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Life Cycle Assessment of Energy Use and Environmental Impacts in Apple Production and Storage: A Case Study of West Azerbaijan Province, Iran

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Abstract

Sustainable agricultural production depends on efficient energy management and mitigation of environmental burdens. Apple is among the most important horticultural crops in cold climates, with Iran ranking as a major global producer. However, a comprehensive understanding of energy use and emissions—particularly covering both orchard production and post-harvest storage—has been lacking for key growing regions such as West Azerbaijan. To fill this gap, this study offers three innovations: (i) concurrent assessment of production and storage in the cold semi-arid context of West Azerbaijan, unlike previous regional studies that treated these phases separately; (ii) application of a quantitative framework using SimaPro 9.5, CML, and Ecoinvent v3.5 to disaggregate each input's contribution across 10 environmental impact categories; and (iii) translation of findings into practical engineering interventions, including tractor fuel optimization and solar-powered cooling systems for local orchards. Average total energy input and yield were 116,505 MJ ha^{-1} and 34,951 kg ha^{-1}. Fuel (39%), NPK fertilizers (22%), and pesticides (14%) dominated energy use, with an energy ratio (0.72 ± 0.06), productivity (0.32 ± 0.03 kg MJ^{-1}), and net energy (−32,621 ± 1,830 MJ ha^{-1}). Environmentally, eutrophication (4.73×10^{-7} kg PO_4 eq), freshwater ecotoxicity (1.37×10^{-7} kg 1,4-DB eq), marine ecotoxicity (8.02×10^{-11} kg 1,4-DB eq), and acidification (1.21×10^{-11} kg SO_2 eq) emerged as the most severe impacts. These insights—previously unavailable—provide a basis for targeted strategies, including high-efficiency machinery, consolidated operations, rooftop solar panels, organic fertilizers, crop diversification, timely pruning, and bio-based pest management.

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1. Introduction

Agricultural systems have undergone profound changes in recent decades, largely driven by mechanization, the expansion of chemical fertilizers and synthetic pesticides, and improved seed varieties. While these developments have enhanced productivity, they have also led to a significant and growing dependence on fossil fuels (Taki et al., 2018). Energy efficiency is now recognized as a key factor in sustainable agricultural production, contributing not only to economic optimization but also to conserving fossil fuel resources and reducing air pollution. Beyond these operational benefits, energy analysis offers a valuable means of assessing the broader environmental impacts of human activities across different production systems (Majeed et al., 2023).

Excessive energy consumption has created serious environmental challenges, including global warming from greenhouse gas emissions, contamination of water, soil, and air, soil fertility decline, erosion, and depletion of natural resources. In this context, efficient energy management is widely regarded as a cornerstone of sustainable development and a critical tool for selecting appropriate mitigation strategies (Ghasemi-Mobtaker et al., 2022). In recent years, Life Cycle Assessment (LCA) has emerged as a robust methodology for evaluating and quantifying the environmental impacts of agricultural products and food supply chains. LCA practitioners systematically analyze inputs, outputs, and emissions across a defined system boundary, covering the entire life cycle of a product or production process (Ampese et al., 2023). Apples are among the most significant fruits cultivated in cold climates and command the highest share of global trade among horticultural crops in these regions. Global apple production was projected to reach 84 million tons in 2025, with Iran contributing about 2 million tons—approximately 2.38% of total world output (FAOSTAT, 2024).

Because a substantial portion of apples are consumed shortly after harvest, and given their perishable nature and the need to meet market demand beyond the harvest season, effective storage is paramount. Several factors critically influence storage success, including temperature, relative humidity, atmospheric pressure, sorting methods, packaging, and the use of protective coatings (Büchele et al., 2024).

Numerous studies have examined energy and environmental aspects of apple production. For instance, a study in Greece found that conventional and integrated orchards had the highest energy inputs. In contrast, organic orchards had the lowest, with insecticides, herbicides, and irrigation identified as the main drivers (Kehagias et al., 2015). In China, research showed that fertilizer production and pest management were the primary sources of environmental impacts (Zhu et al., 2018). Khanali et al. reported that diesel fuel accounted for 77% of total energy consumption in apple production systems. (Khanali et al., 2020). Similarly, Li and Zhang found that farmers' services and economic activities contributed only marginally (0.74–1.56%) to the overall environmental burden (Li & Zhang, 2023).

