Resources, Environment and Sustainability 23 (2026) 100288

Contents lists available at ScienceDirect

Resources, Environment and Sustainability

journal homepage: www.sciencedirect.com/journal/resources-environment-and-sustainability

Research article

Comparative life cycle assessment of olive (*Olea europaea* L.) production under different agricultural systems: Environmental trade-offs and sustainability insights

Makrem Cherni[a,b,c,*], Hajer Ben Ammar[d], Mohamed Guesmi[b,e], Rabii Lanwer[a,b], Yassine Hidri[a], Khaled Ouertani[a], Hakim Boulal[f], Boubaker Dhehibi[g], Aymen Frija[g], Ajmi Larbi[a]

[a] *Research Laboratory "Integrated Olive Protection in the Humid, Sub-humid and Semi-arid Regions of Tunisia" (POI- LR6IO03), Olive Institute (IO), Ariana, Tunisia*
[b] *Faculty of Sciences, Farhat Hached University Campus, University of Tunis El Manar, 1068, Tunis, Tunisia*
[c] *Energy, Water, Environment and Process Laboratory (LR18ES35), National Engineering School of Gabes, University of Gabes, 6072, Gabes, Tunisia*
[d] *Crop Science Department, Agricultural Institute of Slovenia, SI-1000, Ljubljana, Slovenia*
[e] *Laboratoire Des Matériaux Utiles, Institut National de Recherche et d'Analyse Physicochimique Technopole de, Sidi Thabet, 2020, Ariana, Tunisia*
[f] *African Plant Nutrition Institute, UM6P Experimental Farm, Benguerir, 41350, Morocco*
[g] *International Center for Agricultural Research in the Dry Areas (ICARDA), Ariana, Tunisia*

ARTICLE INFO

Keywords:
Olive cultivation
Life cycle assessment (LCA)
Ecosystem impacts
Agri-environmental indicators
Mediterranean cropping systems

ABSTRACT

Introduction: Olive cultivation is a major agroecosystem in the Mediterranean basin, yet the environmental performance of its production systems remains poorly quantified, particularly in North Africa where life cycle inventory (LCI) data are limited.
Methods: This study applied a comparative Life Cycle Assessment (LCA) to eight representative olive production systems (traditional, integrated, and intensive). Primary data were obtained from field surveys and farm records, while secondary data from the Ecoinvent database were used for background processes. Environmental impacts were evaluated per hectare and per ton of olives for global warming potential, acidification, eutrophication and water consumption.
Results: Fertilization and soil management emerged as dominant hotspots across all assessed impact categories, with synthetic inputs contributing up to 576 kg CO_2-eq/ha to global warming potential and driving nutrient-related burdens. Water consumption ranged from 0.98 to 1767 m^3/ha, primarily influenced by irrigation intensity. Overall global warming potential varied from 617 to 2583 kg CO_2-eq/ha, reflecting substantial differences in input levels and resource-use efficiency among systems.
Discussion and conclusions: The results demonstrate that environmental performance is strongly shaped by fertilizer regimes, irrigation practices, and soil management. Precision nutrient management, optimized irrigation, reduced tillage and agroecological interventions could substantially reduce impacts. This study provides one of the first structured LCAs for Tunisian olive systems and offers essential evidence to support the development of robust regional LCI datasets for Mediterranean olive production.

1. Introduction

The cultivation of olives (*Olea europaea* L.) is a cornerstone of Mediterranean agriculture, covering nearly 9 million hectares (ha) across the region and more than 11.1 million ha globally (FAO, 2025). Tunisia alone accounts for approximately 1.93 million ha of harvested olive area, making it one of the largest olive-growing countries worldwide. Beyond its economic value, olive farming holds considerable ecological and cultural significance, particularly in semi-arid environments where it contributes to biodiversity, agroecosystem resilience, and landscape preservation (Avraamides and Fatta, 2008.). However, the intensification of olive production spurred by rising global demand for olive oil has raised pressing concerns regarding its environmental sustainability, particularly with respect to water use, agrochemical dependency, and

* Corresponding author. Research Laboratory "Integrated Olive Protection in the Humid, Sub-Humid And Semi-Arid Regions of Tunisia" (POI- LR6IO03), Olive Institute (IO), Ariana, Tunisia.
E-mail address: makrem.cherni@fst.utm.tn (M. Cherni).

https://doi.org/10.1016/j.resenv.2026.100288
Received 29 September 2025; Received in revised form 4 December 2025; Accepted 1 January 2026
Available online 6 January 2026

greenhouse gas (GHG) emissions (Rapa and Ciano, 2022; Espadas-Aldana et al., 2019; Banias et al., 2017; Loumou and Giourga, 2003).

Olive oil, a staple of the Mediterranean diet, holds significant socioeconomic and cultural value, particularly within the Mediterranean basin, which accounts for over 95 % of global production (Fotia et al., 2021; Ruiz-Carrasco et al., 2023; Tsarouhas et al., 2015). In the 2023/2024 crop year Tunisia ranked fourth worldwide in olive oil production, with about 200,000 t, and remains one of the leading exporters (IOC, 2024). Olive cultivation occupies a substantial share of its agricultural landscape. According to the International Olive Council (IOC, 2025), IOC trade statistics for the last seven crop years (2017/2018–2023/2024) show that Tunisia has been one of the main suppliers on the world market. In 2023/2024 it represented 24.3 % of recorded olive oil imports, second only to Spain (27.9 %) and ahead of Italy (19.6 %). Tunisian exports, primarily composed of virgin olive oils (HS 150910), have remained robust despite market fluctuations, with a 21.2 % increase in export volumes between 2022/2023 and 2023/2024. Olive groves in Tunisia accounted for 36 % of national arable land in 2020 (Ben Abdallah et al., 2021) and represented around 24 % of total national fruit production in 2023 (Agridata, 2023). The sector provides direct and indirect employment to over 1 million Tunisians (OLIVÆ, 2017). However, around 90 % of the olive area is still dominated by traditional rainfed systems, often characterized by low inputs, limited mechanization, and yields below 1 ton (t)/ha^{-1} (Larbi et al., 2017). While certified organic olive farming reached 153,233 ha in 2023 (Willer et al., 2025), the environmental performance of diverse systems remains understudied under the constraints of climate change, water scarcity, and soil degradation. Over the last two decades, Life Cycle Assessment (LCA) has become a widely adopted methodology for evaluating the environmental performance of olive production systems across their full value chains, from cultivation through oil extraction and packaging (Proietti et al., 2017; Salomone and Ioppolo, 2012). Previous studies conducted in Italy, Greece, Portugal, Spain, and Turkey consistently highlight that the agricultural phase accounts for the majority of environmental burdens primarily through fertilizer use, irrigation energy, and field emissions (Brito and Fernandes-Silva, 2022; Sales et al., 2022; De Luca et.,2018; Romero-Gámez et al., 2017). Comparative LCA studies have shown that traditional and organic systems generally perform better per hectare than intensive or super-intensive systems in environmental terms, but may lag behind in productivity and economic efficiency (Tziolas et al., 2022; Taxidis et al., 2015). In contrast, intensive and super-intensive systems achieve high yields but generate elevated impacts per functional unit due to mechanization, synthetic input dependency, and irrigation (Rahmani et al., 2022; Rinaldi et al., 2014). Integrated systems are often proposed as a compromise, balancing reduced environmental burdens with acceptable agronomic outputs (Romero-Gámez et al., 2017).

Beyond diagnostic LCAs, recent work tests technical options to decarbonize olive systems. Hybrid photovoltaic irrigation systems in intensive and super-intensive orchards lower GHG emissions from water pumping by replacing grid and diesel electricity with low-emission solar power (Todde et al., 2019). Thermochemical valorization of olive pomace through gasification has also been evaluated, with gate-to-gate LCA and techno-economic studies in Spain and Morocco showing that integrated plants can supply renewable electricity and biochar while reducing the climate footprint of virgin olive oil production (Fernández-Lobato et al., 2022, 2025).

A key limitation of existing LCAs is that they rarely capture the substantial heterogeneity that characterizes Mediterranean olive systems. This heterogeneity extends beyond broad typologies (traditional, integrated and intensive) and includes marked differences in fertilization regimes, irrigation strategies, planting densities, pruning management, mechanization levels and on-farm energy sources. Several practices with significant environmental implications, such as the open-field burning of pruning residues, which remains widespread in Tunisian orchards and generates direct GHG and particulate emissions, are routinely omitted from LCA inventories. Likewise, irrigated systems in the region predominantly rely on diesel-powered pumping, although photovoltaic irrigation technologies are increasingly promoted as a low-carbon alternative. Incorporating these management differences is essential for accurately diagnosing system-specific hotspots and for evaluating the mitigation potential of emerging practices under real regional conditions. This study bridges a critical gap by coupling multivariate statistical analysis with a cradle-to-gate LCA of eight olive production systems spanning conventional, integrated and organic management in a Mediterranean context. Pearson correlation, hierarchical clustering, and principal component analysis are initially employed to characterize the agronomic and environmental profiles that differentiate the eight olive production systems. A standardized cradle-to-gate LCA, structured around dual functional units (per hectare and per ton of olives) and explicitly incorporating the commonly overlooked open-field burning of pruning residues, is subsequently applied to quantify global warming potential, eutrophication, land use, and additional impact categories. Building on the identified hotspots and system-level trade-offs, photovoltaic-powered irrigation is assessed as a potential pathway for reducing energy-related burdens in irrigated orchards. Through the integration of multivariate diagnostics and LCA modelling, the study establishes a comprehensive analytical framework that pinpoints system-specific leverage points for improving resource efficiency and environmental performance, thereby informing the transition of Tunisian, and more broadly Mediterranean, olive production toward a more resilient and environmentally sustainable future.

2. Methodology

2.1. Goal and scope definition

The primary objective of this study is to conduct a comprehensive LCA of olive fruit production systems in northwestern Tunisia (Fig. 1), with the aim of quantifying and comparing their cradle-to-farm-gate environmental impacts. Eight representative olive production systems listed in Table 1 (ETCIC, ETCIO, ETRC, ETRO, ETIC, IIC, SICIC and SICIO) are assessed. These systems differ according to their system designation (Extensive Traditional, Intensive or Semi-Intensive-Classic), irrigation regime (Complementary Irrigation, Rainfed or Irrigation) and management practice (Conventional or Organic). By compiling a detailed life cycle inventory based on primary data from 104 olive growers in the Béja–Siliana–Kef region of northwest Tunisia and modelling all material and energy flows up to harvest delivery at the mill gate, this study provides the first LCA specifically grounded in regionally representative production conditions for Tunisian olive orchards. The insights gained will inform strategies to optimize orchard management for enhanced resource efficiency and reduced environmental impact.

