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Environmental Impacts of Potato Production under Furrow and Sprinkler Irrigation: A Life Cycle Assessment in a Semi-Arid Region

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ABSTRACT

Water scarcity and increasing environmental pressures have made irrigation management a critical determinant of sustainability in semi-arid agricultural systems. This study quantitatively compared the environmental impacts of potato production under furrow and sprinkler irrigation in the Kuzaran region of Kermanshah Province, western Iran, during the 2023–2024 growing season using a life cycle assessment (LCA) framework in accordance with ISO 14040/44. The functional unit was one ton of potato, with complementary results reported per hectare. System boundaries encompassed on-farm operations from land preparation to harvest, including fertilizers, organic amendments, pesticides, irrigation water, fuel, electricity, machinery, and labor. Environmental impacts were assessed using the CML baseline method across global warming, acidification, eutrophication, abiotic depletion of fossil fuels, human toxicity, and aquatic and terrestrial ecotoxicity categories. Sprinkler irrigation consistently resulted in lower environmental impacts than furrow irrigation across all impact categories and functional units. On a product basis, global warming potential decreased from 301.87 to 186.39 kg CO_2 eq t^{-1} (38%), while abiotic depletion of fossil fuels declined from 2,909.13 to 1,683.63 MJ t^{-1}. Acidification and eutrophication potentials decreased from 6.54 to 3.95 kg SO_2 eq t^{-1} and from 3.47 to 2.14 kg PO_4^{3-} eq t^{-1}, respectively. Human toxicity declined from 44.34 to 28.72 kg 1,4-dichlorobenzene eq t^{-1}. On a per-hectare basis, global warming potential was also lower under sprinkler irrigation (8,946.89 vs. 10,112.84 kg CO_2 eq ha^{-1}). The lower environmental burdens were primarily associated with higher yield, reduced irrigation water abstraction, lower energy demand, and improved nutrient-use efficiency. These findings indicate that irrigation efficiency can simultaneously reduce water use, energy consumption, nutrient losses, and emission intensity, highlighting sprinkler irrigation as a promising strategy for improving the environmental sustainability of potato production in semi-arid regions.

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1. Introduction

The interdependence of water, energy, and food systems has been widely recognized as a central pillar of sustainable development, forming what is commonly referred to as the water–energy–food nexus (Hoff, 2011; Herrera-Franco *et al*., 2023). Rapid population growth, evolving consumption patterns, and increasing climate variability have intensified pressures on this nexus, making the secure provision of food and energy increasingly contingent upon the efficient management of finite natural resources without exacerbating environmental degradation (Dekamin *et al*., 2026b). Within this context, agriculture occupies a pivotal position, as it simultaneously represents the world's largest consumer of freshwater and the primary source of food supply (FAO, 2014). Declining water availability and deteriorating water quality therefore pose serious risks not only to agricultural productivity, but also to food security, public health, and ecosystem integrity, underscoring the necessity of improving water-use efficiency as a foundation for sustainable agricultural development (Bizikova *et al*., 2013). Globally, irrigation dominates freshwater withdrawals, accounting for approximately 70% of total water use, while supporting nearly 40% of food production on just

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over one-fifth of cultivated land (Zhao *et al*., 2025; Perry *et al*., 2017; Gruère and Shigemitsu, 2021). At the same time, agriculture has emerged as a major energy-consuming sector, responsible for roughly 30% of global energy demand, with consumption rising by more than 20% between 2000 and 2018 (IRENA and FAO, 2021). Emissions associated with agricultural production have been estimated at 1.89 kg CO_2 per unit of economic output and 1.63 t CO_2 per hectare of agricultural land (FAOSTAT, 2024). Recent estimates suggest that irrigated agriculture alone consumes about 1,896 petajoules of energy annually and emits approximately 216 million tons of CO_2, corresponding to around 15% of total energy use and greenhouse gas emissions within agricultural operations (Qin *et al*., 2024). Notably, groundwater-based irrigation, despite supplying only 40% of irrigated areas, accounts for nearly 90% of both irrigation-related energy consumption and CO_2 emissions, highlighting the disproportionate environmental burden associated with pumping activities. Consistent with this, Cheng et al. (2013) demonstrated that each additional meter of pumping head increases greenhouse gas emissions by nearly 2%.

Progress toward key Sustainable Development Goals, including poverty alleviation (SDG 1) and zero hunger (SDG 2), particularly in developing and least developed countries, depends on policies and technologies capable of reconciling food production with water and energy constraints (Flammini *et al*., 2014; Ouassissou *et al*., 2022). Widespread water scarcity has accelerated the adoption of pressurized irrigation technologies, which have become a defining feature of agricultural water management in recent decades (Grafton *et al*., 2018). However, their diffusion remains uneven: the proportion of irrigated land equipped with pressurized systems reaches 38.4% in developed countries and 61.3% in developing regions, while remaining negligible in least developed countries (ICID, 2023). Although such systems often improve water productivity (Garcia-Prats and Guillem-Pico, 2016; Nikolaou *et al*., 2020), evidence suggests that they may also trigger unintended outcomes, including intensified groundwater abstraction and soil salinization (Ahmadzadeh *et al*., 2016; Perry *et al*., 2017; Birkenholtz, 2017). Empirical findings from North America indicate that drip irrigation can paradoxically increase total water consumption by enabling crop intensification, thereby accelerating groundwater depletion (Ward and Pulido-Velazquez, 2008).

Irrigation modernization is therefore inseparable from rising energy requirements (Tarjuelo *et al*., 2015). Recent United Nations assessments highlight irrigation-related energy demand and associated emissions as significant barriers to achieving climate and energy targets under SDGs 7 and 13 (UN, 2023). For instance, large-scale irrigation modernization in Spain resulted in a 70% increase in energy consumption (Tarjuelo *et al*., 2015). Similarly, the transition from surface to pressurized irrigation in southern Australia achieved water savings of 10–66%, but led to substantial increases in energy use—up to 163% in surface-water systems—while yielding mixed outcomes in groundwater-dependent areas (Jackson *et al*., 2010). Overall, irrigation pumping alone accounts for 23–48% of total agricultural energy use (Kaab *et al*., 2024), indicating considerable potential for energy savings through targeted improvements in irrigation system design and management (Brown and Elliot, 2005).

Potato (*Solanum tuberosum* L.) is a globally important staple crop due to its high yield potential, short growing cycle, and significant contribution to food security. The total area under potato cultivation across cold, warm, and temperate regions of Iran ranges from 150,000 to 160,000 ha, producing approximately 5.2 million t of potato annually. Kermanshah Province, with about 6,000 ha under cultivation, accounts for an annual production of approximately 280,000 t of potato. In semi-arid regions, potato production is highly dependent on irrigation, making it particularly sensitive to water availability and energy inputs. In Iran, potato cultivation plays a strategic role in agricultural production; however, it is commonly associated with intensive water use, high energy demand for irrigation pumping, and substantial reliance on external inputs.

Potato is among the principal crops cultivated in Kuzaran and constitutes an important component of both household food security and regional agricultural markets. Its high economic value, nutritional relevance, and sensitivity to irrigation management make it particularly appropriate for assessing the implications of different irrigation technologies. In the region, two irrigation methods are predominantly employed.

Traditional furrow irrigation remains widespread due to its relatively low capital requirements and familiarity among farmers, whereas sprinkler irrigation has been gradually adopted as an alternative technology, promoted for its potential to enhance water-use efficiency and improve irrigation control under water-limited conditions.

Consequently, the sustainability of potato production systems is strongly influenced by the choice of irrigation method. Furrow irrigation remains widely practiced because of its low investment costs and operational simplicity, despite its relatively low water-use efficiency and higher potential for nutrient losses. In contrast, sprinkler irrigation systems are increasingly adopted to improve water distribution and crop productivity. Nevertheless, these pressurized systems often require greater energy inputs, which may offset water-related benefits through increased energy consumption and associated emissions. This trade-off highlights the need for integrated assessments that simultaneously address water, energy, and environmental dimensions (Dekamin *et al*., 2026a).