Other LCA studies have addressed energy optimization in different agricultural contexts, such as rice cultivation (Sharifi et al., 2025). Despite this body of research, several gaps remain. A systematic review of the literature reveals that: (1) limited research has addressed the concurrent assessment of apple production and storage in the cold, semi-arid climate of Iran; (2) quantitative disaggregation of input contributions across multiple environmental impact categories is lacking for this region; and (3) context-specific engineering interventions based on local data have not been previously proposed (Bosona, 2024). The present study was designed to address these gaps with three main innovations: (i) concurrent investigation of apple production and storage in West Azerbaijan—a combination previously treated separately in regional studies; (ii) application of a detailed quantitative framework using SimaPro 9.5, the CML methodology, and the Ecoinvent v3.5 database to disaggregate each input's contribution across 10 environmental impact categories; and (iii) provision of practical engineering interventions rooted in biosystems mechanical engineering, including tractor fuel optimization and solar-powered cooling systems, which are directly implementable in local orchards. Unlike most previous LCA studies that examined orchard operations and post-harvest processing separately, this work integrates both stages within a single framework. Furthermore, while earlier regional research relied on aggregated data, our study provides a detailed breakdown of each input's contribution across individual environmental impact categories—an approach not previously applied to the cold, semi-arid context of northwestern Iran. Although focused on West Azerbaijan, the methodology is transferable to other apple-producing regions with similar climatic and management conditions.

2. Materials and Methods

2.1. Study Area and Data Collection

This research was carried out in apple orchards across West Azerbaijan Province—an area spanning approximately 10,548 hectares, situated at an elevation of 1,332 meters above sea level, with geographic coordinates (37° 33' 10.08" N and 45° 04' 33.24" E). We considered a broad statistical population and selected a sample of literate farmers and cold storage managers using simple random sampling. The sample size was determined using Cochran's formula for simple random sampling (Equation 1), where each member of the population had an equal probability of selection at each stage. Data were gathered through 50 structured questionnaires and complemented by face-to-face interviews. Information was collected on various inputs, including apple boxes, transport vehicles, water, energy, and fuel consumed during the apple production cycle.

$$n = \frac{Nt^2\, S^2}{Nd^2 + t^2 s^2} \tag{1}$$

$$d = \frac{t \times s}{\sqrt{n}} \tag{2}$$

where $N = 620$ (the total number of active apple growers in the study region), $t = 1.96$ (the confidence coefficient at the 95% level), $s^2 = 0.174$ (the estimated variance of the energy ratio based on a preliminary pilot study), and $d = 0.736$ (the acceptable margin of error).

software. We performed the subsequent data processing and impact assessment using SimaPro 9.5, applying the CML methodology in conjunction with the Ecoinvent v3.5 database. The CML framework—originally developed by the Center for Environmental Science (CML) at Leiden University in the Netherlands—is a well-established tool for identifying, quantifying, and evaluating the environmental burdens associated with product life cycles. To ensure a robust and comprehensive evaluation of both energy performance and environmental footprints, the study strictly adhered to the ISO 14040 and ISO 14044 standards for Life Cycle Assessment (LCA). Within this framework, the following environmental impact categories were assessed using the CML method during the apple production stage:

Abiotic Depletion (AD): refers to the consumption of non-living mineral and fossil resources utilized throughout production processes.

Acidification Potential (ACP): indicates the potential of a product to release acidifying chemical substances into the atmosphere.

Energy Ratio (ER): the ratio of output energy to input energy.

Eutrophication Potential (EUP): denotes the potential to increase the concentration of nutrient-enriching substances in water bodies.

Global Warming Potential (GWP): represents the contribution to the increase in Earth's average temperature resulting from greenhouse gas emissions.

Ozone Layer Depletion (OLD): refers to the reduction in stratospheric ozone concentration.

Human Toxicity Potential (HTP): reflects the potential of a product to cause harm to human health.

Freshwater Aquatic Ecotoxicity (FAET): indicates the potential of a product to exert toxic effects on freshwater ecosystems.

Marine Aquatic Ecotoxicity (MAET): the negative impacts of chemical substances and toxins on marine organisms.

Terrestrial Ecotoxicity (TEP): denotes soil and land contamination resulting from the release of pollutants and toxic substances.

Photochemical Oxidation (PhO): is a chemical process in which organic compounds are oxidized in the presence of sunlight.

2.2. Energy Flow Assessment in Apple Production

To model energy flow and determine consumption patterns within a given system, the energy input values must first be established. In this study, these values were determined using standard energy conversion coefficients. We tabulated the equivalent energy values of the various inputs and present the corresponding quantities, along with references from several comparable studies, in Table 1 (Khanali et al., 2020). Among the input categories in Table 1, fuel consumption for machinery operations had the highest total energy equivalent. Limited research has addressed the LCA of both apple production and storage in the West Azerbaijan region; therefore, this research is warranted to identify critical energy consumption and emission hotspots.