In accordance with ISO 14040 (ISO 14040:2006) and ISO 14044 (ISO 14044:2006) (ISO 14040, 2006; ISO 14044, 2006), all inputs and outputs were referenced to two rigorously defined functional units, 1 ha of cultivated olive grove and 1 t of olives produced per hectare, to ensure methodological consistency and comparability across systems exhibiting divergent planting densities and yields. In addition to ISO 14040 and ISO 14044, the goal and scope definition and modelling choices were aligned with the EU Product Environmental Footprint method and the draft Product Environmental Footprint Category Rules for olive oil, including their guidance on functional units, system boundaries and background data selection (Wernet et al., 2016). System characterization was achieved through structured, on-farm surveys conducted across the Beja–Siliana–Kef region of northwest Tunisia, covering approximately 100 olive growers. Data collected included management practices, irrigation regimes, planting densities, and yield performance. These observations informed the delineation of eight representative production systems (Table 1), thus establishing a robust foundation for a tailored, system-specific LCA. The systems range from traditional extensive rainfed to modern intensive irrigated management, capturing

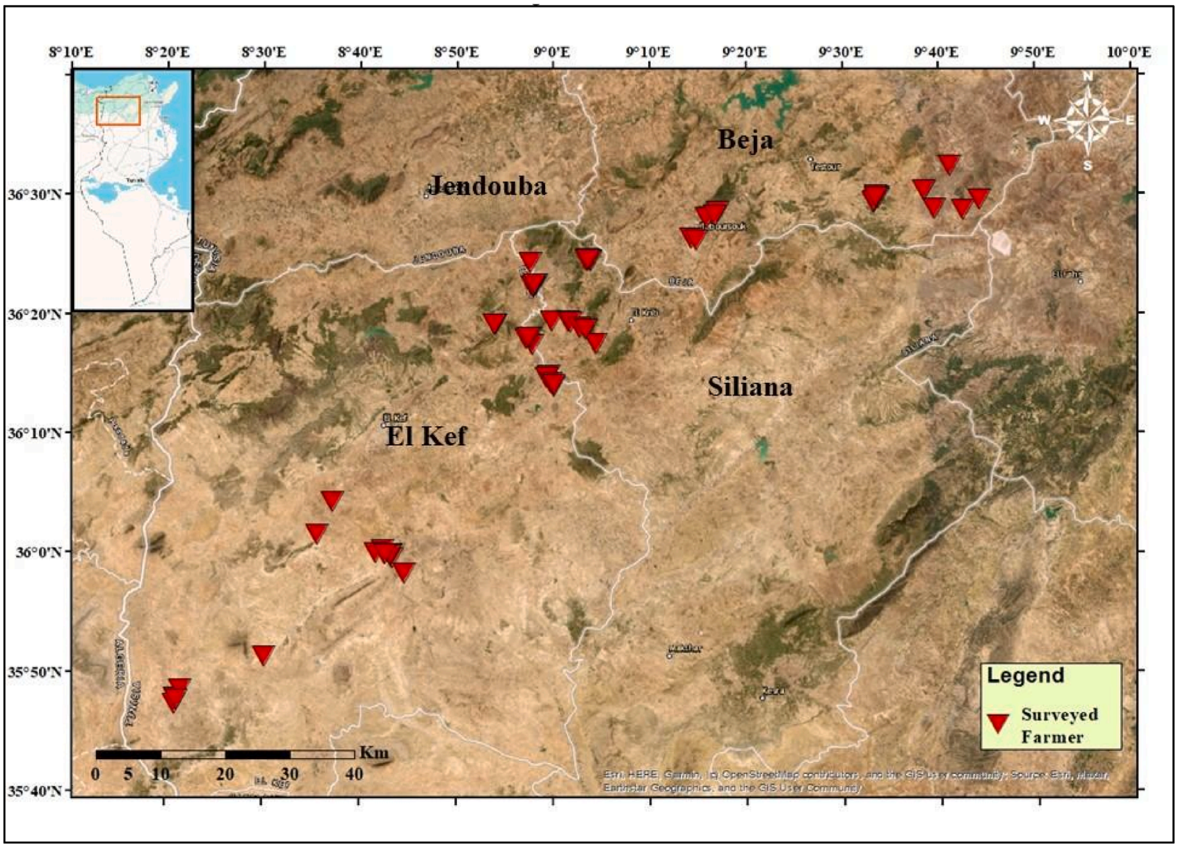

Fig. 1. Geographical distribution of surveyed olive farms in Northwestern Tunisia.

Table 1
Main characteristics and representativeness of the olive production systems surveyed.

Acronym	System	Irrigation	Management	Density (trees/ha)	Olive yield (t/ha)
ETCIC	Extensive Traditional	Complementary Irrigation	Conventional	69–138	1.383
ETCIO			Organic	100–123	1.318
ETRC		Rainfed	Conventional	100–125	1.531
ETRO			Organic	100	1.236
ETIC		Irrigated	Conventional	90–116	1.953
IIC	Intensive			556	8.334
SICIC	Semi-Intensive-Classic			204–290	5.763
SICIO			Organic	151–178	2.703

ETCIC = Extensive Traditional Complementary Irrigation Conventional; ETCIO = Extensive Traditional Complementary Irrigation Organic; ETRC = Extensive Traditional Rainfed Conventional; ETRO = Extensive Traditional Rainfed Organic; ETIC = Extensive Traditional Irrigated Conventional; IIC = Intensive Irrigated Conventional; SICIC = Semi-Intensive Classic Irrigated Conventional; SICIO = Semi-Intensive Classic Irrigated Organic.

the variability of Tunisian olive cultivation practices.

As shown in Fig. 2, the cradle-to-gate system boundaries for olive production encompass the complete spectrum of upstream and on-farm processes, ranging from initial soil preparation and orchard establishment to crop management, harvesting operations, and the final delivery of olives to the mill gate. Soil management is defined by the deployment of agricultural machinery and the attendant consumption of diesel, gasoline and lubricants, whereas nutrient inputs are characterized by their full life-cycle burdens from fertilizer synthesis and packaging to distribution and field application. Similarly, the environmental impacts of pesticides and herbicides encompass production, logistical transport and in-field application phases. Irrigation infrastructure including piping, fittings and associated maintenance is coupled with electricity consumption for water abstraction from the national grid, as well as direct groundwater withdrawals. Harvesting was performed manually, followed by on-farm transport of olives to the mill. Pruning residues were combusted *in situ*, with all resultant emissions quantified. This framework accounts for all energy and material flows, and their associated emissions, up to the point of harvest and delivery to the mill gate, while excluding downstream processes such as oil extraction, packaging, and distribution. In doing so, it provides a transparent, detailed life cycle inventory to support rigorous impact assessment.

A prospective photovoltaic (PV)-based irrigation scenario was defined in which all electricity required for water pumping is supplied by on-farm PV systems rather than the Tunisian grid. PV electricity was modelled with a life-cycle GHG intensity of approximately 50 g CO_2 kWh^{-1}, consistent with recent meta-analyses and Ecoinvent background data, while all other inventory parameters were kept constant (Nugent and Sovacool, 2014; Wernet et al., 2016).

2.2. Data collection

Primary life-cycle inventory data were obtained from the same on-farm survey campaign conducted between May 2023 and October

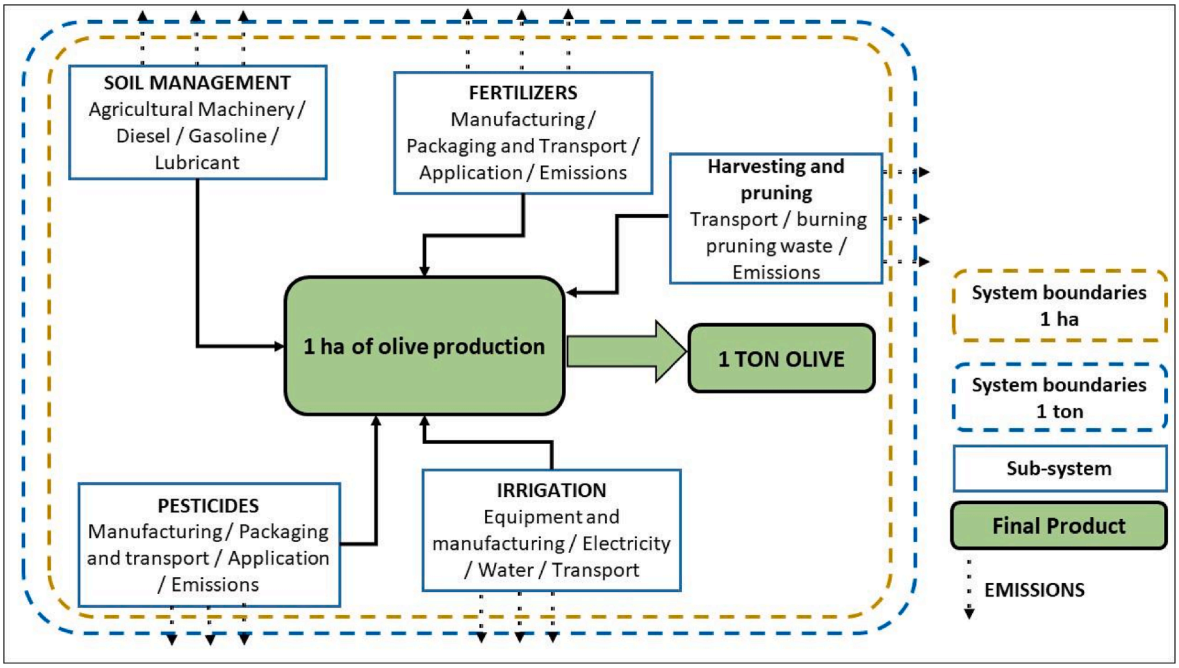

Fig. 2. System boundaries for the cradle-to-gate life cycle assessment of olive cultivation. The assessment integrates upstream production of inputs (agrochemicals, fuels, electricity, and irrigation water), farm-level operations (field management, fertilization, irrigation, crop protection, pruning, and harvesting), and associated direct emissions. The system boundary terminates at the farm gate; milling, and olive oil processing are not considered.

2024. In total, 104 olive growers were interviewed face-to-face using a standardized questionnaire that captured orchard characteristics, irrigation modality (rainfed, supplemental, or full irrigation), fertilization regime (type, rate, and timing of mineral inputs), pesticide and herbicide use, energy consumption (electricity and fuel), machinery operation hours, and annual yields per hectare.To ensure data quality and representativeness, surveyed groves were screened according to the following inclusion criteria: (i) trees in productive phase (>6 years of age); (ii) complete records on fertilizer and pesticide application rates; (iii) documented irrigation data either via utility bills or calculated from pump specifications (capacity, well depth, volume and operating hours); and (iv) consistent machinery-use logs. Farms operating with diesel- or photovoltaic-powered pumps, accounting for less than 5 % of surveyed cases (approximately four holdings), were excluded as they were not representative of the dominant grid-connected systems supplied by the Tunisian Company of Electricity and Gas (STEG). Holdings with missing information on any key input or output parameter were also omitted. After screening, 88 farms remained, which were subsequently classified into eight representative production systems (Table 1). This stratification facilitated a structured comparison of life-cycle impacts across the dominant cultivation systems in the region.

2.3. Life cycle inventory

A life cycle inventory (LCI), defined as the phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 14040:2006), was compiled from high-resolution primary and secondary data sources. All collected inputs (fertilizers, pesticides, energy, and water) were standardized to a per-hectare basis to ensure comparability across orchards of different sizes. Primary data included machinery operation hours, fertilizer and pesticide quantities, fuel, water and electricity consumption, together with observed yields. Direct N_2O emissions from N fertilization were estimated with the Tier 1 EF_1 from the 2006 IPCC Guidelines (Klein, 2006), and NH_3 and NO_x emissions from fertilization and open-field burning of pruning residues were calculated using EMEP/EEA 2023 and Skiba et al. (2021). Emissions of active substances in plant protection products, including copper- and boron-based products, were modelled as 100 % emitted to agricultural soil following WFLDB (2019). The emission factors and default values used are summarized in Supplementary Information S1 and Appendix A (Table A1). To mitigate scale-related bias, these inputs were aggregated through surface-area-weighted averages across each irrigation regime (Table A1 in Appendix). When transport distance to the mill, pruning-residue quantities, or machinery hours were not reported, harmonized assumptions were applied based on system-level medians and published LCA studies on Mediterranean olive systems, with cross-checking against Ecoinvent machinery datasets. The corresponding default values and data sources are provided in Appendix A, Table A1 (Ben Abdallah et al., 2022; Fernández-Lobato et al., 2021; Wernet et al., 2016). Secondary data sources were used to assess upstream processes, fertilizer and pesticide manufacture, machinery production and maintenance, and electricity generation based on the Tunisian grid mix. The Ecoinvent 3.10 database was used to secure these internationally-benchmarked secondary datasets (Frischknecht et al., 2005; ***Supplementary Information, Section S3***). The integration of meticulous primary measurements with robust, standardized secondary data yields a comprehensive and representative LCI, forming the bedrock of our comparative environmental assessment of olive production systems in northwest of Tunisia.

2.4. Life cycle impact assessment

Environmental impacts were assessed using the SimaPro v9.6.0.1 (Sustainability, 2022) software tool, employing the ReCiPe 2016; Huijbregts et al. (2017) Midpoint (H) V1.09 impact assessment method, with the World (2010) H scenario. The Ecoinvent 3.10 (Wernet et al., 2016) database was used as the life cycle inventory source for background data. The ReCiPe 2016 Midpoint (H) method was chosen due to its comprehensive set of midpoint indicators, providing a detailed resolution for analyzing the environmental hotspots in agricultural production systems. The midpoint indicators represent an intermediate level of cause-effect chains, offering robust results for agricultural LCAs, particularly in the olive oil sector.