Life cycle assessment (LCA) provides a comprehensive framework for evaluating environmental impacts across multiple categories by accounting for both direct on-farm emissions and indirect upstream processes (ISO, 2006). While LCA has been applied to various agricultural systems, comparative assessments of potato production under contrasting irrigation methods remain limited, particularly in semi-arid contexts (Keshavarz Afshar and Dekamin, 2022). Moreover, many existing studies focus on single functional units, typically area-based metrics, which may obscure yield-related differences when environmental impacts are expressed per unit of product.

Despite the growing body of literature applying life cycle assessment to irrigated cropping systems, limited attention has been given to the role of yield differentials induced by irrigation technologies in shaping environmental impact intensities. Most existing studies rely on a single functional unit, often area-based, which may obscure important trade-offs between productivity and environmental performance. This study addresses this gap by explicitly comparing furrow and sprinkler irrigation systems using both yield-scaled (per ton of product) and area-scaled (per hectare) functional units. By doing so, it provides new insights into how irrigation efficiency, yield response, and input intensity interact to influence climate, resource depletion, and pollution-related impacts in semi-arid potato production systems. Therefore, this study applies an LCA approach to compare the environmental performance of potato production under furrow and sprinkler irrigation systems in a semi-arid region of Iran. The specific objectives are to quantify key environmental impact categories for each system, to assess differences in impact intensities on both a per-hectare and per-ton basis, and to identify major environmental hotspots within the production systems. By addressing these gaps, the study aims to provide robust evidence to support more sustainable irrigation management and resource-efficient potato production.

2. Materials and methods

2.1. Study area and crop characteristics

The research was carried out in the Kuzaran region of Kermanshah Province, situated in western Iran, an area representative of semi-arid agricultural systems during the 2023–2024 growing season (Fig. 1). The geographical coordinates of Kuzaran extend from 34°43′ to 34°27′ north latitude of the Equator and from 49°36′ to 55°31′ east longitude of the Greenwich meridian. The climate is typified by pronounced seasonal variability, with hot and dry summers, cold winters, and limited annual precipitation that rarely exceeds 450 mm. Rainfall is largely concentrated in late autumn and winter months, resulting in insufficient moisture availability during the main cropping season. The mean annual temperature is close to 14°C; however, considerable intra-annual fluctuations impose additional constraints on crop growth. Under such climatic conditions, agricultural production is highly dependent on supplemental irrigation to achieve stable yields.

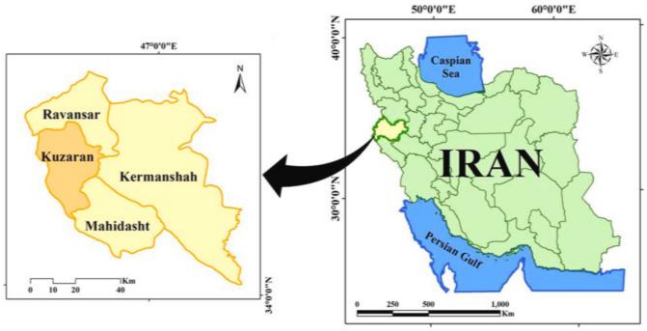


Figure 1. Study area

Soils in the study area are predominantly classified as loam to clay loam. While these soils generally exhibit moderate fertility levels, their effective water-holding capacity is restricted, increasing the vulnerability of crops to moisture stress (Table 1). Consequently, irrigation scheduling and system performance play a decisive role in determining both yield outcomes and resource-use efficiency. These agro-climatic and edaphic conditions provide a suitable context for evaluating irrigation-related resource flows and environmental pressures, while also allowing the findings to be extrapolated to other semi-arid regions experiencing water scarcity and efficiency challenges.

Table 1. Physical and chemical properties of soil samples

Lab No.	Depth (cm)	Soil class	Clay (%)	Silt (%)	Sand (%)	Bulk density (g cm^{-3})	PWP (%)	FC (%)	Infiltration rate (cm h^{-1})	Total neutralizing value (TNV, %)	pH (Saturated paste)	EC $\times 10^{-3}$ (dS m^{-1})
1	0–30	Si-C	52.4	45.0	2.6	1.30	18.0	35.0	1.0	11.2	8.04	1.13
2	30–60	Si-C	50.4	45.0	4.6	1.30	18.0	35.0	—	11.0	7.99	1.79
3	60–90	C	52.4	40.0	7.6	1.30	18.0	35.0	—	15.5	8.10	1.82

2.2. Sampling strategy and data acquisition

Empirical data were collected during two consecutive growing seasons (2022–2023) using an integrated approach that combined structured questionnaires, face-to-face interviews with farmers, and field observations. This triangulated framework ensured the reliable collection of both quantitative input–output data and qualitative information on farm management practices. The questionnaire was developed based on established theoretical foundations and previous LCA studies in agricultural systems. It was designed to gather detailed data on material and energy inputs, labor, machinery use, irrigation practices, and related costs. Quantitative inputs included seeds, fertilizers, pesticides, water, electricity, fuel, and labor, while qualitative sections addressed management decisions affecting resource-use efficiency. This design enabled the systematic identification of physical flows and their corresponding economic values required for LCA-based evaluation. Representative farms were selected using a stratified random sampling method. Villages with substantial potato cultivation were identified, and farms were categorized according to irrigation system (furrow or sprinkler). A total of 50 farms were randomly selected from both categories to capture variations in irrigation practices and their implications for resource consumption and efficiency. Face-to-face interviews were conducted to clarify questionnaire responses and improve data accuracy, particularly for key operations such as irrigation scheduling, machinery use, and labor allocation. Field observations were simultaneously used to verify farmer-reported information and reduce potential reporting bias.

Official statistics and technical guidelines from the Ministry of Agriculture Jihad were used to validate farm-level data, including yield levels, input application rates, and irrigation schedules (https://dpe.maj.ir). The integration of survey data, interviews, observations, and official records resulted in a robust dataset capturing both physical resource flows and their economic dimensions. The data collection process was aligned with MFCA principles by explicitly identifying productive outputs and resource losses, such as water inefficiencies, nutrient losses, energy use for pumping, and labor misallocation. This approach enabled cost attribution to both useful and wasted resources, providing a sound empirical basis for assessing resource-use efficiency and sustainability of potato production under contrasting irrigation systems in semi-arid regions.

2.3. Methodology

The life cycle assessment (LCA) approach was applied to examine the environmental impacts associated with potato production in the Kuzaran region of Kermanshah Province, as this method has been widely and successfully employed in agricultural sustainability studies for many years. According to the ISO standards (ISO, 2006), a conventional LCA framework is structured around four main stages: definition of the goal and scope, life cycle inventory analysis, life cycle impact assessment, and interpretation of results.

2.3.1. Goal and scope definition

This study aimed to assess and compare the environmental impacts of potato production in the

Kuzaran region of Kermanshah Province under two contrasting irrigation systems, namely furrow and sprinkler irrigation. Within the LCA framework, the functional unit (FU) defines the quantified function of the system and provides a common reference for normalizing all input and output flows. In this study, the FU was specified as the production of 1 t of potato per hectare per year. The system boundaries were defined to cover the potato production process from on-farm cultivation activities to the harvest stage. Accordingly, the assessment included the consumption of agricultural inputs, energy, and labor associated with major field operations such as land preparation, planting, irrigation, fertilization, pest management, and electricity use under both irrigation systems. All material, energy, and labor flows occurring during the potato growing period were considered, while post-harvest processes, including storage, transportation, distribution, and marketing, were excluded. A flow diagram illustrating the system boundaries and key processes for the two irrigation systems is presented in Fig. 2.

The system boundaries in this study encompassed the complete on-farm production system of potato cultivation under furrow and sprinkler irrigation practices. The defined boundaries included both foreground and background processes. Background processes comprised the extraction of raw materials, the production of fertilizers, electricity and fuel, and their transportation to the farm gate. Due to the unavailability of detailed and region-specific inventory data in Iran, background data were obtained from the Ecoinvent database (version 3.1). Foreground processes consisted of all field-level operations and the associated emissions to soil, water, and air arising from agricultural activities. The main on-farm operations included land preparation, planting, weed management, fertilizer application (including both organic amendments and mineral fertilizers), irrigation, and harvesting. Crop residues were incorporated back into the soil through tillage practices, which is a common management strategy in the region. This practice contributes to nutrient recycling, enhances soil organic matter content, and reduces the risk of soil erosion. Post-harvest stages, including processing, transportation beyond the farm gate, and final use of the potato product, were not considered within the system boundaries.