Table 1. The input energies and their relevant values in the production of apple products

Production stage	Items (unit)	Energy equivalent (MJ unit^{-1})	Quantity (unit ha^{-1})	Total energy equivalent (MJ ha^{-1})	Reference
Apple production on the farm and transportation to the cold store	Diesel fuel:				
	Machinery (L)	55	1.31×10^3	6.28×10^4	(Kitani, 1999)
	Irrigation (L)	47.8	1.29×10^2	6.18×10^3	(Kitani, 1999)
	Human power (hour)	1.96	1.51×10^2	2.97×10^2	(Unakitan et al., 2010)
	Chemical fertilizers (kg):				
	Nitrogen	66.14	7.40	4.90×10^3	(Ozkan et al., 2004)
	Phosphate	12.44	6.30	7.84×10^2	(Ozkan et al., 2004)
	Potassium	11.15	3.16	3.52×10^2	(Ozkan et al., 2004)
	Animal manure (kg):	0.3	5.96×10^3	1.79×10^3	(Hosseinzadeh-Bandbafha et al., 2017)
	Chemical poisons (kg):				
	Fungicide	2.16×10^2	3.24	7.00×10^3	(Erdal et al., 2007)
	Insecticide	1.012×10^2	3.22	2.25×10^3	(Erdal et al., 2007)
	Herbicide	2.38×10^2	3.73	8.88×10^2	(Erdal et al., 2007)

This study aims to monitor energy use patterns by taking into account the stages involved in apple production and storage within this region. Furthermore, the study seeks to assess the potential energy savings and environmental benefits achievable across the entire chain—from orchard production to cold storage—through modeling, analysis, and evaluation of all phases, facilitated by the capabilities of SimaPro 9.5 software.

2.3. Life Cycle Assessment of Apple Production and Storage

Life Cycle Assessment (LCA) was conducted in accordance with the four-phase

framework established by ISO 14040, which comprises: (1) Goal and Scope definition, (2) Life Cycle Inventory Analysis, (3) Life Cycle Impact Assessment, and (4) Interpretation of Results, as shown in Figure 1.

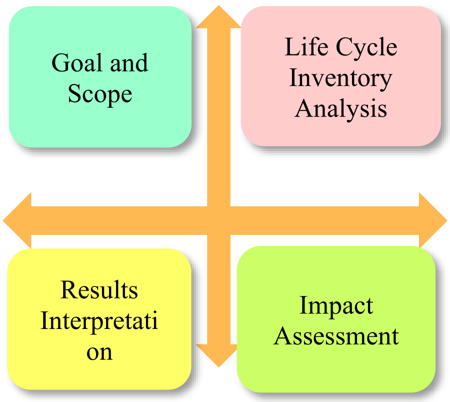

Figure 1. LCA phases

The system boundary covers all operations from orchard establishment to cold storage. Included inputs are diesel fuel for field operations and transport, NPK fertilizers, chemical pesticides, irrigation water, storage electricity, and packaging production. Excluded stages comprise machinery manufacturing and maintenance, depreciation of equipment and infrastructure, orchard construction, transport beyond storage, and packaging disposal. These exclusions were applied consistently to ensure result comparability.

The Life Cycle Inventory (LCI) was compiled from 50 field-collected questionnaires. For each farm, data were recorded on the type and quantity of all inputs, including fuel consumption (L ha^{-1}), fertilizer application rates (kg ha^{-1} for N, P_2O_5, and K_2O), pesticide usage (kg ha^{-1} of active ingredient), irrigation water (m^3 ha^{-1}), electricity consumption (kWh ton^{-1}) for storage, and packaging material (kg ton^{-1}). We converted all input quantities into equivalent energy and emission values using standard coefficients (Table 1) and IPCC emission factors (Table 2). The background data for fertilizer and pesticide production were obtained from the Ecoinvent v3.5 database. Foreground data were collected through direct interviews and farm visits.