Environmental impacts were classified, characterized, and normalized according to the ReCiPe 2016 Midpoint (H) methodology, which provides 18 midpoint impact categories covering all major environmental mechanisms across the life cycle, including climate change, toxicity, eutrophication, acidification, resource depletion, and water use (Huijbregts et al., 2017). All midpoint impact categories provided by the ReCiPe 2016 Midpoint (H) method were assessed, including global warming (GWP), ozone depletion (ODP), ionizing radiation (IR), photochemical ozone formation for human health (OF-HH) and terrestrial ecosystems (OF-TE), particulate matter formation (PMF), terrestrial acidification (TA), freshwater and marine eutrophication (FE, ME), terrestrial and aquatic ecotoxicity (TET, FET, MET), human toxicity (HT-c, HT-nc), land use (LU), mineral and fossil resource scarcity (MRS, FRS), and water consumption (WaC).

2.5. Multivariate data analysis

All analyses were carried out in R (v.4.x) using the tidyverse, FactoMineR, factoextra, corrplot, and pheatmap packages. After appropriate data transformations (log or square root) to improve normality, variables were standardized (mean = 0, SD = 1). The multivariate dataset included agronomic variables (yield, tree density, grove age), input-related variables (fertilizer quantities, irrigation water, diesel consumption, pesticide applications), and pruning-related variables, together with LCA-derived impact indicators (global warming potential, eutrophication, acidification, water consumption). Hierarchical clustering (Euclidean distance, Ward's linkage) was applied to identify system typologies and visualized via dendrograms. Pearson correlation matrices were computed and plotted as heatmaps across all systems and within each management group. Principal component analysis was then performed and displayed as a biplot, with system clusters coloured by management intensity to reveal the main gradients of agronomic and environmental variation.

3. Results

3.1. Distinct input-output regimes across olive production clusters

This section provides an integrated interpretation of agronomic performance, resource-use patterns, and environmental burdens across the eight olive production systems, structured in accordance with ISO 14040/44 principles for life-cycle interpretation. The analysis first characterizes the systems through key descriptors, yield levels, external input intensity, irrigation strategies, and energy dependencies, to contextualize the inventory structure and identify the management attributes that most strongly condition environmental outcomes. Building on this descriptive baseline, correlation analysis, multivariate ordination, and contribution-based LCA results are examined to elucidate how nutrient regimes, irrigation practices, machinery use, and biomass-management decisions interact to shape both productivity and environmental loading. The evaluation distinguishes inherent trade-offs between low-input extensification and high-output intensification, highlighting the nonlinear relationships between resource inputs, emissions, and functional-unit efficiencies. The section concludes by identifying the structural leverage points, synthetic nitrogen use, irrigation energy demand, pruning residue handling, and distance-to-mill logistics, that govern system differentiation and determine the feasibility of targeted mitigation measures within Mediterranean olive cultivation.

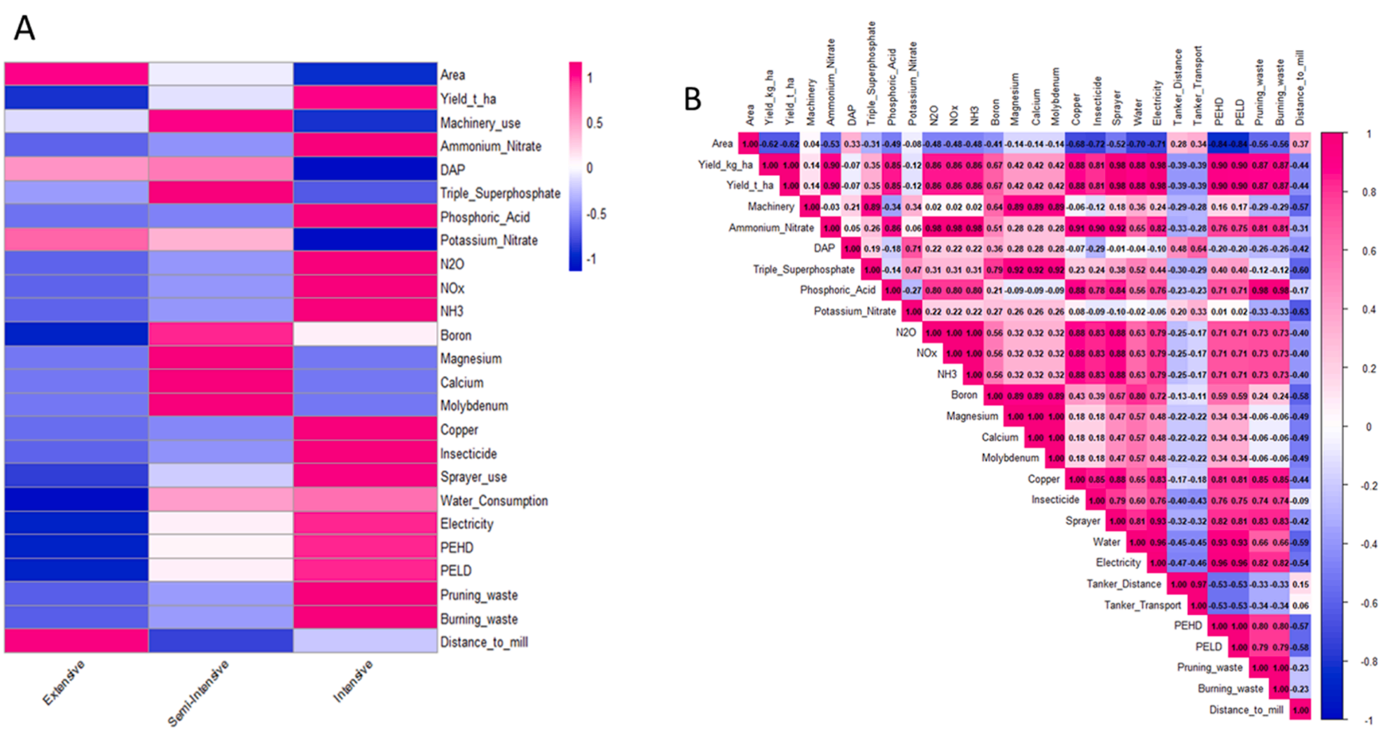

Fig. 3. Comparative heatmaps of olive production systems (A) Normalized heatmap of agronomic and environmental parameters across three olive production systems category (intensification levels): intensive, semi-intensive, and extensive. Each row represents a category, while columns depict measured indicators. The blue-white-pink gradient illustrates relative magnitudes, allowing for visual discrimination among systems in terms of input intensity, yield, and environmental performance. **(B)** Pearson correlation heatmap of all agronomic and environmental parameters across systems. The matrix reveals strong positive correlations (deep pink) and negative correlations (blue) between key variables, including nutrient inputs, emissions, and productivity. This analysis highlights parameter interdependence and helps identify critical trade-offs and synergies within olive farming systems. System acronyms: **Extensive systems**: ETCIC = Extensive Traditional Complementary Irrigated Conventional; ETCIO = Extensive Traditional Complementary Irrigated Organic; ETRC = Extensive Traditional Rainfed Conventional; ETRO = Extensive Traditional Rainfed Organic; ETIC = Extensive Traditional Fully Irrigated Conventional; **Semi-intensive systems**: SICIC = Semi-Intensive Classic Irrigated Conventional; SICIO = Semi-Intensive Classic Irrigated Organic; **Intensive system:** IIC = Intensive Irrigated Conventional.

As illustrated in Fig. 3A, cluster-specific heatmaps reveal three distinct input-output regimes in Mediterranean olive cultivation (see Table 1 for system definitions). Intensive systems (IIC) display exceptionally strong positive correlations (r > 0.85) between yield and synthetic inputs, including ammonium nitrate (~428.57 kg/ha), phosphoric acid (~60 kg/ha), and pesticides, as well as irrigation water (~1664 m^3/ha) and electricity (~1040 kWh/ha). These pronounced numerical differences arise from the high solubility and immediate plant availability of mineral N and P fertilizers, which stimulate canopy development, leaf nitrogen content, photosynthetic activity, and fruit biomass accumulation. At the same time, these fertilizers intensify soil nitrification–denitrification processes, resulting in elevated N_2O, NO_x, and NH_3 emissions, particularly under irrigated conditions that enhance microbial turnover and nutrient mobility. In contrast, extensive systems (ETCIC, ETCIO, ETRC, ETRO, ETIC) are characterized by large farm areas (mean ~79 ha), minimal external inputs (fertilizers, water, energy, plastics), negligible emissions, and low yields (1.24–1.95 t/ha). The pronounced negative correlation between area and yield (r = −0.62) reflects chronic nutrient and water limitations in rainfed orchards, which restrict carbon assimilation, reproductive allocation, and fruit set. Semi-intensive orchards (SICIC, SICIO) occupy an intermediate position, with moderate fertilizer application (e.g., 224.33 kg/ha) of ammonium nitrate, irrigation, and energy consumption supporting mid-range outputs (2.70–5.76 t/ha) and moderate emissions. The strong correlations between water and electricity use with both fertilizers and yield (r > 0.90) further underscore the synergistic role of irrigation in enhancing nutrient uptake, accelerating microbial turnover and amplifying the yield response to applied N and P. Collectively, these mechanistic patterns delineate a clear productivity, environmental impact continuum, identifying synthetic nitrogen availability and irrigation intensity as the principal levers for targeted system optimization.

Based on the comprehensive correlation matrix (Fig. 3B), several salient patterns characterize agronomic and environmental trade-offs across olive production systems. Olive yield expressed in both kg ha^{-1} (original data) and t ha^{-1} (converted values)correlates strongly (r = 0.90–0.98) with synthetic nitrogen (ammonium nitrate), phosphorus fertilizers (phosphoric acid, triple superphosphate), pesticide applications (copper-based fungicides, insecticides), irrigation volume (r = 0.88), grid electricity use (r = 0.98) and associated emissions (N_2O, NO_x, NH_3; r = 0.86–1.00), underscoring the resource intensity of high-output systems such as IIC and SICIC. In contrast, farm area exhibits negative correlations with key inputs, plastic mulch (r = −0.84), water use (r = −0.70) and copper applications (r = −0.68) – and with yield (r = −0.62), while correlating positively with distance to mill (r = 0.37) and tanker transport burdens (r = 0.34). These relationships reveal that extensive orchards (e.g., ETCIO, ETRO) are both less input-intensive and geographically more remote, resulting in lower agronomic efficiency but higher transport impacts. Notably, distance to mill also correlates negatively with machinery use and fertilizer inputs (r = −0.50), highlighting logistical constraints in extensive systems. Finally, burning of the pruning residue correlates closely with nutrient and energy variables particularly phosphoric acid application (r = 0.98) and electricity use (r = 0.82), indicating that biomass management practices are tightly coupled with fertilization and energy regimes.

3.2. PCA of input intensity and management practices in olive production systems

The first two principal components together capture 76.7 % of system variance (Fig. 4). PC1 (55.4 %) contrasts high-input, high-yield systems characterized by synthetic fertilizers, intensive irrigation, pesticide use and elevated $N_2O/NO_x/NH_3$ emissions with low-input extensive regimes (ETCIO, ETRO, ETRC, ETCIC). PC2 (21.3 %) differentiates systems by machinery intensity, pruning residue handling and