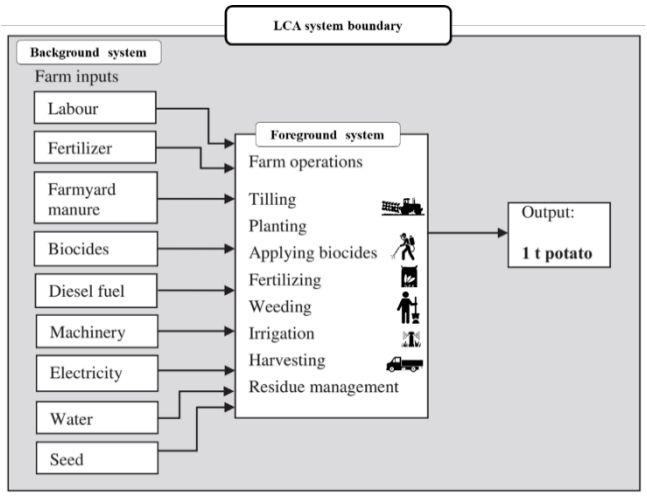


Figure 2. System boundary

2.3.2. Inventory analysis

Data on the quantities of inputs used in potato production were obtained primarily through farm-level surveys conducted among potato growers in the Kuzaran region, supplemented by regional agricultural statistics. The collected data, together with their corresponding sources and underlying assumptions, are summarized in Table 1. Wherever feasible, average values were calculated as area-weighted means, such that input data contributing to the averages were weighted according to the relative extent of potato cultivation under each irrigation system. In cases where area-weighted calculations were not possible, the most reliable available estimates of regional farming practices were adopted. Information related to background processes, including the production of fertilizers and pesticides, fuel and electricity generation, transportation activities, and machinery operation, was mainly derived from established life cycle inventory databases and relevant literature sources. Inventory data for the manufacture of agricultural machinery and irrigation equipment were sourced from internationally recognized databases such as ecoinvent. Emissions arising from potato fields, including nitrogen- and phosphorus-related emissions as well as pesticide losses, were estimated based on published field measurements and modeling studies applicable to semi-arid cropping systems and are reported in Table 2. These on-field emissions exhibit substantial variability due to the complex interactions among soil properties, crop characteristics, irrigation practices, and local climatic conditions. For nitrogen-related emissions, regional differences in processes such as denitrification and nitrate leaching were

considered, allowing the application of differentiated emission factors where sufficient information was available. In contrast, for other emissions, including phosphorus losses, pesticide runoff, and ammonia volatilization, limited regional data necessitated the use of average emission factors across all scenarios. Reliable estimates for certain loss pathways, particularly nitrogen losses via surface runoff, were not available for the study area, representing a recognized limitation of the field emission assessment.

Table 2. Coefficients used in calculating the emissions from fertilizers (IPCC, 2006).

Characteristics		Coefficient
Emissions from fertilizers	$\frac{kg\ NO-N}{kg\ N_{in}\ chemical\ fertilizer\ applied}$	0.012 (to air)
	$\frac{kg\ NO_3^- - N}{kg\ N_{in}\ chemical\ fertilizer\ applied}$	0.3 (to water)
	$\frac{kg\ CO_2 - C}{kg\ Urea - N}$	1.57 (to air)
Conversion of emissions	$kg\ CO_2 - C$ to kg CO_2	$\frac{44}{12}$
	$kg\ N_2O - N$ to kg N_2O	$\frac{44}{28}$
	$kg\ NH_3 - N$ to kg NH_3	$\frac{14}{17}$
	$kg\ NO_3 - N$ to kg NO_3	$\frac{14}{62}$
	$kg\ P_2O_5$ to kg P	$\frac{62}{142}$
	$kg\ N$ to kg NO_2	$\frac{46}{14}$

In this study, non-yield-related outputs of potato production that generate additional environmental and economic pressures were quantified using a life cycle assessment (LCA) approach. These impacts mainly result from on-farm emissions linked to the use of fertilizers, pesticides, fuel, and labor. To ensure methodological rigor, emission factors were adopted from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006) and complemented by crop-specific and regional studies (Mousavi-Avval *et al*., 2017; Dijkman *et al*., 2012; Keshavarz Afshar and Dekamin, 2022). These coefficients convert applied inputs into emission equivalents, allowing the assessment of inefficiencies in both physical and environmental terms.

For fertilizers, nitrogen (N) and phosphorus (P) compounds were the main focus due to their prevalent use in potato cultivation and their significant contribution to environmental emissions. Following IPCC (2006), 1% of applied nitrogen was assumed to be emitted as nitrous oxide (N_2O), 10% as ammonia (NH_3), and 0.3% as nitrate (NO_3^-) leaching. Atmospheric deposition of N_2 was also considered with a conversion factor of 0.001 per unit of nitrogen applied. Since no default IPCC emission factor exists for phosphorus, the P-loss factor was derived from agricultural life cycle inventory datasets (Nemecek and Kägi, 2007), ensuring that nutrient losses were fully represented in the environmental impact assessment. To allow comparison across different pollutants, emissions were standardized using molecular weight ratios, following IPCC guidelines. Carbon emissions were converted to CO_2 using 44/12, N_2O using 44/28, NH_3 using 17/14, NO_3^- using 62/14, and phosphate emissions to P_2O_5 using 164/62. This standardization ensures consistency in units and facilitates integration of emissions into the overall LCA framework.

Labor-related emissions were also accounted for, reflecting the energy consumed through human metabolic processes. A coefficient of 0.7 kg CO_2 per man-hour (Mousavi-Avval *et al*., 2017) was applied. Although smaller than emissions from fuel or fertilizers, including labor, it ensures completeness in environmental accounting. Pesticides and biocides were considered an additional source of environmental losses. Emissions were calculated based on PestLCI 2.0 and related studies, with contributions partitioned to air and water (Dijkman *et al*., 2012). It was assumed that 85% of the active ingredient not absorbed by the crop remains in the soil (Margni *et al*., 2002), reflecting persistence and ecological risk. The calculation procedure involved four steps: (i) quantifying the amount of each input applied per hectare, (ii) multiplying these amounts by the corresponding emission coefficients to estimate environmental losses, (iii) converting emissions to standardized units using molecular weight ratios, and (iv) integrating these emissions into the LCA framework to assess their overall environmental impact. This approach allows the hidden environmental costs of potato production to be explicitly quantified, such as nitrogen leaching or fuel inefficiencies, providing a transparent evaluation of resource-use inefficiencies. By applying these emission-based calculations within the LCA methodology, the study offers a comprehensive assessment of environmental losses associated with potato cultivation under furrow and sprinkler irrigation, highlighting key sources of inefficiency and opportunities for improving sustainability (Table 2).

An inventory analysis was conducted to systematically evaluate the material and energy flows associated with potato production under furrow and sprinkler irrigation systems (Table 3).