To estimate the environmental emissions associated with chemical and organic inputs in apple orchards, we used the emission coefficients recommended by the Intergovernmental Panel on Climate Change (IPCC, 2019). These coefficients enable the conversion of applied nitrogenous and phosphate fertilizers, as well as urea, into their equivalent pollutant loads—including nitrous oxide (N_2O), ammonia (NH_3), carbon dioxide (CO_2), nitrate (NO_3), and phosphate (P_2O_5). As shown in Table 2, the coefficients are organized into three main categories: (a) direct emissions to air and water, (b) indirect emissions resulting from nitrogen deposition, and (c) direct emissions from soil and fertilizer application. These categorized coefficients subsequently served as the basis for calculating key life cycle impact assessment (LCIA) indicators, such as global warming potential, acidification potential, and eutrophication potential.

The functional unit (FU) was defined as one ton (1,000 kg) of fresh apples stored in cold storage. This FU was selected because it represents the standard commercial unit for apple marketing in the region and enables direct comparison with similar LCA studies on apple production (Goossens et al., 2017). All reported inputs and emissions were scaled to this functional unit.

Table 2. The input energies and their relevant values in the production of apple products (IPCC, 2019)

Characteristics (kg)	Coefficient	Pollutant (kg)
a) Pollutants created by chemical fertilizers and livestock:		
1- Nitrogen is used in chemical and farm fertilizers	0.01	N_2O-N (To air)
2- Nitrogen is used in chemical fertilizers	0.1	NH_3-N (To air)
3- Nitrogen is used in farm fertilizers	0.2	NH_3-N (To air)
4- Urea	0.2	CO_2-C (To air)
5- Nitrogen is used in chemical and farm fertilizers	0.3	NO_3-N (To water)
6- Phosphorus is used in chemical fertilizers	0.05	P_2O_5 (To water)
b) Indirect pollutant N_2O created by the deposition of chemical fertilizers and farm:		
1- Nitrogen is used in chemical fertilizers	0.002	N_2O-N (To air)
2- Nitrogen is used in animal manure	0.004	N_2O-N (To air)
c) Direct N_2O pollutant from fertilizers and soil	0.2	NO_x (To air)

This study aims to monitor energy use patterns by accounting for the stages involved in apple production and storage in this region. Furthermore, the study seeks to assess potential energy savings and environmental benefits across the entire chain (from orchard production to cold storage) through modeling, analysis, and evaluation of all phases, facilitated by SimaPro 9.5.

Continuing this study, Figure 2 shows the system boundaries defined for this study, including the inputs, operational processes, prevailing conditions, and storage duration of apples in cold storage. It also includes energy consumption, labor inputs, the machinery used throughout the production cycle, and, ultimately, the range of emissions produced as a result of apple production levels (Khanali et al., 2020).

To sum up, Figure 2 provides a comprehensive overview of apple production, underscoring the interconnections among operational factors and highlighting the importance of sustainable practices to mitigate both waste and environmental impacts.

3. Results and Discussion

Energy Flow Modeling in Apple Production

All numerical values reported in this section are presented as mean ± standard deviation, calculated based on the 50 individual farm-level observations. Table 3 presents energy flow modeling results for apple production systems across several countries, with total energy consumption expressed in MJ per ton. Among the countries listed, Germany exhibited the highest overall energy consumption, while France displayed the lowest range. Furthermore, as shown in Table 3, fossil fuels were the primary driver of total energy consumption during the apple production stage. The energy input per ton of apples in the present study amounted to 3.33×10^3 MJ ton^{-1}— considerably higher than those reported in comparable studies. This elevated energy consumption can be attributed to several factors, including low-efficiency machinery, excessive fuel and chemical fertilizer use, and inadequate cold storage efficiency. In addition, relatively low yields per unit area further contributed to the increased energy intensity. Consequently, efforts to improve energy performance in apple orchards—such as minimizing pesticide application and ensuring timely maintenance of tractors and implements—could substantially reduce fuel consumption.