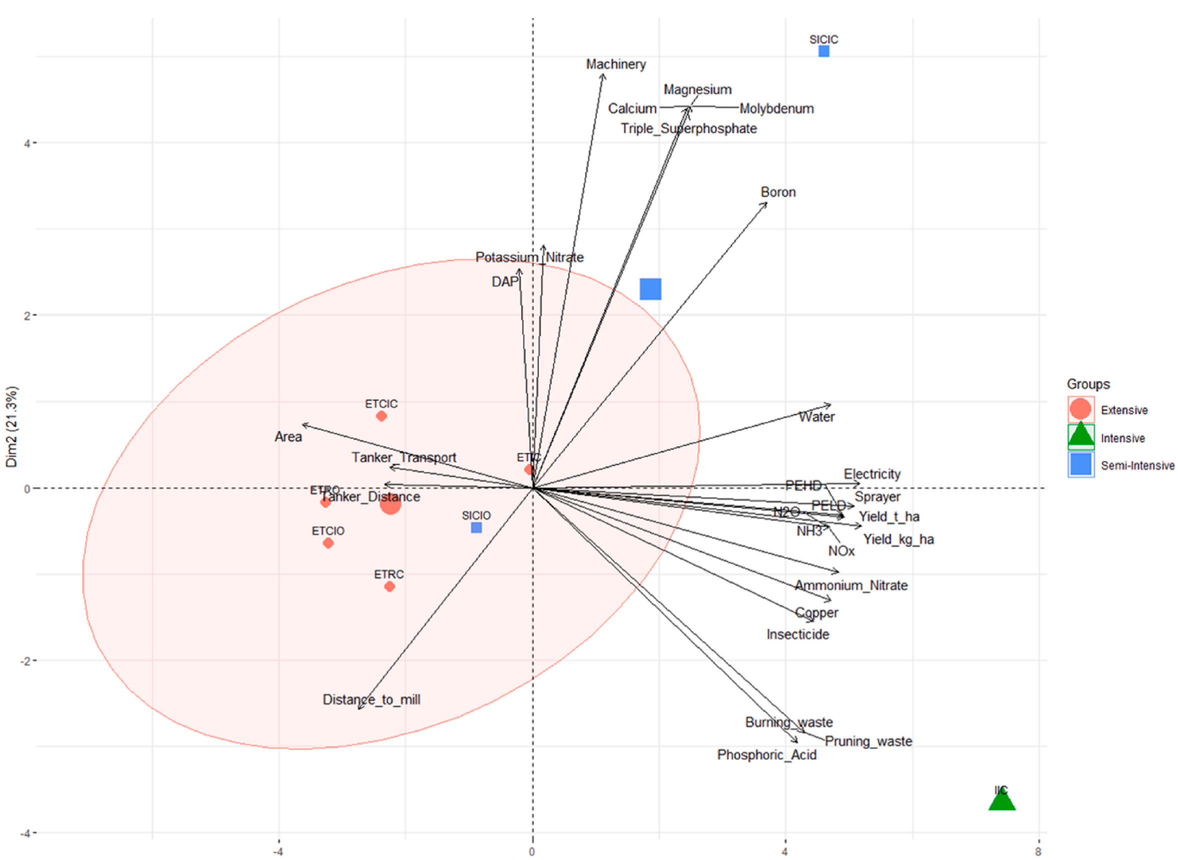

Fig. 4. PCA Biplot of olive production systems based on environmental and agronomic indicators.

tree density, highlighting management nuances among extensive orchards. In the biplot, both IIC and SICIC plot on the far right of PC1, confirming their intensified resource profiles, but diverge on PC2, reflecting differences in fertilizer blend, irrigation scheduling or pruning strategies. Collectively, these axes identify two orthogonal leverage points input intensity versus operational and biomass-management practices for targeted environmental optimization.

At the opposite extreme of PC1, ETCIO and ETRO cluster together, reflecting their minimal reliance on external inputs and correspondingly low emissions. ETIC occupies a central position, indicative of its hybrid strategy of moderate fertilizer application and mechanization despite its extensive classification. SICIO emerges as a distinct outlier, achieving mid-range yields with virtually no synthetic inputs, underscoring its potential as a transitional model between low-input and more intensive regimes.

3.3. Environmental impact analysis

The cradle-to-gate assessment of eight olive production systems, stratified by management practice (conventional vs. organic), irrigation regime (rainfed, complementary, full) and intensity (extensive, semi-intensive, intensive) reveals marked contrasts in environmental performance (Table 2). The analysis was structured in three stages. First, total impacts per hectare and per ton of olives were quantified, and contribution analyses were performed across five agricultural phases: soil management, fertilization, irrigation, pest and weed control, and harvesting/pruning. Second, system-level impacts on both functional units were compared to identify trade-offs between resource use and yield. Third, the role of individual practices within the three dominant typologies, extensive rainfed, intensive irrigated, and semi-intensive systems, was examined to pinpoint environmental hotspots.

The contribution analysis for the functional unit 1 ha, including soil management, fertilization, irrigation, weed and pest control, and harvesting and pruning, is reported in the Supplementary Information (Section S4). The results show that fertilization is the dominant contributor across most impact categories in the intensive (IIC) and semi-intensive (SICIC) systems, particularly for global GWP, FE, ME, and TA. This dominance is attributed to the higher use of synthetic fertilizers, especially nitrogen-based inputs, which are also responsible for emissions of N_2O, a potent GHG. In extensive systems (ETCIC, ETCIO, ETIC, ETRC, ETRO), soil management and irrigation were also important contributors to several impact categories. Soil management, through fuel and lubricant use in mechanized tillage, significantly influenced PMF and ecotoxicity indicators (TET, FET, MET). Fully-irrigated systems (ETIC, IIC, SICIC, SICIO) showed high contributions to water consumption (WaC) and fossil resource scarcity (FRS) due to the electricity demand for water pumping. Harvesting and pruning emerge as major contributors across all systems, with particularly strong effects on PMF, ozone formation in terrestrial ecosystems (OF-TE), and TA. Their influence is most pronounced in high-biomass systems such as IIC and SICIC, while remaining proportionally lower in extensive systems due to reduced residue volumes. For both functional units (1 ha and 1 t), the life cycle inventory applies harmonized cradle-to-gate boundaries, incorporating soil management, fertilization, irrigation, weed and pest control, harvesting and pruning to ensure consistency and comparability across systems.

Fig. 5 presents the environmental contributions of each stage when impacts are normalized per 1 t of olives. Unlike the hectare-based assessment, this analysis includes the harvesting and pruning stage, which accounts for a significant share of impacts especially particulate matter formation (PMF), human toxicity (HT-c, HT-nc), and ozone formation (OF-HH and OF-TE) in extensive and organic systems (e.g., ETRC, ETRO, ETCIO). This is largely due to the open-field burning of pruning residues, a common practice in these systems that releases considerable quantities of CO, NO_x, NH_3, PM2.5, and persistent organic pollutants. Its inclusion is crucial, as this stage is frequently omitted in LCA studies despite its contribution to air pollution and health-related impacts. In contrast, intensive systems (IIC) and semi-intensive systems (SICIC, SICIO) exhibit a dilution effect, where higher yields reduce the environmental burden per ton across most impact categories. Fertilization still dominates many indicators in IIC, but its relative contribution is reduced compared to per-hectare results. The organic semi-intensive system (SICIO) showed lower impacts in toxicity and eutrophication categories, yet had relatively higher impacts in energy-related categories due to irrigation electricity use. Overall, this functional unit highlights the trade-off between productivity and environmental performance, emphasizing that yield is a key driver of efficiency in LCA of olive systems.

3.3.1. Detailed analysis of environmental impacts by production system

The results of the LCA revealed significant differences in the environmental impacts of the eight olive production systems studied, as detailed in Table 2. These variations are primarily attributable to agricultural inputs, cultivation intensity, and specific system-level agronomic management practices. The analysis by impact category, both per cultivated hectare and per ton of olives produced, allows for the identification of environmental hotspots and a comparison of the performance of each system.

3.3.2. GWP

Intensive and semi-intensive systems (IIC and SICIC) showed the highest GWP, each reaching around 2500 kg CO_2 eq per hectare. Although IIC applies almost twice as much mineral nitrogen as SICIC, the latter shows higher machinery use, larger inputs of organic fertilisers, and greater harvesting and pruning loads per hectare, which together offset part of the difference in fertiliser-related emissions and lead to similar total GWP at the hectare scale. A major driver of GWP in both systems is electricity consumption for irrigation, which alone accounts for 42–55 % of total GWP depending on the system, given the high emission factor of the Tunisian grid (0.7–0.8 kg CO_2 kWh^{-1}). This makes irrigated systems particularly sensitive to both pumping depth and irrigation volume, and the greater nitrogen fertilizer inputs in these systems, which contribute directly to N_2O emissions. In contrast, organic and rainfed systems (ETCIO, ETRO, ETRC) show much lower GWP per hectare (611–695 kg CO_2 eq), reflecting the environmental advantage of low-input practices. However, when GWP is expressed per ton of olives produced, intensive systems can appear more efficient because of their higher yields, even if their absolute per-hectare impacts remain higher.

3.3.3. ODP and IR

ODP and IR are also more pronounced in intensive systems. For example, IIC recorded 1.86×10^{-2} kg CFC11 eq for ODP and 38.5 kBq Co-60 eq for IR. These impacts stem mainly from electricity production and chemical input manufacturing, both more intensive in high-input systems. By contrast, organic and rainfed systems, with their minimal reliance on synthetic inputs and external energy, show substantially lower ODP and IR values.

3.3.4. OF-HH, OF-TE and PMF

OF-HH and OF-TE, along with fine PMF, are also major concerns. Intensive systems (IIC and SICIC) show higher contributions due to fuel combustion by agricultural machinery and fertilizer production. Organic systems mitigate these impacts by reducing machinery use and avoiding synthetic fertilizers. However, some organic systems (ETCIO, ETRO) record higher PMF per ton of olives than conventional systems because their lower yields dilute environmental performance at the product level. TA and freshwater (FE) and marine (ME) eutrophication show a strong dependence on fertilisation intensity. Intensive systems (IIC and SICIC) present the highest impacts, with fertilisation contributing more than half of total TA and over 70 % of ME. In IIC, fertilisation represents about 56 % of TA, 40 % of FE, and 84 % of ME, while SICIC shows similar contributions, reaching 54 % of TA, 41 % of FE, and 70 % of ME. These

Table 2
Comparative environmental impacts of eight olive production systems in northwest Tunisia. expressed per hectare of cultivation and per ton of olives produced.

Impact category/ Unit	Extensive										Intensive	Semi intensive				
	Complementary irrigation				Full irrigation		Rainfed				Full irrigation					
	Conventional		Organic		Conventional		Conventional		Organic		Conventional				Organic	
	1 ha ETCIC	1 t olive ETCIC	1 ha ETCIO	1 t olive ETCIO	1 ha ETIC	1 t olive ETIC	1 ha ETRC	1 t olive ETRC	1 ha ETRO	1 t olive ETRO	1 ha IIC	1 t olive IIC	1 ha SICIC	1 t olive SICIC	1 ha SICIO	1 t olive SICIO
GWP kg CO2 eq	1.31E+03	9.46E+02	6.44E+02	4.89E+02	1.25E+03	6.39E+02	7.09E+02	4.63E+02	6.18E+02	5.00E+02	2.58E+03	3.10E+02	2.56E+03	4.44E+02	8.93E+02	3.30E+02
ODP kg CFC11 eq	7.27E-03	5.25E-03	2.11E-04	1.60E-04	5.96E-03	3.05E-03	5.45E-03	3.56E-03	2.17E-04	1.75E-04	1.87E-02	2.24E-03	1.14E-02	1.99E-03	2.78E-04	1.03E-04
IR kBq Co-60 eq	2.62E+01	1.89E+01	8.46E+00	6.42E+00	1.81E+01	9.25E+00	9.86E+00	6.44E+00	5.54E+00	4.48E+00	3.93E+01	4.72E+00	3.54E+01	6.14E+00	9.10E+00	3.37E+00
OF-HH kg NO_x eq	1.26E+01	9.12E+00	8.83E+00	6.69E+00	1.22E+01	6.24E+00	9.20E+00	6.01E+00	9.20E+00	7.44E+00	2.34E+01	2.81E+00	2.01E+01	3.49E+00	1.01E+01	3.73E+00
PMF kg $PM_{2.5}$ eq	1.12E+01	8.12E+00	9.20E+00	6.98E+00	1.08E+01	5.53E+00	8.86E+00	5.78E+00	8.66E+00	7.00E+00	2.77E+01	3.33E+00	1.50E+01	2.60E+00	1.22E+01	4.50E+00
OF-TE kg NO_x eq	2.85E+01	2.06E+01	1.82E+01	1.38E+01	2.81E+01	1.44E+01	2.33E+01	1.52E+01	1.77E+01	1.43E+01	7.03E+01	8.44E+00	4.29E+01	7.44E+00	2.33E+01	8.63E+00
TA kg SO_2 eq	1.77E+01	1.28E+01	6.67E+00	5.06E+00	1.22E+01	6.24E+00	9.89E+00	6.46E+00	6.28E+00	5.08E+00	3.37E+01	4.05E+00	2.21E+01	3.84E+00	8.13E+00	3.01E+00
FE kg P eq	2.24E-01	1.62E-01	1.15E-01	8.71E-02	1.54E-01	7.89E-02	6.70E-02	4.38E-02	5.75E-02	4.65E-02	2.63E-01	3.16E-02	2.94E-01	5.10E-02	9.14E-02	3.38E-02
ME kg N eq	4.22E-02	3.05E-02	1.03E-02	7.84E-03	3.55E-02	1.82E-02	2.90E-02	1.90E-02	7.52E-03	6.08E-03	1.05E-01	1.26E-02	7.16E-02	1.24E-02	1.10E-02	4.06E-03
TETkg 1.4-DCB eq	1.95E+04	1.41E+04	1.28E+04	9.68E+03	1.05E+04	5.38E+03	6.56E+03	4.28E+03	7.44E+03	6.02E+03	1.71E+04	2.05E+03	2.07E+04	3.60E+03	8.03E+03	2.97E+03
FET kg 1.4-DCB eq	5.07E+01	3.67E+01	2.51E+01	1.91E+01	3.78E+01	1.94E+01	2.04E+01	1.33E+01	1.36E+01	1.10E+01	9.77E+01	1.17E+01	8.48E+01	1.47E+01	3.05E+01	1.13E+01
MET kg 1.4-DCB eq	8.61E+01	6.22E+01	4.87E+01	3.69E+01	6.52E+01	3.34E+01	3.94E+01	2.57E+01	2.50E+01	2.03E+01	1.44E+02	1.73E+01	1.35E+02	2.34E+01	4.87E+01	1.80E+01
HT-c kg 1.4-DCB eq	2.70E+02	1.95E+02	1.69E+02	1.28E+02	1.49E+02	7.64E+01	9.19E+01	6.00E+01	9.16E+01	7.41E+01	2.72E+02	3.26E+01	2.93E+02	5.08E+01	1.09E+02	4.02E+01
HT-nc kg 1.4-DCB eq	1.76E+03	1.27E+03	1.14E+03	8.67E+02	9.97E+02	5.11E+02	6.14E+02	4.01E+02	7.02E+02	5.68E+02	1.68E+03	2.02E+02	2.00E+03	3.47E+02	7.74E+02	2.86E+02
LUm^2a crop eq	4.61E+02	3.33E+02	2.51E+01	1.90E+01	3.92E+02	2.01E+02	1.03E+01	6.71E+00	1.03E+01	8.37E+00	5.47E+01	6.56E+00	3.02E+02	5.25E+01	1.35E+01	4.99E+00
MRS kg Cu eq	2.04E+01	1.47E+01	3.33E+00	2.53E+00	1.39E+01	7.10E+00	2.10E+00	1.37E+00	1.83E+00	1.48E+00	9.14E+00	1.10E+00	1.53E+01	2.65E+00	2.34E+00	8.65E-01
FRS kg oil eq	3.25E+02	2.35E+02	1.81E+02	1.37E+02	3.64E+02	1.86E+02	1.72E+02	1.13E+02	1.78E+02	1.44E+02	7.50E+02	9.00E+01	7.62E+02	1.32E+02	3.09E+02	1.14E+02
WaC m^3	1.48E+02	1.07E+02	9.36E+01	7.10E+01	4.99E+02	2.55E+02	3.77E+00	2.46E+00	9.88E-01	8.00E-01	1.68E+03	2.02E+02	1.77E+03	3.07E+02	1.25E+03	4.63E+02