Table 3. Input-outputs for potato production under sprinkler and furrow irrigation systems, expressed per hectare

Potato			Sprinkler	Furrow
Inputs	Human labor	h	156	210
	Agricultural machinery	kg	60	100
	Nitrogen	kg	300	350
	Phosphate	kg	217	400
	Potassium	kg	183	300
	Poultry manure	kg	8000	10000
	Pesticides	kg	7	7
	Herbicide	kg	9.3	10
	Fungicides	kg	6.5	7
	Irrigation water	m^3	9110	13587
	Electricity	kWh	2351	2034
	Diesel fuel	kg	150	200
	Seed	kg	2200	2200
Positive Output	Yield	kg	40000	27500
Negative Inputs	NH_3 by poultry manure to air (N)	kg	113.9	169.8
	Irrigation water loss	m^3	3644	8152.2
	NH_3 from chemical fertilizers to air	kg	97.8	114.1
	N_2O to air	kg	3.8	4.4
	Nitrate to water	kg	7.5	8.8
	Phosphate to water	kg	4.8	6.1
	Emissions by biocides to air	kg	4.7	5
	Emissions by biocides to water	kg	3.3	3.5
	Emissions by biocides to soil	kg	3.25	3.5

2.3.3. Environmental impact categories

In this study, the life cycle impact assessment was performed using the CML approach developed by the Institute of Environmental Sciences at Leiden University. This method was selected due to its transparent structure, scientific robustness, and wide international acceptance in agricultural LCA studies (Bruijn *et al*., 2002). The selection of impact categories was guided by the study objectives, the defined system boundaries, and the key environmental concerns associated with irrigated potato production systems, in accordance with ISO standards (ISO, 2006). The life cycle impacts related to potato cultivation under furrow and sprinkler irrigation were calculated and characterized using the CML 2 Baseline 2000 method. The impact categories considered in the analysis included eutrophication potential, acidification potential, global warming potential, Human toxicity, Fresh water aquatic eco toxicity, and Abiotic depletion (fossil fuels). The inclusion of these categories allows for a more comprehensive comparison of the environmental performance of furrow and sprinkler irrigation systems, particularly in the context of water scarcity and land resource management in semi-arid regions. The LCA was performed using SimaPro software (version 9.2) as the computational platform. Following the definition of the study objectives and system boundaries, the life cycle inventory (LCI) was developed and implemented within the LCA framework. This stage involved a systematic process comprising data compilation, numerical processing, and allocation of flows among the defined system units. Both quantitative and qualitative information related to each process included within the system boundary were documented and incorporated into the model. Depending on data availability, inventory inputs were obtained through direct measurement, secondary calculations, or informed estimations, consistent with established LCA practice (Renaud-Gentié *et al*., 2015).

3. Results and discussion

3.1. LCA results and interpretation

In this study, the analysis focused on the classification and characterization phases of the life cycle assessment, following the ISO 14040/44 guidelines (ISO, 2006). The results presented here provide a comparative evaluation of the environmental impacts, land use, and water requirements associated with potato production under furrow and sprinkler irrigation systems. This section highlights the

quantified differences between the two irrigation strategies, offering insights into their relative performance in terms of resource efficiency and environmental sustainability in the semi-arid context of the Kuzaran region.

Table 4 presents a consolidated overview of the life cycle impact assessment results for potato production under sprinkler and furrow irrigation systems, expressed both per hectare and per ton of product. This table provides a holistic comparison of the two irrigation strategies across all evaluated environmental impact categories before disaggregating the results by individual impact pathways. A consistent pattern emerges from the aggregated results: sprinkler irrigation exhibits lower environmental burdens than furrow irrigation in all impact categories, regardless of whether impacts are expressed on an area-based or product-based functional unit.

Differences between the two systems become more evident when environmental impacts are expressed per ton of potato produced. This pattern reflects the combined effects of lower input use and higher yields under sprinkler irrigation. Across impact categories, including global warming potential, fossil fuel depletion, acidification, eutrophication, and toxicity-related indicators, furrow irrigation consistently exhibits higher impact intensities per unit of output. On a per-hectare basis, the magnitude of differences between systems is generally smaller but remains consistently in favor of sprinkler irrigation, indicating that efficiency gains are not limited to yield normalization alone. Overall, Table 4 highlights that irrigation system choice exerts a broad and systematic influence on environmental performance, affecting climate-related impacts, resource depletion, and ecological and human health indicators simultaneously. This aggregated comparison provides the contextual foundation for the subsequent sections, in which each impact category is examined in detail to elucidate the underlying drivers of these observed differences.

Table 4. Life cycle impact category results for potato production under sprinkler and furrow irrigation systems. All impact categories were calculated using the CML baseline method.

Impact category	Unit	Sprinkler 1 ton	Furrow 1 ton	Sprinkler 1 ha	Furrow 1 ha
Abiotic depletion (fossil fuels)	MJ	1683.63	2909.13	80814.56	97456.01
Global warming (GWP100a)	kg CO_2 eq	186.39	301.87	8946.89	10112.84
Human toxicity	kg 1,4-DB eq	28.72	44.34	1378.62	1485.56
Fresh water aquatic ecotox.	kg 1,4-DB eq	4311.89	6189.45	206970.90	207346.68
Marine aquatic Eco toxicity	kg 1,4-DB eq	57152.06	93975.68	2743299.20	3148185.48
Terrestrial Eco toxicity	kg 1,4-DB eq	337.03	483.47	16177.91	16196.56
Acidification	kg SO_2 eq	3.95	6.54	189.60	219.11
Eutrophication	kg PO_4^{---} eq	2.14	3.47	102.79	116.31

3.2. Global warming potential

The global warming potential (GWP), expressed as kg CO_2-equivalent per functional unit (1 ha potato), is illustrated in Fig. 3 for both furrow and sprinkler irrigation systems. A clear distinction between the two irrigation methods is observed, with the sprinkler irrigation system exhibiting a consistently lower GWP compared to the furrow system under both normalization approaches. On a per-hectare basis, total GWP amounts to 8946.9 kg CO_2 eq for sprinkler irrigation compared with 10112.8 kg CO_2 eq for furrow irrigation. When normalized per ton of potato, this difference becomes more pronounced, with values of 186.4 and 301.9 kg CO_2 eq t^{-1}, respectively.

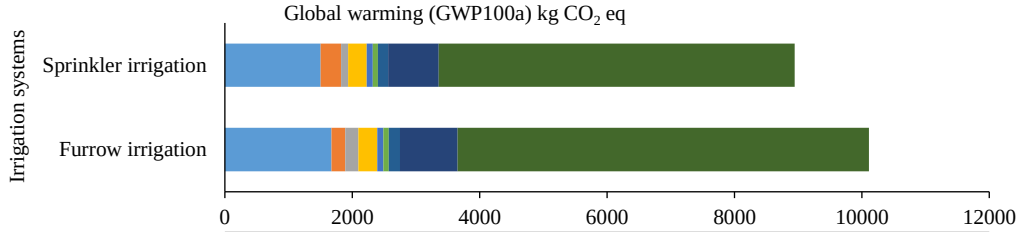
This difference is primarily attributable to substantial variations in yield, water use, and energy-related inputs between the two systems. As shown in Table 3, the average yield under sprinkler irrigation reaches 40,000 kg ha^{-1}, whereas furrow irrigation produces only 27,500 kg ha^{-1}. When emissions are normalized per ton of potato, the higher productivity of the sprinkler system effectively dilutes greenhouse gas emissions, resulting in a markedly lower GWP per unit of product.

From an inventory perspective, furrow irrigation requires considerably higher inputs of diesel fuel (200 kg ha^{-1} compared with 150 kg ha^{-1}), irrigation water (13,587 m^3 ha^{-1} compared with 9,110 m^3 ha^{-1}), nitrogen fertilizers (350 vs. 300 kg ha^{-1}), phosphate fertilizers (400 vs. 217 kg ha^{-1}), and poultry manure (10,000 vs. 8,000 kg ha^{-1}). These higher input levels directly translate into increased CO_2, N_2O, and NH_3 emissions, which collectively drive the elevated GWP observed for the furrow irrigation system.

Electricity consumption associated with water pumping represents a dominant contributor to GWP in

both systems, particularly given Iran's strong dependence on natural gas–based electricity generation. However, the substantially lower irrigation water requirement and reduced water losses under sprinkler irrigation (3,644 m^3 ha^{-1} versus 8,152 m^3 ha^{-1} in furrow irrigation) significantly reduce electricity demand and associated indirect emissions. In addition, lower nitrogen-related emissions under sprinkler irrigation, including N_2O emissions to air (3.8 kg ha^{-1} compared with 4.4 kg ha^{-1}) and nitrate leaching to water (7.5 vs. 8.8 kg ha^{-1}), further contribute to its superior climate performance. A broad examination of research addressing energy consumption, economic performance, and environmental burdens in agricultural production systems consistently identifies electricity use as a dominant contributor to overall impacts. Across diverse cropping systems and analytical frameworks, electricity emerges as a critical hotspot influencing both environmental pressure and production efficiency, largely due to its role in irrigation, mechanization, and upstream energy supply chains (Mohammadi *et al*., 2015; Doukkali and Lejarsab, 2015; Ghasemi-Mobtaker *et al*., 2020; Canaj and Mehmeti, 2022; Esfehani, 2022; Kaab *et al*., 2024).