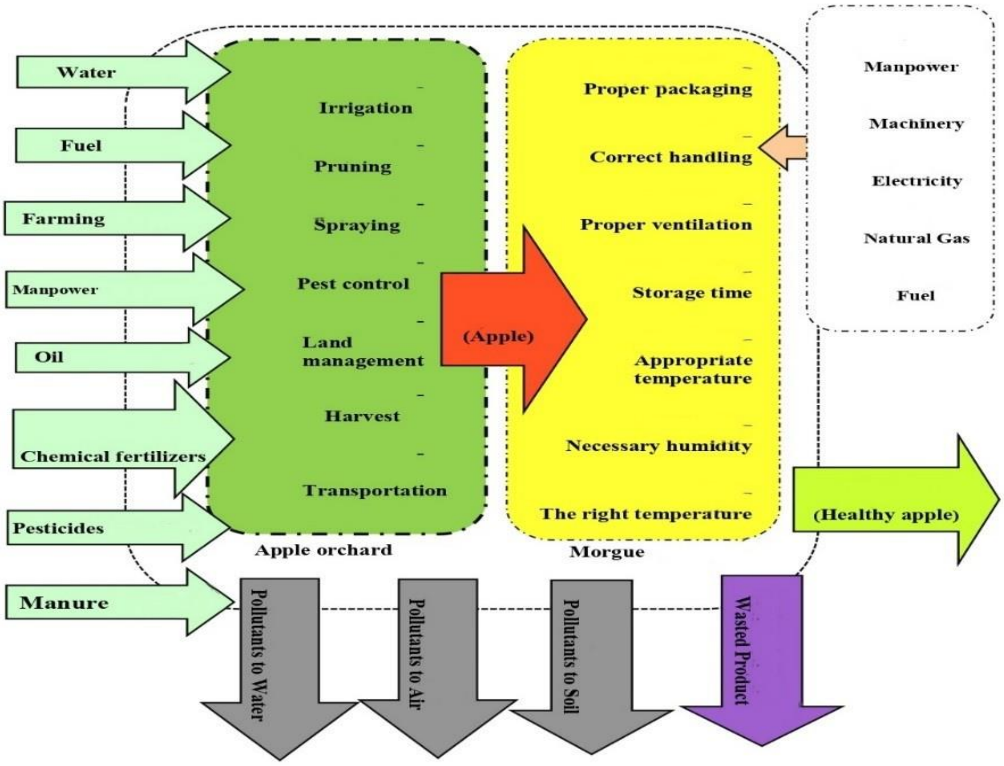

Figure 2. Boundaries of the apple production and storage system in orchard and refrigerator based on LCA

Table 3. The input energies and their relevant values in the production of apple products in several countries

Country/Region	Total energy consumption (MJ ton^{-1})	Consumptions	Reference
South America	$4 \times 10^2 – 2 \times 10^3$	Mechanization, pesticides, Machinery, Fertilizer, Herbicide.	(i Canals et al., 2007)
France	$8.8 \times 10^2 – 1.16 \times 10^3$	Mechanization, pesticides, Machinery, Fertilizer, Herbicide.	(Alaphilippe et al., 2016)
Italy	$1.54 \times 10^3 – 1.74 \times 10^3$	Fertilizer, Mowing, Irrigation, Antiparasitic treatment	(Longo et al., 2017)
New Zealand/Central Otago and Hawke's Bay	$7 \times 10^2 – 4 \times 10^3$	Mechanization, Pesticide, Machinery, Fertilizer, Herbicide.	(i Canals et al., 2006)
Greece	2.50×10^3	Fuel, Machinery, Fertilizers, Fungicides, Insecticides, Manpower	(Akdemir et al., 2012)
Turkey	1.59×10^3	Chemical fertilizer, Electricity, Chemicals, Fuel, Manpower, Machinery, Irrigation water, Farm fertilizer	(Blanke & Burdick, 2005)

The contribution of different energy sources was subsequently examined. Figure 3 presents a pie chart showing the share of each energy source in the total energy consumed for apple production. Each share of the chart represents the percentage contribution of a specific energy input. Among all the factors considered, fuel and NPK fertilizers accounted for the largest shares, at 39% and 22%, respectively, while manure contributed the smallest proportion, with only 3%.

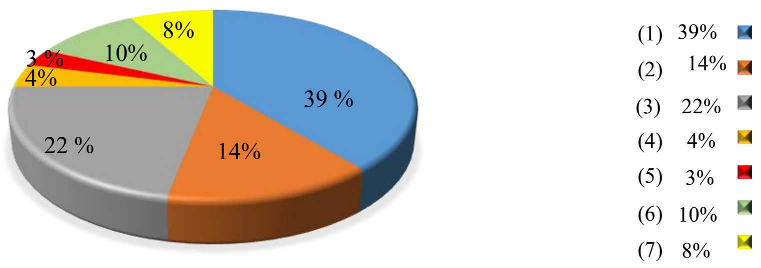

Figure 3. The share of different energy sources in the total energy used for apple production: 1) Fuel, 2) Pesticide, 3) NPK fertilizers, 4) Human force, 5) Animal manure, 6) Irrigation water, 7) Volk oil

The predominance of diesel fuel consumption (39%) in our study can be explained by several technical factors also observed in earlier work on agricultural machinery efficiency (Pishgar-Komleh et al., 2021). First, tractors in the region are on average over 15 years old—well beyond the 8- to 10-year replacement benchmark suggested by international guidelines (Kitani, 1999). Such aging equipment typically operates at lower thermal efficiency and higher specific fuel consumption (Taghavifar & Mardani, 2015a). Second, our field surveys identified frequent mismatches between tractor power and implement size, leading to excessive wheel slippage and increased draft loads. Third, the absence of a preventive maintenance program—including regular injector and air filter adjustments—results in incomplete combustion, which can increase fuel consumption by an additional 15% to 20% (Russo & Comi, 2024).