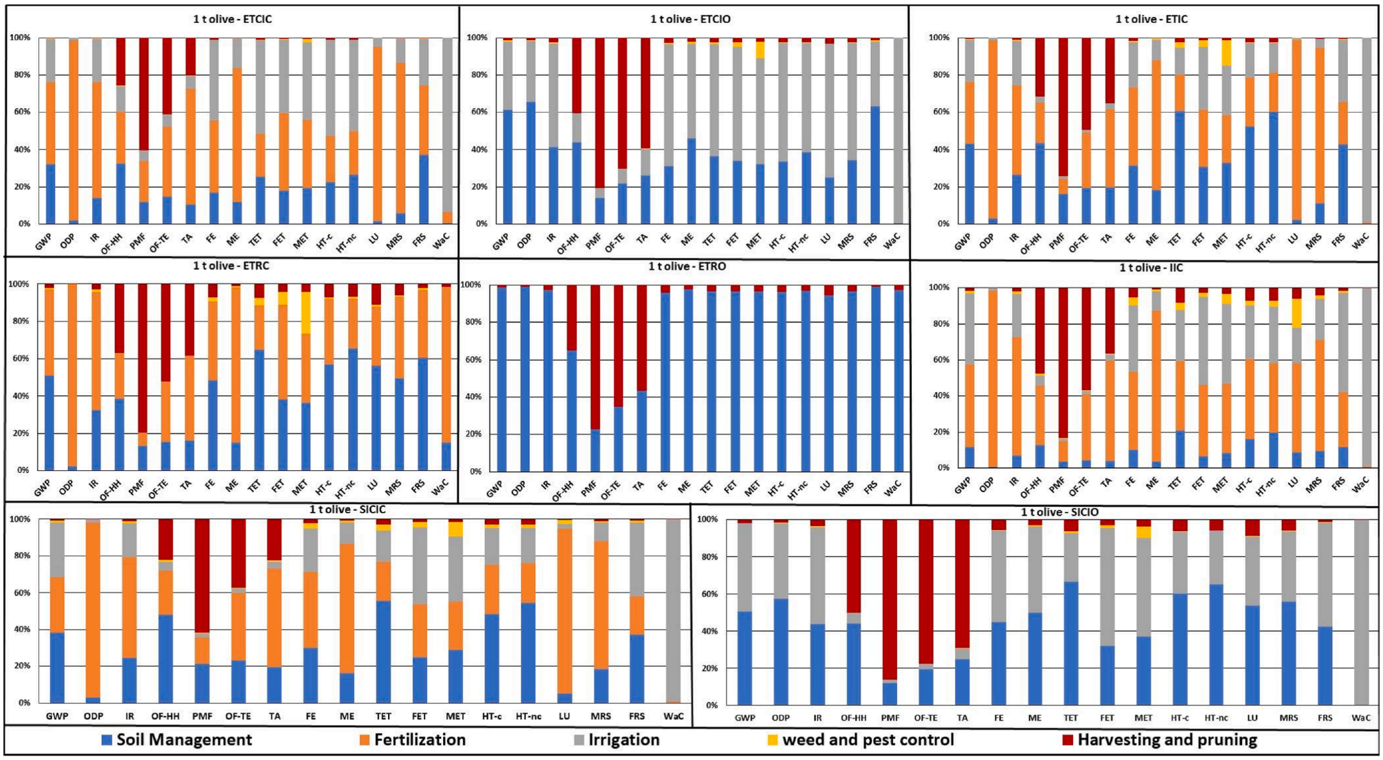

Fig. 5. Contribution analysis of olive production subsystems per t of olive (Acronyms GWP global warming potential ODP ozone depletion IR ionizing radiation OF-HH photochemical ozone formation human health OF-TE photochemical ozone formation terrestrial ecosystems PMF particulate matter formation TA terrestrial acidification FE freshwater eutrophication ME marine eutrophication TET terrestrial ecotoxicity FET freshwater ecotoxicity MET marine ecotoxicity HT-c human toxicity cancer HT-nc human toxicity non-cancer LU land use MRS mineral resource scarcity FRS fossil resource scarcity WaC water consumption.).

high shares reflect the magnitude of nitrogen and phosphorus inputs and the associated losses to air and water. Systems without mineral fertilisers display much lower values, although residual emissions linked to soil processes and baseline nutrient availability still contribute to FE and ME. The gradient across systems underlines the dominant role of fertilisation in driving acidification and eutrophication impacts.

Ecotoxicity, terrestrial (TET), freshwater (FET), and marine (MET) along with human toxicity (carcinogenic = HT-c, non-carcinogenic = HT-nc), are mainly driven by pesticide use and chemical input production. Intensive systems, which use more plant protection products, exhibit higher impacts in these categories. Organic systems, which avoid synthetic pesticides, show substantially lower values. Table 2 confirms this trend, with consistently lower ecotoxicity and human toxicity in organic systems.

3.3.5. LU, MRS, FRS, and WaC

LU is directly related to the cultivated area and production intensity. Extensive systems naturally have a lower LU impact per hectare, but potentially higher per ton of product due to lower yields. Mineral resource scarcity (MRS) and fossil resource scarcity (FRS) are linked to energy consumption and input production. Intensive systems, with their high energy and fertilizer consumption, have higher FRS and MRS impacts. Water consumption (WaC) is, as expected, highest in irrigated systems (IIC, SICIC, ETIC), highlighting the importance of water management in arid and semi-arid regions. Rainfed systems (ETRC, ETRO) have negligible water consumption, making them more resilient to water shortages.

3.4. Mitigation strategies: Electrification via photovoltaic integration

3.4.1. Hectare-scale mitigation impacts of photovoltaic-powered irrigation

Photovoltaic (PV) water pumps, whose solar electricity emits only 30–50 g CO_2 kWh^{-1} compared with 0.7–0.8 kg CO_2 kWh^{-1} from Tunisia's grid, deliver significant life-cycle GHG reductions despite manufacturing impacts. Integrating on-site PV electricity into irrigated olive orchards reduces GWP and FRS burdens while creating upstream trade-offs (Fig. 6A; ***Supplementary Information, Section S6***). Across four irrigated systems, PV irrigation lowers GWP by 14.2 % (ETIC), 29.9 % (IIC), 22.7 % (SICIC) and 33.6 % (SICIO), and cuts FRS by 19–40.2 %. TA and OF-HH/OF-TE decrease by up to 3.6 % as combustion emissions fall, while FET declines by 13.8–29.1 % and MET by 9.4–17.1 %. TET rises marginally (~1 %) due to PV manufacturing. IR impacts increase by 5–18 %, and LU nearly doubles (up to +97 % in SICIO), underscoring the potential of agrivoltaic designs. MRS shows modest reductions (≤9 %), and WaC remains unchanged (<0.1 %), since irrigation volume dominates this category.

3.4.2. Ton-scale mitigation impacts of PV-powered irrigation

On a per-ton basis (Fig. 6B), PV irrigation delivers similar benefits. GWP decreases by 14.1 % (ETIC: 639 → 549 kg CO_2 eq), 29.4 % (IIC: 310 → 219), 22.6 % (SICIC: 444 → 344), and 33.1 % (SICIO: 330 → 221). FRS reductions reach 40.5 % (SICIO: 114 → 72 kg oil eq), while TA, OF-HH, OF-TE and PMF decline by 2–11 %. However, PV manufacturing shifts some burdens upstream: IR rises by 5.3–17.2 %, TET by 1.8 %, and FE by 4.7 % in some cases. Despite these trade-offs, aquatic toxicity benefits persist, with FET reduced by 22.8–31.9 % and MET by 4.5–18.4 %. LU approximately doubles under intensive regimes, while WaC remains unchanged, being dominated by irrigation volume.

Overall, these results confirm that PV powered irrigation can reduce climate and resource related impacts per ton of olives, while the end of life management of PV modules remains outside the scope of this assessment.

3.5. Sensitivity analysis

A one-way sensitivity analysis was performed to evaluate the influence of key foreground parameters on the life-cycle results. Fertilizer inputs (all mineral and organic components, including associated N_2O,