Overall, the results demonstrate that sprinkler irrigation achieves a lower GWP than furrow irrigation both per hectare and per ton of potato produced. This finding underscores the importance of irrigation efficiency and yield enhancement as key leverage points for mitigating climate change impacts in irrigated potato production systems under semi-arid conditions.



	Furrow irrigation	Sprinkler irrigation
On- farm emissions	1671.5	1501.31
Urea, as 100% CO(NH2)2 (NPK 46.6-0-0)	217.56	324.12
Triple superphosphate	205.96	111.74
Potatoes, start material, at seed production	297.45	289.83
Insecticide, at plant	93.98	93.99
Fungicide, at plant	85.62	79.51
Herbicide, at plant	176.42	164.07
Insecticide emissions, at farm	0	0
Fungicide emissions, at farm	0	0
Herbicide emissions, at farm	0	0
Energy, from diesel burned in machinery	904.4623	791.38
Electricity, high voltage	6459.838	5590.93

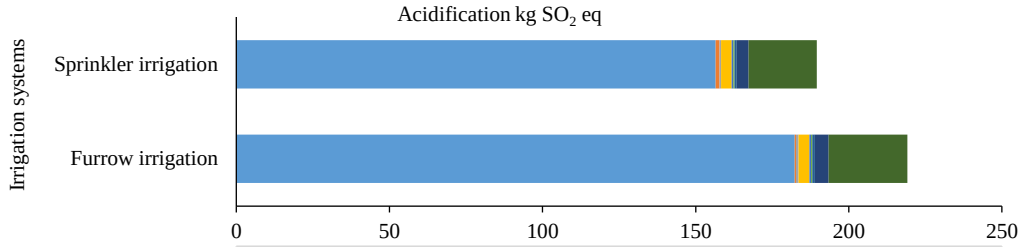
Figure 3. Global warming potential of furrow and sprinkler irrigation systems

3.3. Acidification potential

The acidification potential (AP), expressed as kg SO_2-equivalent, is presented in Fig. 4 for both irrigation systems. Acidification impacts are notably higher under furrow irrigation, reflecting its greater reliance on nitrogen-based inputs and higher on-farm emissions to the atmosphere. Acidification potential (AP), expressed as kg SO_2-equivalent, follows a pattern similar to that observed for GWP. Total acidification amounts to 189.6 kg SO_2 eq ha^{-1} under sprinkler irrigation and 219.1 kg SO_2 eq ha^{-1} under furrow irrigation, corresponding to 3.95 and 6.54 kg SO_2 eq t^{-1} of potato, respectively.

According to Table 3, ammonia emissions originating from poultry manure application reach 169.8 kg ha^{-1} under furrow irrigation, compared with 113.9 kg ha^{-1} under sprinkler irrigation. Similarly, ammonia emissions from chemical fertilizers are higher in the furrow system (114.1 kg ha^{-1}) than in the sprinkler system (97.8 kg ha^{-1}). These emissions play a decisive role in acidification processes through atmospheric deposition of nitrogen compounds.

In addition to fertilizer-related emissions, higher diesel fuel consumption and more intensive machinery use under furrow irrigation amplify emissions of nitrogen oxides (NO_x) and sulfur dioxide (SO_2), further increasing the acidification burden. When normalized per ton of potato, the lower yield of the furrow system intensifies these impacts, whereas the higher productivity of sprinkler irrigation reduces acidification potential per unit of output. The results clearly indicate that sprinkler irrigation offers a more environmentally favorable profile in terms of acidification potential, mainly due to reduced nitrogen losses, lower fossil fuel consumption, and improved yield efficiency.



	Furrow irrigation	Sprinkler irrigation
On- farm emissions	182.4	156.48
Urea, as 100% CO(NH2)2 (NPK 46.6-0-0)	0.359162	1.346
Triple superphosphate	0.813166	0.441
Potatoes, start material, at seed production	3.573851	3.482
Insecticide, at plant	0.508851	0.509
Fungicide, at plant	0.447196	0.415
Herbicide, at plant	0.857514	0.797
Insecticide emissions, at farm	0	0
Fungicide emissions, at farm	0	0
Herbicide emissions, at farm	0	0
Energy, from diesel burned in machinery	4.425892	3.873
Electricity, high voltage	25.72675	22.266

Figure 4. Acidification potential of furrow and sprinkler irrigation systems

3.4. Abiotic depletion potential

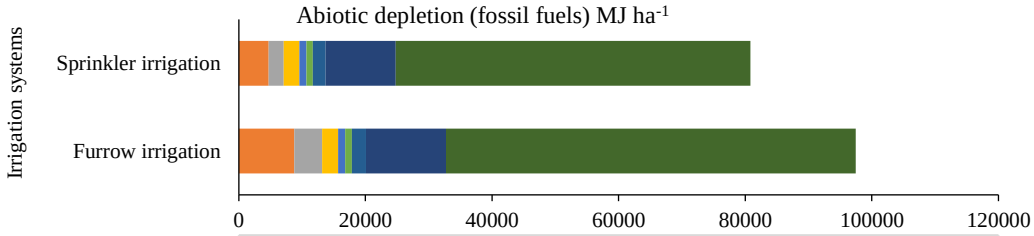
The furrow irrigation system exhibits a substantially higher ADP than the sprinkler system, primarily driven by increased use of mineral fertilizers, fossil fuels, and electricity. Abiotic depletion potential (ADP), expressed in MJ of fossil energy, indicates a substantial difference between the two irrigation systems. Total fossil energy depletion reaches 97,456 MJ ha^{-1} under furrow irrigation, compared with 80,815 MJ ha^{-1} under sprinkler irrigation. On a product basis, the corresponding values are 2,909 and 1,684 MJ t^{-1} of potato, respectively. Phosphate and potassium fertilizer application rates under furrow irrigation (400 and 300 kg ha^{-1}, respectively) are almost double those under sprinkler irrigation (217 and 183 kg ha^{-1}) (Fig. 5). Since these fertilizers rely on finite mineral resources, their intensive use significantly elevates abiotic depletion impacts. Furthermore, higher diesel fuel consumption and electricity demand associated with excessive water pumping under furrow irrigation exacerbate fossil fuel depletion. In contrast, the sprinkler irrigation system demonstrates lower abiotic resource consumption due to more efficient water use, reduced energy demand, and lower fertilizer inputs. When expressed per ton of potato, the disparity becomes even more pronounced, highlighting the critical role of yield improvement and input optimization in reducing pressure on non-renewable resources.

3.5. Human toxicity

Human toxicity potential, expressed as 1,4-dichlorobenzene equivalents, is illustrated in Fig. 6. Human toxicity potential, expressed as kg 1,4-dichlorobenzene (1,4-DB) equivalents, is consistently higher for furrow irrigation than for sprinkler irrigation. Total impacts amount to 1,485.6 kg 1,4-DB eq ha^{-1} for furrow irrigation and 1,378.6 kg 1,4-DB eq ha^{-1} for sprinkler irrigation, corresponding to 44.3 and 28.7 kg 1,4-DB eq t^{-1}, respectively.