These findings suggest that straightforward engineering measures (such as timely filter replacements, proper tire pressure adjustments, and the use of GPS-based systems to reduce operational overlaps) could lower fuel consumption by up to 25% (Pishgar-Komleh et al., 2021). The substantial contributions of NPK fertilizers (22%) and chemical pesticides (14%) to environmental impacts—particularly eutrophication (4.73×10^{-7} kg $PO_{4\ eq}$) and freshwater aquatic ecotoxicity (1.37×10^{-7} kg 1/4-DB $_{eq}$)—point to the impact of chemical input use in the region. According to the IPCC (2019) report, approximately 30% to 50% of applied nitrogen is lost through surface runoff and deep leaching into groundwater, which is a primary driver of eutrophication (Le Feon et al., 2023).

Furthermore, the reliance on traditional spraying methods rather than modern boom sprayers contributes to heterogeneous application, leading to a 40% increase in pesticide usage (Alaphilippe et al., 2016). In our study region, pesticide consumption was reported to be about 30% higher than the European average, due to warmer climate conditions and higher pest pressure. Table 4 subsequently presents the contribution of apple production to various environmental impact categories, detailing the magnitude and indicators of the harmful effects associated with apple production. Each row shows a specific impact category, with its unit and corresponding value. Notably, the indicators for Human Toxicity Potential (HTP), Freshwater Aquatic Ecotoxicity (FAET), Marine Aquatic Ecotoxicity

(MAET), and Terrestrial Ecotoxicity (TEP) share a common unit of kg 1/4-DB $_{eq}$. Among these, MAET recorded the highest value, while TEP exhibited the lowest. This table encapsulates the environmental challenges posed by apple production and provides valuable information for improved planning.

Table 4. The share of apple production in different categories of impacts

Index	Abbreviation	Unit	Amount	Performance of index loss
Abiotic depletion	AD	kg Sb $_{eq}$	1.26×10^{-5}	Reduction of fossil fuels
Acidification	ACP	kg SO_2 eq	1.21×10^{-11}	Acidification of the soil
Eutrophication	EUP	kg PO_4 eq	4.73×10^{-7}	Algae formation caused by the introduction of nitrate into waters
Global warming	GWP	kg $CO_{2\ eq}$	8.72×10^{-1}	Global Warming
Ozone layer depletion	OD	kg CFC-11 $_{eq}$	2.24×10^{-7}	Ozone layer damage
Human toxicity	HTP	kg 1/4-DB $_{eq}$	1.83×10^{-1}	Human poisoning
Freshwater aquatic ecotoxicity	FAET	kg 1/4-DB $_{eq}$	1.37×10^{-7}	Freshwater aquatic poisoning
Marine aquatic ecotoxicity	MAET	kg 1/4-DB $_{eq}$	8.02×10^{-11}	Marine aquatic poisoning
Terrestrial ecotoxicity	TEP	kg 1/4-DB $_{eq}$	1.11×10^{-2}	Soil poisoning
Photochemical oxidation	PhO	kg $C_2H_{4\ eq}$	1.54×10^{-4}	Summer smoke phenomenon

Figure 4 further shows the contribution of different inputs to different impact categories during the apple production stage, as assessed using the CML methodology. In this figure, the vertical axis represents the percentage contribution, while the horizontal axis shows the impact categories associated with emissions from apple production. For the AD, HTP, FAET, and TEP categories, pesticides accounted for the largest shares, at 48%, 41%, 69%, and 49%, respectively. Furthermore, in the GW, OLD, and PhO categories, fuel was the dominant contributor, representing 47%, 31%, and 42%, respectively. In the MAET category, Volk oil was identified as the primary source, contributing 36%. For the ACP and EUP categories, NPK fertilizers accounted for the largest shares, at 49% and 54%, respectively. Overall, this figure suggests that fuel, NPK fertilizers, and pesticides account for most impacts across most environmental categories.

