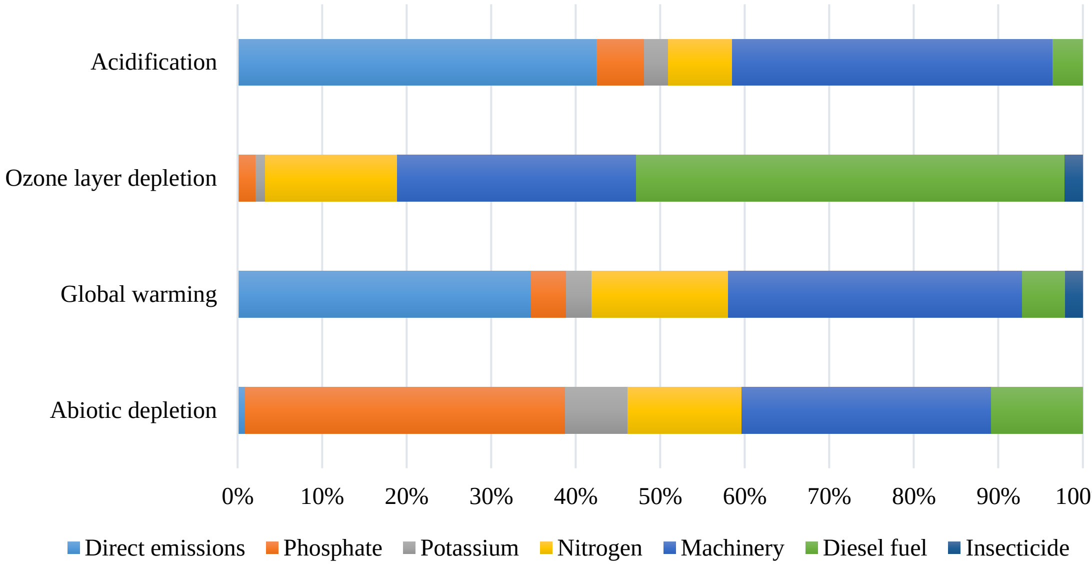

Figure 1. The role of inputs in the rate of environmental indices of quinoa production

Table 4. Emissions from quinoa production

Emissions	Unit	Amount
Emission to air		
Carbon dioxide	(kg)	540.63
Methane	(kg)	0.016
Dinitrogen monoxide	(kg)	0.01
Sulfur dioxide	(kg)	0.13
Nitrogen oxide	(kg)	21.24
Emission to water		
Phosphorus	(kg)	0.76
Nitrate	(kg)	9.64
Emission to soil		
Cadmium	(mg)	3987
Copper	(mg)	11231
Zinc	(mg)	94562
Lead	(mg)	421563
Nickel	(mg)	9887.00
Chrome	(mg)	57421
Mercury	(mg)	43

Table 5. Values of the environmental impact of one ton of quinoa grain production

Impacts categories	Unit	Value
Global warming	kg CO_2 eq.	873
Abiotic depletion	kg Sb eq.	0.214
Ozone layer depletion	kg CFC-11 eq.	0.0002
Acidification	kg SO_2 eq.	11.3
Eutrophication	kg Po_4^{3-} eq.	2.98

3.2.1. Global warming

According to Table 5, the environmental burden of global warming potential was 873 kg CO_2 eq. Among the greenhouse gases, the amount of emissions related to CO_2 and CH_4 had the highest and lowest contributions, respectively. GWP was reported to be 353.99 kg CO_2 eq for the production system of quinoa in Isfahan province, Iran (Lotfalian Dehkordi and Forootan, 2020). Also, this index was reported to be 1164.12 kg CO_2 eq. (Fallahpour et al., 2012) and 624 kg CO_2 eq. (Ghasemi-Mobtaker et al., 2020) for the wheat production systems in Khorasan and Hamadan Provinces in Iran. The main reason for the production and emission of greenhouse gases, especially CO_2 and N_2O, in agricultural ecosystems is related to the consumption of fossil fuels and the use of machinery in various agricultural operations and the consumption of nitrogen fertilizers (Alaphilippe et al., 2013; Brentrup et al., 2004; Milà i Canals et al., 2006).

Brentrup et al. (2004) reported that 59% of the direct emission of CO_2 is related to factories producing nitrogen chemical fertilizers. Connor et al. (2011) also stated that 14% of the net emission of carbon dioxide in agricultural ecosystems is related to tillage operations, so in order to reduce carbon dioxide emissions from agricultural ecosystems, minimal and reduced tillage methods should be used.

3.2.2. Abiotic Depletion

Abiotic depletion refers to the use and subsequent reduction of non-renewable resources, such as fossil fuels and minerals. According to the results of this study, the production of one ton of quinoa leads to an abiotic depletion potential of 0.214 kg antimony equivalent (Sb eq.) (Table 5). The analysis further indicates that the primary contributors to this impact category are machinery and phosphate fertilizers (Figure 1). This finding contrasts with a study by Lotfalian Dehkordi and Forootan (2020), who calculated a significantly higher value of 1.8 kg Sb eq. for one ton of quinoa in Isfahan, Iran, and attributed the largest environmental impact in this category to pesticides and phosphate fertilizers.