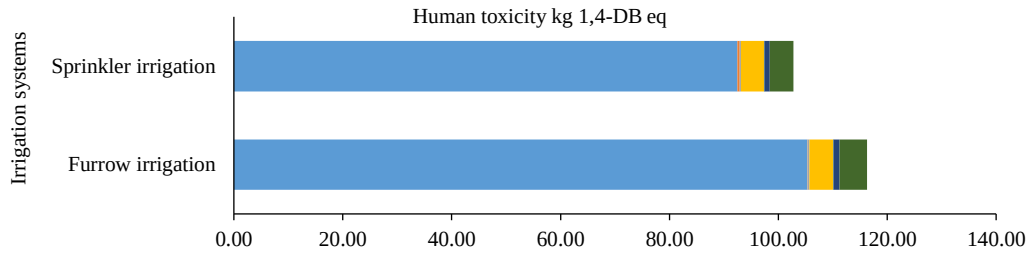
The furrow irrigation system shows higher toxicity impacts compared with sprinkler irrigation, largely as a result of more intensive agrochemical use and higher

emission levels. Although pesticide application rates are similar in both systems, emissions to air, water, and soil are consistently higher under furrow irrigation (Table 3). For example, emissions of biocides to air reach 5 kg ha^{-1} in furrow irrigation compared with 4.7 kg ha^{-1} in sprinkler irrigation, while emissions to water and soil follow similar trends. In addition, higher fertilizer application rates and greater nitrate and phosphate losses contribute indirectly to human toxicity through contamination of water resources. Upstream processes related to the manufacture and transport of fertilizers, pesticides, and fuels further amplify human toxicity impacts in the furrow system. Overall, sprinkler irrigation demonstrates a reduced human toxicity potential, reflecting its lower input intensity and improved environmental performance.



	Furrow irrigation	Sprinkler irrigation
On- farm emissions	0	0
Urea, as 100% CO(NH2)2 (NPK 46.6-0-0)	8726.932	4689.86
Triple superphosphate	4415.587	2395.46
Potatoes, start material, at seed production	2522.651	2457.97
Insecticide, at plant	1143.306	1143.31
Fungicide, at plant	1055.937	980.51
Herbicide, at plant	2191.511	2038.11
Insecticide emissions, at farm	0	0
Fungicide emissions, at farm	0	0
Herbicide emissions, at farm	0	0
Energy, from diesel burned in machinery	12677.7	11092.7
Electricity, high voltage	64722.4	56016.65

Figure 5. Abiotic depletion potential of furrow and sprinkler irrigation systems



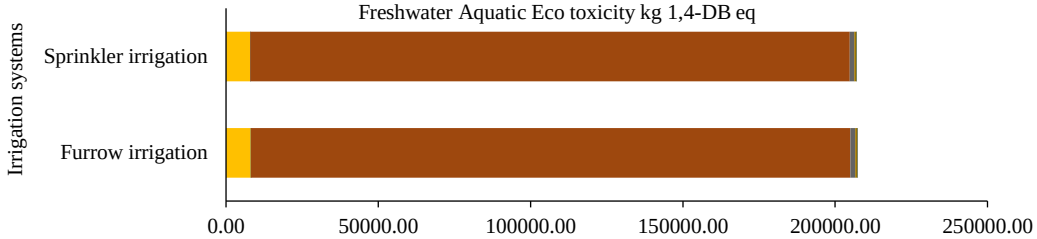
	Furrow irrigation	Sprinkler irrigation
On- farm emissions	105.29	92.48
Urea, as 100% CO(NH2)2 (NPK 46.6-0-0)	0.04	0.43
Triple superphosphate	0.37	0.20
Potatoes, start material, at seed production	4.35	4.24
Insecticide, at plant	0.04	0.05
Fungicide, at plant	0.04	0.04
Herbicide, at plant	0.07	0.07
Insecticide emissions, at farm	0.00	0.00
Fungicide emissions, at farm	0.00	0.00
Herbicide emissions, at farm	0.00	0.00
Energy, from diesel burned in machinery	1.03	0.90
Electricity, high voltage	5.09	4.40

Figure 6. Human toxicity potential of furrow and sprinkler irrigation systems

3.6. Freshwater aquatic ecotoxicity

The freshwater aquatic ecotoxicity results, shown in Fig. 7, indicate that furrow irrigation exerts a higher ecological burden on freshwater ecosystems than sprinkler irrigation. Freshwater aquatic ecotoxicity exhibits high absolute values for both irrigation systems, indicating the sensitivity of this impact category to agricultural emissions. Total freshwater ecotoxicity amounts to 207,347 kg 1,4-DB eq ha^{-1} under furrow irrigation and 206,971 kg 1,4-DB eq ha^{-1} under sprinkler irrigation. When expressed per ton of potato, however, the difference becomes more pronounced, with values of 6,189 and 4,312 kg 1,4-DB eq t^{-1}, respectively.

This difference is primarily driven by greater nutrient and pesticide losses to water bodies. As reported in Table 3, nitrate leaching (8.8 kg ha^{-1} vs. 7.5 kg ha^{-1}) and phosphate losses to water (6.1 vs. 4.8 kg ha^{-1}) are higher under furrow irrigation. These losses, combined with higher emissions of biocides to water, increase the risk of toxic effects on aquatic organisms. When normalized per ton of potato, the lower yield of furrow irrigation further intensifies these impacts. The sprinkler irrigation system, by contrast, reduces runoff and leaching losses through improved water control, thereby lowering freshwater ecotoxicity potential and offering a more sustainable alternative for protecting aquatic ecosystems.



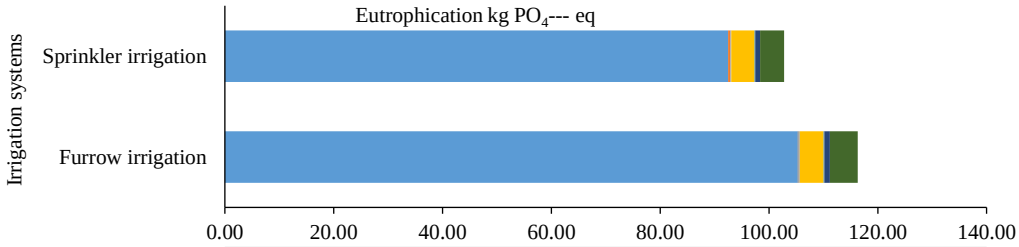
	Furrow irrigation	Sprinkler irrigation
On- farm emissions	83.59	83.59
Urea, as 100% CO(NH2)2 (NPK 46.6-0-0)	0.15	0.08
Triple superphosphate	0.25	0.13
Potatoes, start material, at seed production	8088.44	7881.04
Insecticide, at plant	0.37	0.37
Fungicide, at plant	0.36	0.33
Herbicide, at plant	0.57	0.53
Insecticide emissions, at farm	196830.50	196830.47
Fungicide emissions, at farm	1613.46	1498.21
Herbicide emissions, at farm	700.22	651.2
Energy, from diesel burned in machinery	0.47	0.41
Electricity, high voltage	28.35	24.54

Figure 7. Freshwater aquatic eco-toxicity potential of furrow and sprinkler irrigation systems

3.7. Eutrophication

Eutrophication potential, expressed as PO_4^{3-} equivalents, is presented in Fig. 8. Eutr ophication potential, expressed as kg PO_4^{3-} equivalents, shows one of the clearest contrasts between the two irrigation systems. Total eutrophication reaches 116.3 kg PO_4^{3-} eq ha^{-1} under furrow irrigation, compared with 102.8 kg PO_4^{3-} eq ha^{-1} under sprinkler irrigation. On a per-ton basis, the respective values are 3.47 and 2.14 kg PO_4^{3-} eq t^{-1}.

Among all impact categories, eutrophication exhibits one of the largest contrasts between the two irrigation systems. Furrow irrigation shows substantially higher eutrophication impacts due to excessive phosphorus application and higher nutrient losses to water. Phosphate fertilizer use under furrow irrigation (400 kg ha^{-1}) is nearly twice that under sprinkler irrigation (217 kg ha^{-1}), and phosphate emissions to water are correspondingly higher (6.1 vs. 4.8 kg ha^{-1}). In addition, higher poultry manure application rates further exacerbate phosphorus enrichment of soil and water bodies. These results indicate that nutrient management inefficiencies under furrow irrigation significantly increase the risk of eutrophication, particularly in surface and groundwater systems. Sprinkler irrigation, through reduced fertilizer requirements, lower nutrient losses, and higher yield efficiency, demonstrates a substantially lower eutrophication potential both per hectare and per ton of potato produced.