Table 5 summarizes the findings of several studies on the environmental impacts of apple production, with a particular concentration on global warming potential (GWP), expressed in kg CO_2 equivalent per ton. Among the compared countries, Italy recorded the highest GWP, while France showed the lowest. For our study region, the

GWP was calculated at 6.44×10^2 kg CO_2 eq/ ton, notably higher than those reported for the other countries examined. This comparison underscores that apple production and storage in our study area exert a relatively greater contribution to global warming, highlighting the urgent need for targeted mitigation measures

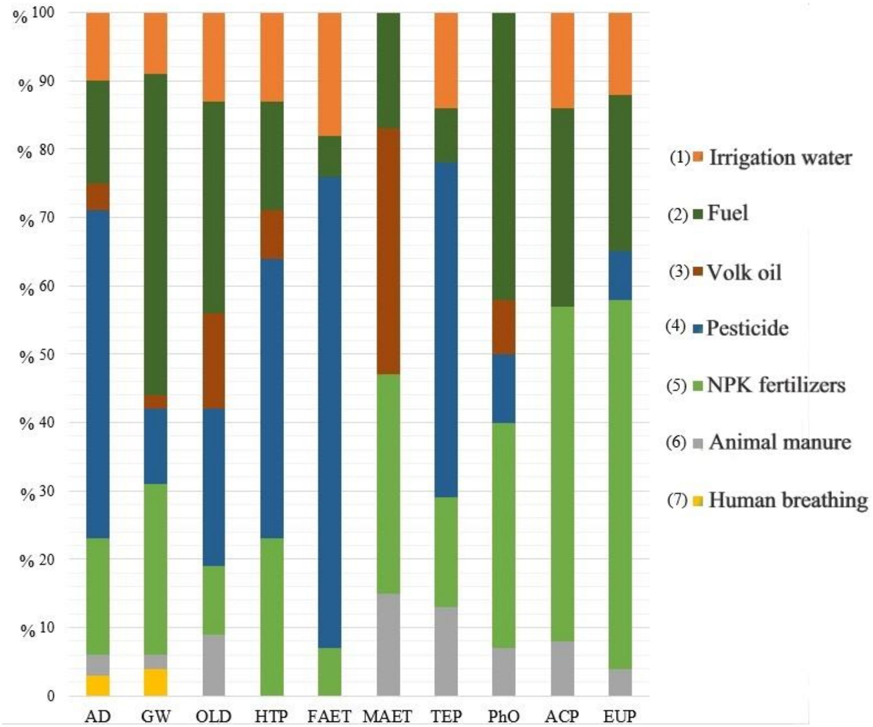

Figure 4. The ratio of different inputs in different categories of effects in the apple production stage based on CML: 1) Irrigation water, 2) Fuel, 3) Volk oil, 4) Pesticide, 5) NPK fertilizers, 6) Animal manure, 7) Human breathing

Table 5. The results of several studies on the impact of apple production on global warming

Country/Region	System border	Earth Warming (kg CO_2 eq /ton)	Reference
Belgium	From the garden to after harvest	$6.50 – 1.54 \times 10^2$	(Goossens et al., 2017)
France	From the garden to after harvest	$8.98 – 7.55 \times 10^2$	(Alaphilippe et al., 2016)
Italy	From the garden to after harvest	$2.04 \times 10^2 – 1.64 \times 10^2$	(Cerutti et al., 2013)
Spain	From the garden to after harvest	1.09×10^2	(Vinyes et al., 2017)
Iran / West Azerbaijan	From the garden to after harvest	6.44×10^2	This work

3.1. Energy Analysis in Apple Production

To validate the LCA results, we performed cross-validation using ReCiPe 2016 for a subset of impact categories, including GWP, acidification, and eutrophication. The results showed a high correlation between the two methods ($R^2 > 0.92$), confirming the consistency of our impact calculations.

Energy consumption per ton of apples in the present study was higher than in other apple production studies. This is largely attributable to the intensive use of inputs—particularly fuel, fertilizers, and pesticides—in the orchards under investigation. According to previous reports, the share of diesel fuel in apple production was 22% for Tehran Province (Rafiee et al., 2010), and 16% for Urmia City (Taghavifar & Mardani, 2015b). Additionally, irrigation water was identified as another major input in the study region, accounting for 10% of total energy consumption. Adopting appropriate spraying techniques could serve as an effective strategy to reduce the overuse of chemical pesticides (Naderi et al., 2020). The energy productivity index (EP) was calculated to be 0.32 ± 0.03 kg MJ^{-1}, indicating that 0.32 kg of apples are produced per MJ of energy input. Because larger orchards tend to have better energy ratios (ER), it is advisable to consolidate smaller orchards to improve overall ER in apple production. Overall, implementing proper management of energy resources—such as fuel, fertilizers, and pesticides—along with improved operational scheduling could be viable strategies for enhancing energy productivity.