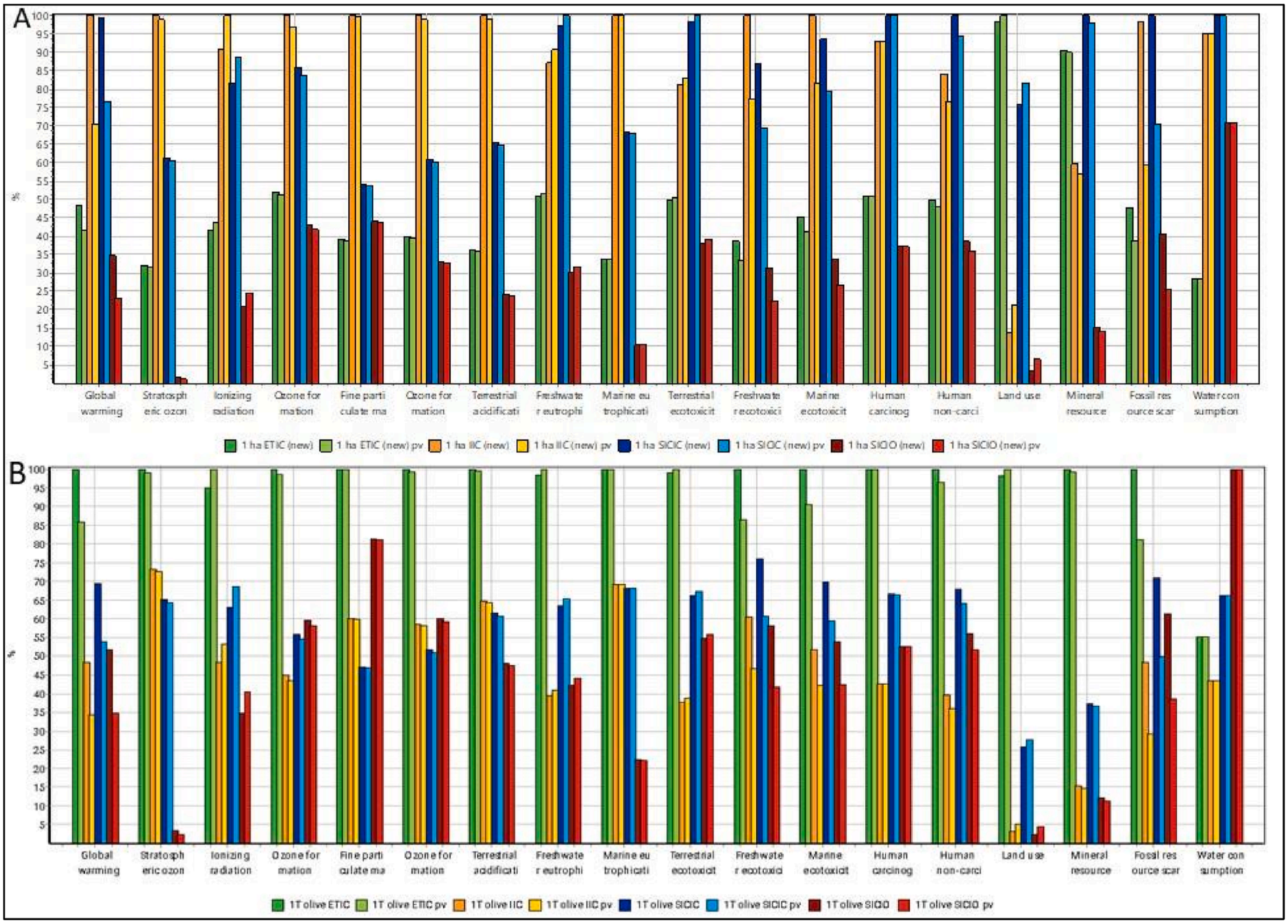

Fig. 6. Comparative life-cycle environmental impacts of photovoltaic versus grid-powered irrigation in olive orchards: (A) Hectare-scale and (B) per-ton analyses across four agrosystems.

NOx and NH_3 emissions), soil-management fuel use, and electricity consumption for irrigation were varied by −20, −10, +10 and + 20 % relative to their baseline values. The full recalculated results for all ReCiPe Midpoint (H) impact categories are provided in ***Supplementary Information "S7, Sensitivity Analyses"***.Varying fertilizer inputs produced the strongest shifts in GWP, terrestrial acidification and eutrophication across all systems, with intensive and semi-intensive systems showing the highest sensitivity due to elevated nitrogen application. Electricity variation affected fossil resource scarcity, ionizing radiation and water consumption primarily in irrigated systems. Soil-management variation influenced particulate matter formation and ozone-related categories. Despite quantitative changes, the relative ranking of systems remained consistent: intensive and semi-intensive irrigated systems maintained the highest impacts per hectare, while extensive organic systems remained the lowest. For example, adjusting fertilizer inputs by ±20 % changed GWP by −9 to +11 % in extensive systems (ETCIC, ETRC), by −7 to +9 % in ETIC, and by −8 to +10 % in the intensive and semi-intensive systems (IIC, SICIC), confirming that nitrogen-related emissions remain the dominant driver of climate impacts. These results confirm that the comparative patterns are robust to uncertainty in the main inventory parameters.

4. Discussion

This study delivers a system-sensitive evaluation of Mediterranean olive production by coupling multivariate statistical techniques with a cradle-to-gate LCA. Three distinct management regimes emerge from the dataset (i) intensive systems (e.g., IIC), which maximize yields (up to 8.33 t ha^{-1}) but rely on substantial synthetic-nutrient inputs, extensive irrigation energy and agrochemicals; (ii) extensive rainfed systems (e.g., ETRO, ETCIO), which minimize external inputs and associated emissions at the expense of lower yields (1.24–1.95 t ha^{-1}); and (iii) semi-intensive systems (e.g., SICIC, SICIO), which balance moderate inputs with mid-range productivity and relatively lower environmental burdens. Correlation analysis revealed that yields in intensive systems scale almost linearly with reactive-nitrogen emissions ($r = 0.98$), while extensive systems show a negative relationship between farm area and yield ($r = -0.62$ to -0.70), reflecting their lower agronomic efficiency but reduced impacts. Semi-intensive systems occupy an intermediate niche, balancing moderate inputs with mid-range productivity. A notable inverse correlation between distance to mill and yield ($r = -0.44$) highlights logistical inefficiencies that can exacerbate post-harvest losses and transport impacts. When these multivariate insights are overlaid on LCA results, synthetic nitrogen and irrigation emerge as the principal drivers of environmental burden, validating our recommendation of PV-driven irrigation to decouple water-energy demands from GHG and eutrophication impacts. This combined framework equips researchers, practitioners and policymakers with actionable, data-driven guidance to enhance resource efficiency and minimize the ecological footprint of olive production in Tunisia and comparable Mediterranean regions.

The Tunisian olive systems exhibit GWP values of 617–695 kg CO_2

eq/ha in extensive rainfed groves and up to 2583 kg CO_2 eq/ha in intensive irrigated systems, as shown in Fig. 7 and **Supplementary Information**, **Section S5**. Across Mediterranean LCA studies, GWP ranges from approximately 140 kg CO_2 eq/ha in low-input rainfed orchards to more than 10,000 kg CO_2 eq/ha in highly irrigated systems (Romero-Gámez et al., 2017; De Gennaro et al., 2012; Lehmann et al., 2020; Pattara et al., 2016; Sales et al., 2022). Reported country-level intervals include 141–3090 kg CO_2 eq/ha for Spain, 918–2300 kg CO_2 eq/ha for Greece, 602–7000 kg CO_2 eq/ha for Italy, and values exceeding 10,000 kg CO_2 eq/ha for Turkey (De Luca et al., 2018; Guarino et al., 2019; Pergola et al., 2013). When expressed per ton of olives, the values obtained in this study (310–946 kg CO_2 eq t^{-1}) align with published benchmarks of 233–865 kg CO_2 eq/t (Maesano et al., 2021; Rahmani et al., 2022). These patterns confirm that irrigation intensity and nitrogen fertilisation are the main drivers of GWP variability in Mediterranean olive production and demonstrate that the Tunisian results are consistent with regional trends. Nitrogen fertilization requirements can be further reduced through the integration of legume-based cover crops or intercropping systems, which fix atmospheric N_2 and enhance soil nitrogen availability, thereby lowering the need for synthetic inputs and associated emissions (Crews and Peoples, 2004; Jensen et al., 2020). While GWP remains a key focus, other impact categories such as TA, FE, ecotoxicities (TET, FET, MET), and WaC present critical trade-offs. In particular, our findings indicate that fertilizer use and irrigation energy are the primary contributors to TA (kg SO_2 eq) and eutrophication (FE and ME, kg P/N eq), especially in intensively-fertilized systems (IIC, SICIC). These results are consistent with Romero-Gámez et al. (2017), who emphasized nutrient leaching and NH_3 volatilization as hotspots in conventional olive orchards.

An important limitation is that, consistent with most existing LCAs of olive production, the inventory does not explicitly quantify nitrate leaching to groundwater. Recent studies indicate that fertilizer-induced NO_3^-–N leaching can represent approximately 8–40 % of applied nitrogen, depending on soil characteristics, climate, and management practices, thereby highlighting the broad variability of associated emission factors (Pan et al., 2024). In view of this variability and the absence of site-specific measurements for Tunisian orchards, groundwater NO_3^- flows were not approximated using generic factors. Consequently, FE and ME estimates should be interpreted as conservative with respect to total nitrogen losses. By contrast, emissions of pesticides were fully accounted for by allocating 100 % of the applied mass to the agricultural soil compartment, together with other phytosanitary inputs (e.g., copper and boron formulations), following the inventory modelling rules of the World Food LCA Database (Nemecek et al., 2019).

Pesticide applications, notably copper-based fungicides, emerged as the primary drivers of both (HT-c) and ecotoxicity (TET, FET, MET) burdens in conventional systems (ETCIC, ETIC), corroborating findings by Fernández-Lobato et al. (2024) and Maesano et al. (2021). In contrast, organic and integrated regimes exemplified by ETRO and SICIO demonstrated up to a 70 % reduction in toxicity-related impact metrics per ton of olives, owing to their minimal reliance on synthetic agrochemicals. This stark divergence highlights the efficacy of chemical-input reduction strategies in mitigating toxicity hotspots within Mediterranean olive production.

WaC showed the most pronounced variation among the olive production systems assessed, ranging from less than 100 m^3/ha in rainfed systems such as ETRO and ETRC to approximately 1700 m^3/ha in fully-irrigated systems like SICIC. These results fall within the range reported in the literature for Mediterranean olive production systems and underscore the high variability of water-related impacts depending on

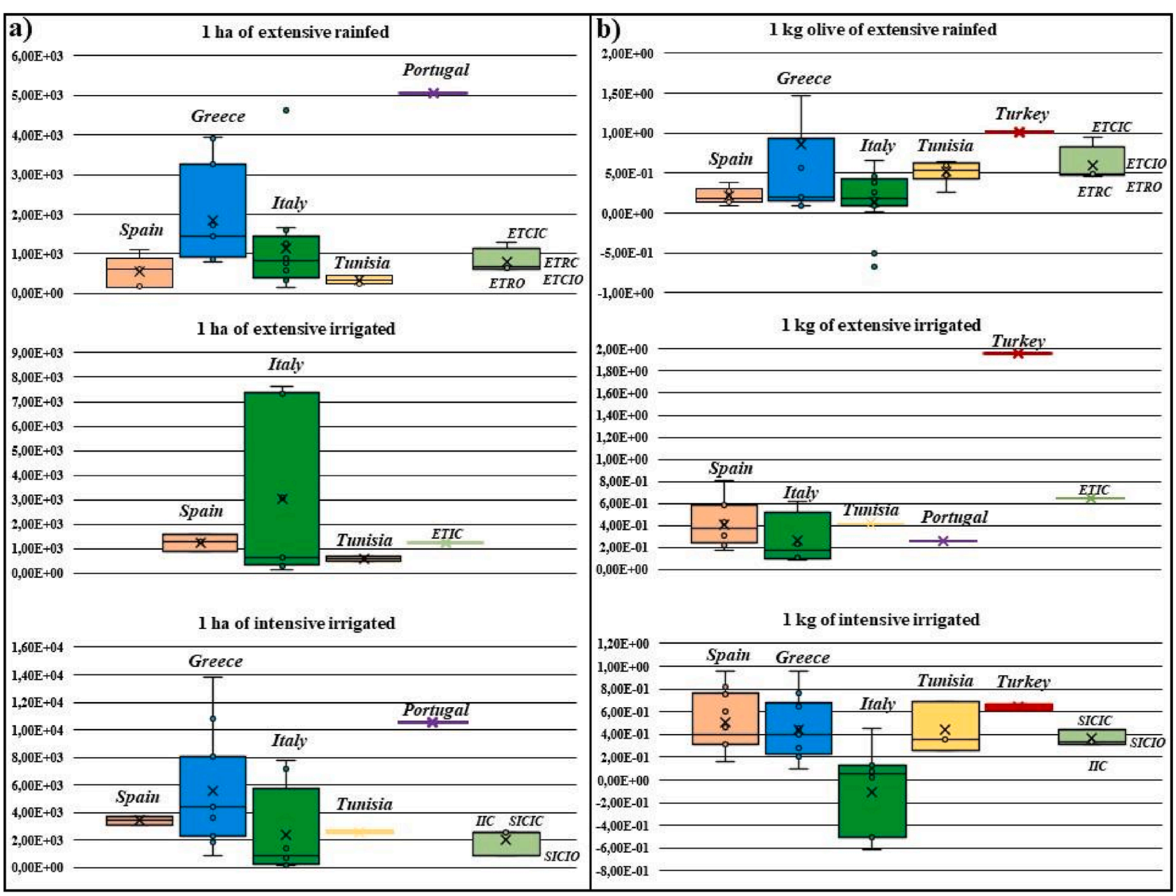

Fig. 7. Comparative GWP of Mediterranean olive production systems, expressed per hectare of cultivation ((a)left panels) and per kilogram of olives ((b)right panels). Tunisian systems (ETCIC, ETCIO, ETRC, ETRO, ETIC, IIC, SICIC, SICIO) are compared with values reported for Spain, Greece, Italy, Portugal, and Turkey.

irrigation intensity and regional practices. However, interpretation of these values remains complex, as different life cycle impact assessment methods (e.g., ReCiPe, AWARE, or Water Scarcity Index) apply different characterization models and factors. While ReCiPe considers generic WaC per unit volume, indicators like the Water Scarcity Index incorporate local water availability (WTA), leading to quantitatively divergent results depending on the spatial context (Maesano et al., 2021). Therefore, while fully-irrigated systems improve productivity and reduce impacts per ton of olives, they may also contribute disproportionately to regional water stress depending on water source and management, making site-specific evaluation essential for sustainable irrigation planning.