	Furrow irrigation	Sprinkler irrigation
On- farm emissions	105.29	92.48
Urea, as 100% CO(NH2)2 (NPK 46.6-0-0)	0.04	0.43
Triple superphosphate	0.37	0.20
Potatoes, start material, at seed production	4.35	4.24
Insecticide, at plant	0.04	0.05
Fungicide, at plant	0.04	0.04
Herbicide, at plant	0.07	0.07
Insecticide emissions, at farm	0.00	0.00
Fungicide emissions, at farm	0.00	0.00
Herbicide emissions, at farm	0.00	0.00
Energy, from diesel burned in machinery	1.03	0.90
Electricity, high voltage	5.09	4.40

Figure 8. Eutrophication potential of furrow and sprinkler irrigation systems

3.8. Comparison with previous studies

The findings of the present study are consistent with those reported by Economou et al. (2023), who assessed the environmental impacts of potato production in Cyprus using a cradle-to-farm-gate LCA framework. In both studies, energy use related to irrigation and machinery operations emerged as the dominant contributor to global warming potential. While seasonal variability was identified as a key driver of impact reduction in subtropical systems, the present study demonstrates that irrigation system efficiency plays an equally critical role in semi-arid regions, leading to substantial reductions in environmental burdens when impacts are expressed per ton of product. A similar emphasis on management practices is reported by Kumar et al. (2023), who compared conventional and organic potato cultivation systems in India. Their results identified fertilization as the main environmental hotspot in conventional systems and irrigation as the dominant contributor in organic cultivation. This aligns with the present study, where irrigation-related energy consumption and associated emissions significantly influenced global warming and eutrophication potentials, confirming irrigation management as a critical leverage point for improving environmental performance across different cultivation systems.

Busch and Wydra (2023) expanded the system boundary by integrating agrivoltaic systems with conventional potato production in Germany. Their results showed that coupling potato cultivation with on-site renewable energy production substantially reduced impacts across most environmental categories compared to conventional energy supply. While the present study does not include on-farm energy generation, both studies consistently highlight energy sourcing and irrigation-related electricity or fuel consumption as decisive factors influencing the overall environmental footprint of potato production.

In rain-fed potato systems of the Peruvian Central Andes, Grados and Schrevens (2019) reported relatively low global warming potential but high acidification and eutrophication impacts due to imbalanced fertilizer use. In contrast, the present study observed higher climate-related impacts driven by irrigation energy demand, reflecting the technological and water-management differences between rain-fed and irrigated systems. Nevertheless, both studies converge on the conclusion that optimizing input quantities and improving resource-use efficiency are essential for reducing environmental burdens per ton of potato produced.

Shahmohammadi et al. (2018) compared mechanized and semi-mechanized potato cultivation systems in Iran and identified diesel fuel consumption, particularly for irrigation pumping, as a major source of global warming and ozone depletion impacts. These findings strongly support the results of the present

study, where irrigation energy demand was a dominant contributor to environmental impacts, further confirming that mechanization and irrigation technology selection are key determinants of sustainability in potato production systems.

A broader crop-level perspective was provided by Abdelkader et al. (2022), who evaluated the energy and environmental footprints of major vegetable crops in southern Egypt. Although potato production required the highest energy input per hectare, it exhibited relatively low greenhouse gas emissions per ton of yield. This observation is consistent with the present study, where higher yields under improved irrigation systems contributed to lower impact intensities per functional unit, highlighting the importance of yield normalization in LCA-based comparisons.

Recent evidence from Abdelhamid et al. (2025) further reinforces the role of irrigation systems and water sources in shaping environmental outcomes. Their comparison of groundwater-based center pivot irrigation and surface-water-fed drip irrigation revealed nearly a 49% reduction in global warming potential under drip irrigation. These results closely align with the present study, which similarly demonstrates that efficient irrigation systems significantly reduce energy consumption, emissions, and overall environmental impacts of potato production.

Overall, comparison with previous studies confirms that energy use, irrigation practices, and input management consistently represent environmental hotspots in potato cultivation across diverse agro-climatic regions. The present study contributes to this body of knowledge by quantitatively demonstrating that upgrading irrigation systems can yield environmental benefits comparable to those achieved through changes in cropping systems, energy sources, or seasonal management, thereby reinforcing irrigation modernization as a key pathway toward sustainable potato production.

A key contribution of this study lies in demonstrating that the choice of functional unit fundamentally affects the interpretation of environmental performance. While differences between irrigation systems are moderate when impacts are expressed per hectare, they become substantially amplified when normalized per ton of potato, reflecting the decisive role of yield improvement. This finding underscores that irrigation technologies should not be evaluated solely based on input reduction, but rather in terms of their capacity to enhance productivity while simultaneously lowering emission intensities. In semi-arid regions, where land and water resources are limited, yield-scaled environmental indicators provide a more policy-relevant basis for assessing sustainability and guiding irrigation modernization strategies.

The present study provides a comprehensive life cycle–based comparison of the environmental performance of potato production under furrow and sprinkler irrigation systems in a semi-arid region of western Iran. By integrating detailed farm-level inventory data with the CML impact assessment framework, the analysis offers robust evidence that irrigation technology plays a decisive role in shaping environmental outcomes, not only through direct water use but also via its cascading effects on energy demand, fertilizer efficiency, emissions, and yield performance. Overall, the results consistently indicate that sprinkler irrigation outperforms furrow irrigation across all evaluated environmental impact categories, including global warming potential, acidification, eutrophication, abiotic resource depletion, human toxicity, and freshwater aquatic Ecotoxicity.

One of the most salient findings of this study is the strong linkage between irrigation efficiency and climate-related impacts. The lower global warming potential associated with sprinkler irrigation is primarily driven by its substantially higher yield per hectare and reduced water and energy requirements. In the studied system, sprinkler irrigation achieved an average yield of 40 t ha^{-1}, compared with 27.5 t ha^{-1} under furrow irrigation. When environmental burdens are normalized to the functional unit of one ton of potato, this yield gap becomes a critical determinant of performance, as emissions related to fuel use, electricity generation, and fertilizer application are effectively diluted in the sprinkler system. Similar conclusions have been reported in previous LCA studies of irrigated cropping systems, which emphasize that productivity gains can offset, or even outweigh, the additional infrastructure or energy requirements associated with pressurized irrigation technologies. In this regard, the present results reinforce the notion that yield-scaled environmental indicators provide a more meaningful basis for comparing agricultural systems than area-based metrics alone, particularly in regions facing land and water constraints.

Energy consumption emerges as another central driver of environmental impacts, especially for global warming and abiotic depletion categories. Furrow irrigation exhibits markedly higher diesel fuel use and electricity demand, largely due to inefficient water conveyance and greater irrigation water losses. The observed irrigation water loss under furrow irrigation exceeds 8,000 m^3 ha^{-1}, more than double that of the sprinkler system. In a national context where electricity production relies heavily on fossil fuels, primarily natural gas, such inefficiencies translate directly into higher indirect greenhouse gas emissions. This finding is consistent with earlier studies conducted in Iran and other semi-arid regions, which have highlighted irrigation pumping as a dominant hotspot in the environmental profile of irrigated agriculture. Consequently, improvements in irrigation efficiency represent a high-impact mitigation option for reducing both energy demand and climate-related emissions in potato production systems. Solar-driven irrigation systems, which have been applied in agricultural practices for several decades, represent an increasingly attractive alternative to conventional energy-dependent irrigation methods (FAO and GIZ, 2018). Their adoption has been associated with improved availability of irrigation water, yield enhancement, and a noticeable reduction in labor requirements, thereby contributing to greater food security and higher farm-level incomes. From an energy and economic perspective, solar-powered irrigation significantly decreases dependence on grid electricity and fossil fuels, resulting in lower operating costs, reduced pressure on public energy subsidies, and diminished reliance on imported fuels. Moreover, the decentralized nature of solar irrigation systems supports the development of small-scale rural enterprises, enhances the stability and resilience of local power infrastructures, and leads to measurable reductions in greenhouse gas emissions and other pollutants (IRENA, 2016).