3.2.3. Ozone Layer Depletion

Ozone layer depletion is a natural process exacerbated by the presence of certain human-made gases in the atmosphere. While ozone loss is a natural occurrence resulting from common gases like methane and nitrous oxide, the introduction of compounds such as chlorofluorocarbons (CFCs) significantly accelerates this process (Guinée, 2002; Madronich and Granier, 1994).

In this study, the ozone layer depletion potential was calculated to be 0.0002 kg CFC equivalent (CFC eq.) per ton of quinoa production (Table 5). The main contributors to this impact were fuel and agricultural machinery (Figure 1). In comparison, Lotfalian Dehkordi and Forootan (2020) reported a value of 19 mg CFC eq. for one ton of quinoa in Isfahan, citing chemical fertilizers and pesticides as the primary sources of impact. Similarly, a study on quinoa production in Peru found that machinery and chemical fertilizers were the largest contributors to this indicator across all regions studied (Cancino-Espinoza et al., 2018).

3.2.4. Acidification

Acidification is a key environmental impact category caused by the emission of sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NO_x). These emissions primarily result from the application of chemical fertilizers and animal manure, as well as the combustion of diesel fuel. This index is expressed in kilograms of SO_2 equivalent (kg SO_2 eq.) (Brentrup et al., 2004; Mogensen et al., 2009).

The acidification potential for one ton of quinoa production was calculated to be 11.3 kg SO_2 eq. (Table 5). The largest contributors to this category were machinery and direct emissions. Specifically, the analysis showed that SO_2 emissions (from the burning of petroleum products) and NO_x emissions (from fuel consumption in machinery) accounted for 0.15 kg SO_2 eq. and 23.53 kg SO_2 eq. per ton of quinoa, respectively.

This finding is significantly lower than values reported for other crops. For instance, the acidification potential for rice paddy production in China was reported as 52.26 kg SO_2 eq. per ton (She et al., 2018), while Fallahpour et al. (2012) found a value of 1.95 kg SO_2 eq. for wheat.

The results suggest that the acidification potential can be mitigated through several management strategies. These include adopting low-input management, selecting appropriate planting patterns and crop rotation, reducing the use of nitrogen fertilizers in favor of organic alternatives, replacing outdated machinery, and minimizing tillage operations to decrease fuel consumption. Such measures can effectively lower the acidification index and reduce the overall environmental harm of quinoa cultivation (Khoshnevisan et al., 2013; Nemecek and Schnetzer, 2011).

3.2.5. Eutrophication

Eutrophication is the excessive enrichment of terrestrial and aquatic ecosystems with nutrients, which can lead to an undesirable increase in biomass production. In aquatic environments, this can trigger harmful algal blooms and, ultimately, the suffocation of lakes. This impact is primarily driven by the leaching of nitrogen and phosphorus compounds from agricultural fields (Milà i Canals et al., 2006). Specifically, nitrogen oxides (NO_x) and ammonia (NH_3) contribute to terrestrial eutrophication, while the runoff of nitrogen and phosphorus compounds affects aquatic systems. The NOx emissions are mainly associated with the use of machinery and transportation (Brentrup et al., 2004).

The calculated eutrophication potential for one ton of quinoa production was 2.98 kg Po_4^{3-} eq. (Table 5). The largest contributing factor to this impact was direct on-farm emissions. The high consumption of chemical fertilizers (nitrogen and phosphorus) and animal manure for quinoa cultivation was the main reason for this elevated potential (Table 1). For comparison, other studies have reported significantly higher values for different crops; for example, the rapeseed and sunflower production in Chile had eutrophication potentials of 7.2 and 9 kg Po_4^{3-} eq., respectively (Iriarte et al., 2010).

4. Conclusion

The results of this study on energy inputs within the quinoa production system reveal that the highest energy consumption is attributed to tractor and combine harvester fuel, followed by the use of chemical fertilizers, with water ranking third. Similarly, machinery, fuel, and chemical fertilizers were identified as the most significant contributors to environmental damage. A key issue identified in the studied region is the unscientific application of chemical fertilizers, particularly urea. Farmers in most fields do not use fertilizers based on soil tests or scientific principles. Instead, they rely on traditional experience and the misconception that a higher application rate directly leads to a proportional increase in yield. However, the integrated and optimized use of chemical fertilizers not only boosts crop yield but also significantly reduces environmental risks. To promote a shift in this mindset, a promising strategy would be to support and incentivize farmers who adopt healthier and more sustainable production practices, such as the optimized or integrated use of chemical and organic fertilizers.

Furthermore, most of the agricultural machinery and equipment used in the study area were found to be outdated and inefficient. This condition directly contributes to increased fuel consumption and, consequently, greater environmental pollution. Therefore, regular and proper maintenance of agricultural machinery is crucial to reduce diesel fuel consumption and mitigate the associated environmental hazards. In summary, implementing sustainable practices such as crop residue management, conservation agriculture, and reduced tillage methods is strongly recommended. These strategies offer viable solutions to decrease the reliance on chemical fertilizers and fossil fuels, thereby enhancing the overall sustainability of quinoa production in the region.

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