3.2. Energy Analysis for Apple Storage

Figure 5 illustrates each input's contribution to total energy consumption during the apple storage stage. The results show that the average energy input required to store 1 ton of apples was estimated at 15,726 MJ. Under the assumptions of this study, storing 1 ton of apples in cold storage requires 100 boxes, each with a capacity of 10 kg. Considering an average box weight of 0.5 kg, the total weight of the boxes amounts to 50 kg. Given the energy required for producing each kg of box material, box manufacturing was identified as one of the primary contributors to energy consumption in post-harvest operations.

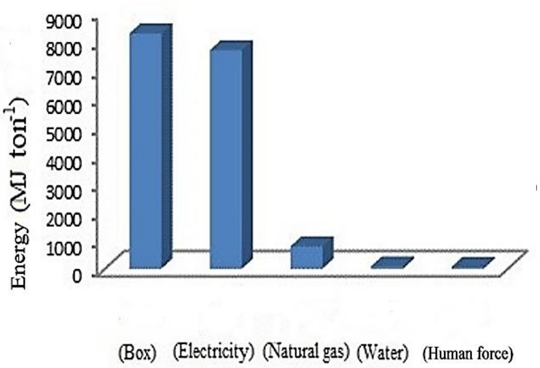

Figure 5. The share of each input to the total input energy in the apple storage stage

In the storage stage, electricity was the second-largest input after packaging boxes, with an energy input of 7.25×10^3 MJ per ton, while labor accounted for the lowest share of energy consumption. Given electricity's importance as a key input, cold storage systems should be designed to use energy more efficiently. The most effective and practical measures for apple cold storage facilities in West Azerbaijan include a combination of proper insulation, energy-efficient compressors, solar integration, and smart energy management systems.

3.3. Environmental Impact Analysis of Post-Harvest Operations

In this study, we considered direct and indirect emissions associated with various inputs for each impact category, expressed per ton of stored apples. The global warming potential (GWP) for the post-harvest stage was found to be 1.1 kg CO_2 eq/ton. Emissions from electricity production for orchard operations and box making contributed the greatest environmental burden across all impact indicators, except ozone layer depletion (OLD). To improve environmental performance at this stage, upgrading cold storage technology offers a viable pathway, and the study region has substantial potential to implement modern energy generation systems. For instance, cold storage facilities could be supplied with electricity by installing solar panels on their rooftops.

3.4. Monte Carlo uncertainty analysis

Monte Carlo simulation (1,000 iterations) showed that the coefficient of variation for the main environmental impact categories ranged from 12% to 18%, with GWP the most uncertain (CV = 18%), primarily due to farm-level diesel consumption variability. Sensitivity analysis further identified fuel use and nitrogen fertilization as the most influential parameters, together accounting for over 70% of the variation in GWP, acidification, and eutrophication. These findings underscore that improving fuel efficiency and nitrogen management could substantially reduce environmental impacts.

4. Conclusions

Fuel use, fertilizer use, and chemical inputs such as pesticides were relatively high in the apple orchards studied. The total energy input for the orchards was 1.165×10^5 MJ ton^{-1}. In this study, the energy productivity index was calculated as 0.32 ± 0.03 kg MJ^{-1}, indicating that 0.32 kg of apples are produced per MJ of energy consumed. The global warming potential (GWP) for the post-harvest stage was 1.1 kg CO_2 eq, while the average energy input required to store one ton of apples was estimated at 15,726 MJ.

Based on the observed inefficiencies, adopting high-efficiency machinery and implementing routine preventive maintenance are recommended as practical first steps. While integrating solar energy for cold storage appears promising given the observed energy demand profile, large-scale application requires prior techno-economic feasibility studies. Likewise, improving tractor-implement matching and operational scheduling could enhance fuel efficiency, though these suggestions warrant further evaluation through field experiments. Finally, interpret the findings in light of the data limitations discussed earlier.

The findings of this study, while region-specific, offer valuable lessons for other apple-producing regions in Iran and neighboring countries that share similar climatic and management characteristics. The identification of fuel, fertilizers, and pesticides as key environmental hotspots is consistent with findings from other studies suggesting that the inefficiencies observed are not unique to West Azerbaijan but may reflect broader challenges in semi-aridapple production systems.

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