Nutrient management practices further explain the observed differences between the two irrigation systems, particularly with respect to eutrophication and acidification potentials. Furrow irrigation is characterized by significantly higher application rates of nitrogen and phosphorus fertilizers, as well as poultry manure, which in turn lead to greater ammonia volatilization, nitrate leaching, and phosphate runoff. These nutrient losses are key contributors to acidification through atmospheric deposition of nitrogen compounds and to eutrophication via nutrient enrichment of water bodies. The results demonstrate that phosphate-related impacts are especially sensitive to irrigation method, with furrow irrigation showing nearly double the phosphate fertilizer input and substantially higher phosphorus emissions to water. This highlights the strong interaction between irrigation practices and nutrient use efficiency, as excessive or poorly synchronized fertilizer application under low-efficiency irrigation systems amplifies both economic losses and environmental burdens.

The superiority of sprinkler irrigation in reducing eutrophication potential is particularly relevant in semi-arid regions, where water bodies are often highly vulnerable to nutrient enrichment due to limited dilution capacity. By delivering water more uniformly and reducing surface runoff, sprinkler irrigation minimizes nutrient transport to surface and groundwater systems. These findings align with the broader literature on sustainable nutrient management, which emphasizes the need to integrate irrigation scheduling and fertilizer application strategies to reduce nutrient losses. From a policy perspective, the results suggest that promoting sprinkler irrigation could contribute not only to water conservation but also to improved water quality outcomes at the watershed scale.

Human toxicity and freshwater aquatic ecotoxicity results further underscore the environmental advantages of sprinkler irrigation. Although pesticide application rates are similar in both systems, higher emissions to air, soil, and water are observed under furrow irrigation, reflecting greater losses and less controlled application conditions. In addition, upstream processes associated with the production and transport of fertilizers and fuels contribute substantially to toxicity-related impact categories. The lower toxicity potentials observed for sprinkler irrigation, therefore, reflect a combination of reduced input intensity, improved resource-use efficiency, and higher yield performance. These results are consistent with previous LCA studies that identify agrochemical production and field emissions as major contributors to toxicity impacts in crop production systems.

Despite its advantages, sprinkler irrigation is not without challenges, and these practical considerations

must be acknowledged when interpreting the results. The adoption of sprinkler systems often requires higher initial investment costs, reliable access to electricity, and regular maintenance of equipment. In semi-arid regions such as the study area, fluctuations in energy supply and rising energy prices may constrain the feasibility of widespread adoption, particularly for smallholder farmers. While these economic and infrastructural aspects fall outside the system boundaries of the present LCA, they represent important contextual factors that influence real-world decision-making. Future studies that integrate life cycle costing or material flow cost accounting with LCA could provide a more holistic assessment of trade-offs between environmental performance and economic viability.

Several methodological limitations of the present study should also be considered. First, the analysis relies partly on emission factors derived from international databases and literature sources, due to the lack of region-specific measurements for certain emission pathways. While these coefficients are widely used and consistent with ISO-based LCA practice, they inevitably introduce uncertainty, particularly for nitrogen-related emissions such as denitrification and leaching, which are highly sensitive to local soil, climate, and management conditions. Second, the system boundaries exclude post-harvest stages such as storage, transportation, processing, and marketing. Although this exclusion is justified by the study's focus on on-farm irrigation practices, including downstream stages, it could alter the relative importance of certain impact categories, especially when comparing systems with different yield levels. Third, temporal variability in climatic conditions across growing seasons was not explicitly modeled, and the results therefore represent average conditions rather than extreme drought or wet years, which may differentially affect irrigation performance.

Another limitation relates to the functional unit choice. While the use of one ton of potato as the primary functional unit is appropriate for comparing production efficiency and environmental intensity, complementary functional units, such as per hectare or per unit of economic value, could provide additional insights into land-use efficiency and farmer-level decision-making. Future research could adopt a multi-functional-unit approach to capture these different perspectives more explicitly.

Building on these limitations, several directions for future research can be identified. First, there is a clear need for field-based measurements of nutrient and water losses under different irrigation systems in semi-arid environments. Such data would enable the development of region-specific emission factors, thereby reducing uncertainty and improving the accuracy of LCA results. Second, integrating dynamic modeling approaches that account for interannual climatic variability and long-term changes in groundwater levels could enhance understanding of the cumulative environmental impacts of irrigation practices. Third, coupling LCA with economic and social assessment tools, such as life cycle costing or social LCA, would allow for a more comprehensive sustainability evaluation, capturing trade-offs among environmental, economic, and social dimensions.

In addition, future studies could explore the environmental performance of alternative irrigation technologies, such as drip or subsurface irrigation, which may offer further improvements in water and nutrient use efficiency. Comparative assessments across multiple irrigation technologies and cropping systems would provide valuable guidance for policymakers and extension services aiming to promote sustainable irrigation strategies. Finally, scenario-based analyses examining the effects of improved fertilizer management, renewable energy integration for irrigation pumping, or changes in crop varieties could identify synergistic pathways for reducing the environmental footprint of potato production.

In conclusion, the findings of this study clearly demonstrate that sprinkler irrigation represents a more environmentally sustainable option than furrow irrigation for potato production in semi-arid regions. By reducing water and energy consumption, enhancing yield, and minimizing nutrient and emission losses, sprinkler irrigation delivers consistent environmental benefits across multiple impact categories. While practical and economic constraints must be addressed to facilitate broader adoption, the results provide strong scientific support for policies and management strategies that prioritize efficient irrigation technologies as a cornerstone of sustainable agricultural development.

4. Conclusion

This study applied a life cycle assessment (LCA) framework to systematically compare the environmental performance of potato production under furrow and sprinkler irrigation systems in a semi-arid region of western Iran. By evaluating multiple impact categories—including global warming potential, acidification, eutrophication, abiotic resource depletion, human toxicity, and freshwater aquatic ecotoxicity—the analysis provides a comprehensive and integrated assessment of how irrigation technology influences the sustainability of potato cultivation.

The results clearly demonstrate that sprinkler irrigation consistently outperforms furrow irrigation across all evaluated environmental indicators. The superior performance of the sprinkler system is primarily driven by its higher yield per hectare, lower irrigation water requirement, reduced energy consumption, and improved nutrient-use efficiency. When impacts are normalized per ton of potato produced, the yield advantage of sprinkler irrigation plays a decisive role in diluting emissions and resource use, resulting in substantially lower environmental burdens. In contrast, furrow irrigation is characterized by higher water losses, greater reliance on fossil energy for pumping and field operations, and excessive application of fertilizers and organic amendments, which together lead to elevated greenhouse gas emissions, nutrient losses, and toxicity-related impacts.

From an environmental perspective, the most pronounced differences between the two systems are observed in global warming and eutrophication potentials. Higher electricity demand and fuel use under furrow irrigation significantly increase climate-related impacts, while inefficient phosphorus and nitrogen management exacerbate eutrophication risks in surrounding aquatic ecosystems. The sprinkler system, by enabling more controlled water application and reducing runoff and leaching, mitigates these impacts and offers a more resource-efficient production pathway. Moreover, lower abiotic depletion and toxicity potentials associated with sprinkler irrigation highlight its advantages in reducing dependence on non-renewable resources and minimizing risks to human health and freshwater ecosystems.

Despite these clear environmental benefits, the study also recognizes that the adoption of sprinkler irrigation may be constrained by economic, technical, and infrastructural factors, such as higher initial investment costs, maintenance requirements, and dependence on reliable energy supply. While these aspects were beyond the defined system boundaries of the present LCA, they represent critical considerations for real-world implementation and policy design. Addressing these constraints through supportive policies, targeted subsidies, farmer training, and integration of renewable energy sources could enhance the feasibility and long-term sustainability of sprinkler irrigation systems.

Overall, the findings of this research underscore the pivotal role of irrigation management in shaping the environmental footprint of potato production in semi-arid regions. The study provides strong scientific evidence that transitioning from traditional furrow irrigation to more efficient sprinkler systems can substantially reduce environmental impacts while maintaining or increasing crop productivity. These insights are directly relevant for policymakers, extension services, and farmers seeking to balance food production goals with environmental protection. Future research that integrates environmental, economic, and social dimensions will further support the development of holistic and context-specific strategies for sustainable irrigation and agricultural intensification.

Conflict of interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No humans or animals were used in the present research. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publications

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

All authors had an equal role in study design, work, statistical analysis and manuscript writing.

Informed consent

The authors declare not to use any patients in this research.

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