Land use impacts (m^2a crop eq) and mineral resource scarcity (kg Cu eq) were also prominent in high-density systems such as IIC and SICIC. However, these systems compensated with high yields (up to 8.3 t/ha), reducing impacts when normalized per ton of olives. This reflects the well-established yield impact trade-off: extensive production systems can improve environmental performance per unit of product, but amplify absolute impacts at landscape scale, a trend also discussed by Navarro et al. (2018) and Guarino et al. (2019).

Quantifying pruning-residue burning increased terrestrial acidification by up to 12 %, particulate-matter formation by 8 % and terrestrial eutrophication by 10 % in conventionally managed systems (ETCIC, ETRC), based on emission factors of 0.0023 kg NO_x, 0.0024 kg NH_3 and 0.0054 kg $PM_{2.5}$ per kg dry matter (EEA, 2023; SI S2). By integrating this often neglected source, our LCI better reflects on-farm burdens and shows that a simple no-burning scenario, where pruning residues are retained on the soil, would reduce these impact categories by about 20–35 % compared with the current practice. These reductions are in line with LCA studies reporting benefits of alternative residue management options such as mulching, composting or bioenergy recovery in Mediterranean orchards (Sales et al., 2022; Fernández-Lobato et al., 2022). Systems combining organic amendments with reduced tillage and mechanical weeding (ETCIO, SICIO) achieved 40–60 % lower toxicity and eutrophication impacts and a 25 % reduction in GWP, validating the effectiveness of agroecological practices (Sales et al., 2022; Guermazi et al., 2017). Previous field and modelling studies in Mediterranean olive groves report that introducing intercropping or cover crops can enhance soil carbon sequestration by about 15 % and reduce synthetic nitrogen demand by roughly 30 % (Aguilera-Huertas et al., 2024; Tziolas et al., 2022)Collectively, our findings demonstrate that achieving environmental sustainability in Tunisian olive production requires a coordinated strategy of irrigation efficiency, organic nutrient management, input minimization and renewable-energy integration, rather than a binary choice between traditional and intensive models. Future research should refine site-specific LCAs accounting for local climate, soil and socio-economic factors and evaluate circular pathways for pomace, pruning biomass and wastewater valorization to further close resource loops (Galán-Martín et al., 2022; Ben Abdallah et al., 2022). Management strategies must be aligned with the prevailing agroclimatic context (Maffia et al., 2020). In the water-limited central and southern regions, low-input rainfed or deficit-irrigated systems, coupled with stringent nitrogen management and systematic residue mulching, represent the most environmentally robust option, as they avoid the substantial increases in water consumption and eutrophication potential associated with highly irrigated intensive orchards. Conversely, in the more humid northern zones, semi-intensive and intensive systems can be environmentally acceptable, provided they are integrated with photovoltaic-powered irrigation and substantially reduced agrochemical inputs. Such configurations help contain GWP, freshwater eutrophication, ecotoxicity, and land-use pressures while maintaining competitive productivity.

4.1. Future perspectives

Ensuring the long-term sustainability of olive production hinges on integrating technological and agronomic innovations that reduce environmental impacts while maintaining economic viability. These options need to be adapted to regional agroclimatic conditions, with water-saving low-input management prioritized in water-scarce central and southern areas and PV-based irrigation and diversified cover-crop systems more relevant in the humid northern regions. Further gains are expected from next-generation perovskite/Si modules and improved recycling (Pandey et al., 2025a, 2025b; Yu and Yang, 2025; Cayuela et al., 2024; Wernet et al., 2016; Nugent and Sovacool, 2014; Peng et al., 2013). Renewable biofuels, such as biodiesel from waste oils or sustainably cultivated biomass, can cut CO_2-equivalent emissions by 50–90 %, lower intermediate-volatility organic compounds, particulate, and hydrocarbon outputs, and support rural biofuel value chains, especially when engine tuning mitigates modest NO_x increases at B20 blends (Cui et al., 2025; Tilman et al., 2009). Intercropping or agroforestry using leguminous cover crops (e.g., vetch) either alone or in rotation/association with cereals (e.g., barley, rye) fixes 40–80 kg N ha^{-1} yr^{-1} biologically (reducing synthetic fertilizer demand and N_2O emissions by up to 35 %), accrues 0.2–0.4 Mg C ha^{-1} yr^{-1} in soil organic carbon, enhances biodiversity, controls erosion, and diversifies farm income (Yu et al., 2025; Aguilera-Huertas et al., 2024; Tziolas et al., 2022; Zuazo et al., 2020).

Addressing this gap in soil emissions requires integrating LCA with process-based biogeochemical modelling. A promising pathway is to couple olive LCIs with the DNDC model, following the workflow demonstrated by Medel-Jiménez et al. for arable systems, in which DNDC-simulated soil nitrogen and carbon fluxes are directly transferred to the life-cycle inventory (Medel-Jiménez et al., 2022, 2024). Such an integration would enable the derivation of site-specific emission factors for NO_3^- leaching and gaseous nitrogen species in Tunisian olive orchards, thereby substantially reducing current uncertainty in FE, ME, and TA indicators.

To translate these synergies into practice, future research must focus on long-term PV-battery hybrid trials in semi-arid orchards, high-blend biodiesel performance testing in off-road machinery, and system-level agroforestry modeling under Mediterranean climate scenarios. Policy instruments such as feed-in tariffs, irrigation subsidies, and carbon pricing should also be realigned to incentivize on-farm adoption.

5. Conclusion

This study demonstrates that Mediterranean olive production is governed by a fundamental yield–impact trade-off. Intensive orchards reach productivity levels of up to 8.3 t ha^{-1} but incur disproportionately high burdens in agrochemical use, energy demand, and emissions, whereas extensive and semi-intensive systems, despite lower yields, substantially mitigate environmental pressures. The multivariate pre-LCA assessment reveals that gradients in fertilization, irrigation, and pesticide inputs are the dominant drivers of GWP, TA, FE, ME, TET, FET, MET and WaC, while also highlighting underappreciated levers such as mill proximity and pruning-residue management.

These findings argue against the binary “traditional versus intensive” paradigm and underscore the need for context-specific LCA frameworks that explicitly incorporate soil heterogeneity, climatic variability, water scarcity and circular-resource strategies. Integrating clean-energy technologies, especially PV-powered irrigation and replacing fossil fuels with renewable bioenergy, alongside improved agronomic interventions such as strategic intercropping and optimized residue valorization, can reorient olive production toward a more climate-resilient and resource-efficient trajectory. Achieving this transition will require targeted R&D

investment, enabling policy instruments, and sustained cross-sectoral collaboration to foster technology transfer and accelerate adoption at the farm level.

CRediT authorship contribution statement

Makrem Cherni: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Hajer Ben Ammar:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **Mohamed Guesmi:** Writing – original draft, Visualization, Software. **Rabii Lanwer:** Investigation, Formal analysis, Data curation. **Yassine Hidri:** Investigation, Formal analysis, Data curation. **Khaled Ouertani:** Investigation, Formal analysis, Data curation. **Hakim Boulal:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Boubaker Dhehibi:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Aymen Frija:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Ajmi Larbi:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was conducted with the support of the Multifunctional Landscape Program (AoW3 on Markets and Business Models) under a grant agreement (#200419) with the International Center for Agricultural Research in the Dry Areas (ICARDA - https://www.icarda.org/). We would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund: https://www.cgiar.org/funders, and the APNI project "Out-scaling 4R Nutrient Stewardship Knowledge to Support Olive Production". The authors gratefully acknowledge the contributions of all stakeholders and partners involved.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resenv.2026.100288.

References

Agridata, 2023. Production et superficie des fruits. https://catalog.agridata.tn/fr/dataset/production-et-superficie-des-fruits-pour-la-campagne-2021-2022.

Aguilera-Huertas, J., Parras-Alcántara, L., González-Rosado, M., Lozano-García, B., 2024. Intercropping in rainfed Mediterranean olive groves contributes to improving soil quality and soil organic carbon storage. Agric. Ecosyst. Environ. 361, 108826. https://doi.org/10.1016/j.agee.2023.108826.

Avraamides, M., Fatta, D., 2008. Resource consumption and emissions from olive oil production: a life cycle inventory case study in Cyprus. J. Clean. Prod. 16, 809–821. https://doi.org/10.1016/j.jclepro.2007.04.002.

Ben Abdallah, S., Elfkih, S., Suárez-Rey, E.M., Parra-López, C., Romero-Gámez, M., 2021. Evaluation of the environmental sustainability in the olive growing systems in Tunisia. J. Clean. Prod. 282, 124526. https://doi.org/10.1016/j.jclepro.2020.124526.

Ben Abdallah, S., Parra-López, C., Elfkih, S., Suárez-Rey, E.M., Romero-Gámez, M., 2022. Sustainability assessment of traditional, intensive and highly-intensive olive growing systems in Tunisia by integrating life cycle and multicriteria decision analyses. Sustain. Prod. Consum. 33, 73–87. https://doi.org/10.1016/j.spc.2022.06.022.

Brito, T., Fernandes-Silva, A., 2022. Life cycle assessment for olive production: a case study for the region of Trás-os-Montes, Portugal. Proc. Latv. Acad. Sci. Sect. B Nat. Exact Appl. Sci. 76, 526–530. https://doi.org/10.2478/prolas-2022-0081.

Cayuela, J.A.F., García, A.M., García, I.F., Díaz, J.A.R., 2024. Life cycle assessment of large-scale solar photovoltaic irrigation. Sci. Total Environ. 954, 176813. https://doi.org/10.1016/j.scitotenv.2024.176813.

Crews, T.E., Peoples, M.B., 2004. Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. Agric. Ecosyst. Environ. 102 (3), 279–297. https://doi.org/10.1016/j.agee.2003.09.018.

Cui, M., Hou, X., Han, Y., Zhang, Y., Liu, Z., Li, J., Chen, Y., Zhang, F., Yan, C., Zhang, Y., 2025. Real-world emissions and formation mechanism of IVOCs from biodiesel-fueled agricultural machinery. Environ. Sci. Technol. 59, 9017–9026. https://doi.org/10.1021/acs.est.4c11004.

De Gennaro, B., Notarnicola, B., Roselli, L., Tassielli, G., 2012. Innovative olive-growing models: an environmental and economic assessment. J. Clean. Prod. 28, 70–80. https://doi.org/10.1016/j.jclepro.2011.11.004.

De Luca, A.I., Falcone, G., Stillitano, T., Iofrida, N., Strano, A., Gulisano, G., 2018. Evaluation of sustainable innovations in olive growing systems: a life cycle sustainability assessment case study in southern Italy. J. Clean. Prod. 171, 1187–1202. https://doi.org/10.1016/j.jclepro.2017.10.119.

EEA, 2023. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023: Technical Guidance to Prepare National Emission Inventories. Publications, Office, LU.

Espadas-Aldana, G., Vialle, C., Belaud, J.-P., Vaca-Garcia, C., Sablayrolles, C., 2019. Analysis and trends for life cycle assessment of olive oil production. Sustain. Prod. Consum. 19, 216–230. https://doi.org/10.1016/j.spc.2019.04.003.

FAO, 2025. FAOSTAT - Crops and livestock products: Metadata. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data/QCL/visualize.

Fernández-Lobato, L., López-Sánchez, Y., Blejman, G., Jurado, F., Moyano-Fuentes, J., Vera, D., 2021. Life cycle assessment of the Spanish virgin olive oil production: a case study for Andalusian region. J. Clean. Prod. 290, 125677. https://doi.org/10.1016/j.jclepro.2020.125677.

Fernández-Lobato, L., López-Sánchez, Y., Baccar, R., Fendri, M., Vera, D., 2022. Life cycle assessment of the most representative virgin olive oil production systems in Tunisia. Sustain. Prod. Consum. 32, 908–923. https://doi.org/10.1016/j.spc.2022.06.002.

Fernández-Lobato, L., Ruiz-Carrasco, B., Tostado-Véliz, M., Jurado, F., Vera, D., 2024. Environmental impact of the most representative Spanish olive oil farming systems: a life cycle assessment study. J. Clean. Prod. 442, 141169. https://doi.org/10.1016/j.jclepro.2024.141169.

Fotia, K., Mehmeti, A., Tsirogiannis, I., Nanos, G., Mamolos, A.P., Malamos, N., Barouchas, P., Todorovic, M., 2021. LCA-Based environmental performance of olive cultivation in Northwestern Greece: from rainfed to irrigated through conventional and smart crop management practices. Water 13, 1954. https://doi.org/10.3390/w13141954.

Galán-Martín, Á., Contreras, M.D.M., Romero, I., Ruiz, E., Bueno-Rodríguez, S., Eliche-Quesada, D., Castro-Galiano, E., 2022. The potential role of olive groves to deliver carbon dioxide removal in a carbon-neutral Europe: opportunities and challenges. Renew. Sustain. Energy Rev. 165, 112609. https://doi.org/10.1016/j.rser.2022.112609.

Guarino, F., Falcone, G., Stillitano, T., De Luca, A.I., Gulisano, G., Mistretta, M., Strano, A., 2019. Life cycle assessment of olive oil: a case study in southern Italy. J. Environ. Manag. 238, 396–407. https://doi.org/10.1016/j.jenvman.2019.03.006.

Guermazi, Z., Gharsallaoui, M., Perri, E., Gabsi, S., Benincasa, C., 2017. Integrated approach for the eco design of a new process through the life cycle analysis of olive oil: total use of olive by-products. Eur. J. Lipid Sci. Technol. 119, 1700009. https://doi.org/10.1002/ejlt.201700009.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

IOC, 2024. International Olive Council, Key Figures on the World Market for Olive Oils. Data Adopted at the 120th Session of the Council of Members Madrid Spain November 2024. International Olive Council, Madrid Spain. Available at: https://www.internationaloliveoil.org/what-we-do/statistics/#datafiles.

IOC, 2025. International Olive Council. World Trade in Olive Oil and Table Olives – 2024/2025 Crop Year. Economic and Promotion Unit – Economic Research and Statistics Department.

ISO 14040, 2006. Environmental Management-Life cycle assessment-principles and framework. https://www.iso.org/standard/37456.html.

ISO 14044, 2006. Environmental Management-Life cycle assessment-requirements and guidelines. https://www.iso.org/standard/38498.html.

Jensen, E.S., Carlsson, G., Hauggaard-Nielsen, H., 2020. Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: a global-scale analysis. Agron. Sustain. Dev. 40, 5. https://doi.org/10.1007/s13593-020-0607-x.

Klein, D., 2006. N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application, 1 (No Title).

Larbi, A., Msallem, M., Sai, M.B., 2017. L'Intensification Des Oliviers En Tunisie: Les Avantages, Les Problemes Et Les Perspectives. Olive Tree Institute (IO).

Lehmann, L.M., Borzęcka, M., Żyłowska, K., Pisanelli, A., Russo, G., Ghaley, B.B., 2020. Environmental impact assessments of integrated food and non-food production systems in Italy and Denmark. Energies 13, 849. https://doi.org/10.3390/en13040849.

Loumou, A., Giourga, C., 2003. Olive groves: "the life and identity of the Mediterranean". Agric. Hum. Val. 20, 87–95. https://doi.org/10.1023/A:1022444005336.

Maesano, G., Chinnici, G., Falcone, G., Bellia, C., Raimondo, M., D'Amico, M., 2021. Economic and environmental sustainability of olive production: a case Study. Agronomy 11, 1753. https://doi.org/10.3390/agronomy11091753.

Maffia, A., Pergola, M., Palese, A.M., Celano, G., 2020. Environmental impact assessment of organic vs. integrated olive-oil systems in Mediterranean context. Agronomy 10, 416. https://doi.org/10.3390/agronomy10030416.

Medel-Jiménez, F., Piringer, G., Gronauer, A., Barta, N., Neugschwandtner, R.W., Krexner, T., Kral, I., 2022. Modelling soil emissions and precision agriculture in fertilization life cycle assessment - a case study of wheat production in Austria. J. Clean. Prod. 380, 134841. https://doi.org/10.1016/j.jclepro.2022.134841.

Medel-Jiménez, F., Krexner, T., Gronauer, A., Kral, I., 2024. Life cycle assessment of four different precision agriculture technologies and comparison with a conventional scheme. J. Clean. Prod. 434, 140198. https://doi.org/10.1016/j.jclepro.2023.140198.

Navarro, A., Puig, R., Martí, E., Bala, A., Fullana-i-Palmer, P., 2018. Tackling the relevance of packaging in life cycle assessment of virgin olive oil and the environmental consequences of regulation. Environ. Manag. 62, 277–294. https://doi.org/10.1007/s00267-018-1021-x.

Nemecek, T., Bengoa, X., Lansche, J., Roesch, A., Faist-Emmenegger, M., Rossi, V., Humbert, S., 2019. Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 3.5, December 2019. World Food LCA Database (WFLDB). Quantis and Agroscope Lausanne and Zurich, Switzerland.

Nugent, D., Sovacool, B.K., 2014. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: a critical meta-survey. Energy Policy 65, 229–244. https://doi.org/10.1016/j.enpol.2013.10.048.

OLIVÆ, 2017. Journal Officiel Du Conseil Oléicole International, 124, pp. 4–7.

Pan, Y., She, D., Ding, J., Abulaiti, A., Zhao, J., Wang, Y., Liu, R., Wang, F., Shan, J., Xia, Y., 2024. Coping with groundwater pollution in high-nitrate leaching areas: the efficacy of denitrification. Environ. Res. 250, 118484. https://doi.org/10.1016/j.envres.2024.118484.

Pandey, G., Lyden, S., Franklin, E., Harrison, M.T., 2025a. Agrivoltaics as an SDG enabler: Trade-offs and co-benefits for food security, energy generation and emissions mitigation. Resources, Environment and Sustainability 19, 100186. https://doi.org/10.1016/j.resenv.2024.100186.

Pandey, G., Lyden, S., Franklin, E., Millar, B., Harrison, M.T., 2025b. A systematic review of agrivoltaics: productivity, profitability, and environmental co-benefits. Sustain. Prod. Consum. 56, 13–36. https://doi.org/10.1016/j.spc.2025.03.006.

Pattara, C., Salomone, R., Cichelli, A., 2016. Carbon footprint of extra virgin olive oil: a comparative and driver analysis of different production processes in Centre Italy. J. Clean. Prod. 127, 533–547. https://doi.org/10.1016/j.jclepro.2016.03.152.

Peng, J., Lu, L., Yang, H., 2013. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renew. Sustain. Energy Rev. 19, 255–274. https://doi.org/10.1016/j.rser.2012.11.035.

Pergola, M., Favia, M., Palese, A.M., Perretti, B., Xiloyannis, C., Celano, G., 2013. Alternative management for olive orchards grown in semi-arid environments: an energy, economic and environmental analysis. Sci. Hortic. 162, 380–386. https://doi.org/10.1016/j.scienta.2013.08.031.

Proietti, S., Sdringola, P., Regni, L., Evangelisti, N., Brunori, A., Ilarioni, L., Nasini, L., Proietti, P., 2017. Extra Virgin Olive oil as carbon negative product: experimental analysis and validation of results. J. Clean. Prod. 166, 550–562. https://doi.org/10.1016/j.jclepro.2017.07.230.

Rahmani, A., Parashkoohi, M.G., Zamani, D.M., 2022. Sustainability of environmental impacts and life cycle energy and economic analysis for different methods of grape and olive production. Energy Rep. 8, 2778–2792. https://doi.org/10.1016/j.egyr.2022.01.197.

Rapa, M., Ciano, S., 2022. A review on life cycle assessment of the olive oil production. Sustainability 14, 654. https://doi.org/10.3390/su14020654.

Rinaldi, S., Barbanera, M., Lascaro, E., 2014. Assessment of carbon footprint and energy performance of the extra virgin olive oil chain in Umbria, Italy. Sci. Total Environ. 482–483, 71–79. https://doi.org/10.1016/j.scitotenv.2014.02.104.

Romero-Gámez, M., Castro-Rodríguez, J., Suárez-Rey, E.M., 2017. Optimization of olive growing practices in Spain from a life cycle assessment perspective. J. Clean. Prod. 149, 25–37. https://doi.org/10.1016/j.jclepro.2017.02.071.

Ruiz-Carrasco, B., Fernández-Lobato, L., López-Sánchez, Y., Vera, D., 2023. Life cycle assessment of olive oil production in Turkey, a territory with an intensive production Project. Agriculture 13, 1192. https://doi.org/10.3390/agriculture13061192.

Sales, H., Figueiredo, F., Vaz Patto, M.C., Nunes, J., 2022. Assessing the environmental sustainability of Portuguese olive growing practices from a life cycle assessment perspective. J. Clean. Prod. 355, 131692. https://doi.org/10.1016/j.jclepro.2022.131692.

Salomone, R., Ioppolo, G., 2012. Environmental impacts of olive oil production: a Life Cycle Assessment case study in the province of Messina (Sicily). J. Clean. Prod. 28, 88–100. https://doi.org/10.1016/j.jclepro.2011.10.004.

Skiba, U., Medinets, S., Cardenas, L.M., Carnell, E.J., Hutchings, N.J., Amon, B., 2021. Assessing the contribution of soil NO x emissions to European atmospheric pollution. Environ. Res. Lett. 16, 025009.

Sustainability, Pr, 2022. SimaPro LCA software for informed change-makers. Pré Sustainability.

Taxidis, E.T., Menexes, G.C., Mamolos, A.P., Tsatsarelis, C.A., Anagnostopoulos, C.D., Kalburtji, K.L., 2015. Comparing organic and conventional olive groves relative to energy use and greenhouse gas emissions associated with the cultivation of two varieties. Appl. Energy 149, 117–124. https://doi.org/10.1016/j.apenergy.2015.03.128.

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., Williams, R., 2009. Beneficial Biofuels—The food, energy, and environment trilemma. Science 325, 270–271. https://doi.org/10.1126/science.1177970.

Todde, G., Murgia, L., Deligios, P.A., Hogan, R., Carrelo, I., Moreira, M., Pazzona, A., Ledda, L., Narvarte, L., 2019. Energy and environmental performances of hybrid photovoltaic irrigation systems in Mediterranean intensive and super-intensive olive orchards. Sci. Total Environ. 651, 2514–2523. https://doi.org/10.1016/j.scitotenv.2018.10.175.

Tsarouhas, P., Achillas, Ch, Aidonis, D., Folinas, D., Maslis, V., 2015. Life Cycle Assessment of olive oil production in Greece. J. Clean. Prod. 93, 75–83. https://doi.org/10.1016/j.jclepro.2015.01.042.

Tziolas, E., Ispikoudis, S., Mantzanas, K., Koutsoulis, D., Pantera, A., 2022. Economic and environmental assessment of olive agroforestry practices in Northern Greece. Agriculture 12, 851. https://doi.org/10.3390/agriculture12060851.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.

Willer, H., Travnicek, J., Schlatter, B., 2025. The World of Organic Agriculture. Statistics and Emerging Trends 2025. Research Institute of Organic Agriculture FiBL, Frick, and IFOAM – Organics International, Bonn.

Yu, Z., Yang, Y., 2025. Carbon footprint of global cotton production. Resources, Environment and Sustainability 20, 100214. https://doi.org/10.1016/j.resenv.2025.100214.

Yu, W., Zhao, P., Li, C., Wang, D., Ming, C., Chen, L., Zhou, L., Zhu, Q., Tang, L., Zhou, Y., Long, G., 2025. Intercropping achieves long-term dual goals of yield gains and soil N_2O emission mitigation. Resources, Environment and Sustainability 20, 100210. https://doi.org/10.1016/j.resenv.2025.100210.

Zuazo, V.H.D., Rodríguez, B.C., García-Tejero, I.F., Ruiz, B.G., Tavira, S.C., 2020. Benefits of organic olive rainfed systems to control soil erosion and runoff and improve soil health restoration. Agron. Sustain. Dev. 40, 41. https://doi.org/10.1007/s13593-020-00644-1.