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Life Cycle Assessment of Dietary Oils Reveals Nutrient-Linked Trade-Offs

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ABSTRACT

Life Cycle Assessment (LCA) is widely used to evaluate the environmental impacts of food production; however, most applications rely on mass- or volume-based functional units that may not reflect the primary function of food, namely the provision of human nutrition. Enviro-nutritional Life Cycle Assessment (n-LCA) seeks to address this context-specific limitation by integrating nutritional attributes into environmental assessments. In this study, a nutrient-specific n-LCA framework is applied to dietary oils, using extra virgin olive oil (EVOO) as a demonstrator system. An attributional LCA was conducted to quantify environmental impacts across 14 Tuscan EVOO production systems from cradle to bulk processed oil production, with climate change impacts characterised using the Intergovernmental Panel on Climate Change's Sixth Assessment Report factors. Carbon footprint results were subsequently normalised to nutrient-specific functional units to support category-level comparison of dietary oils based on fatty acid composition and vitamin E content, enabling calculation of a nutritional carbon footprint expressed per unit nutrient. This approach facilitates comparison of dietary oils based on their efficiency in delivering specific nutritional functions rather than on mass alone. Nutrient-specific rankings reveal trade-offs between environmental performance and nutritional function across oils, highlighting the importance of functional unit selection when assessing the sustainability of dietary fats. Overall, the results demonstrate the utility of nutrient-specific n-LCA for improving the interpretability and relevance of environmental assessments of foods, particularly at the product level.

1 | Introduction

Human health and environmental impact indicators associated with food production and consumption have traditionally been treated as separate scientific domains (Guo et al. 2022). However, growing evidence suggests that improving diet quality could prevent approximately one in five deaths from non-communicable diseases worldwide while simultaneously reducing environmental burdens (Afshin et al. 2019). As a result, assessing the healthfulness of food items within the context of environmental limits has emerged as an important food sustainability objective (McLaren et al. 2021), giving rise to so-called enviro-nutritional impact assessments.

Life Cycle Assessment (LCA) is a widely applied tool for evaluating the environmental impacts of food production systems (Meier et al. 2015; Clark and Tilman 2017; Heller et al. 2013; Meier et al. 2024; Kyttä, Ghani, et al. 2025; Kyttä, Kårlund, et al. 2025). LCA is an internationally standardised methodology that quantifies potential environmental impacts across a product's supply chain, from raw material extraction and processing through manufacturing, transport, use and

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end-of-life management (Guinée 2002). In agri-food LCAs, functional units are most commonly defined on a mass- or volume-based basis often ending at the farmgate exit (Roy et al. 2009; McAuliffe et al. 2020; ISO 14040 2006; ISO 14044 2006). Whilst such functional units fairly facilitate comparisons between products possessing the same or similar nutritional composition (e.g., intensive vs. extensive production systems of the same produce), they do not reflect the primary function of food systems, which is the provision of human nutrition (McAuliffe et al. 2020; Ridoutt 2021). That said, for many consumer-level applications, such as olive oil use where purchase and consumption volumes are largely insensitive to nutritional variation, mass- or volume-based functional units remain appropriate and informative, especially when comparisons are in the same oil-type.

Nutritional Life Cycle Assessment (n-LCA) has therefore emerged as an approach for integrating nutritional attributes into conventional LCA frameworks, most commonly through modification of the functional unit or denominator (Ridoutt 2021). This enables environmental impacts to be expressed per nutritionally relevant unit, such as energy content, protein quantity or quality, or composite nutrient indices, thereby improving the interpretability of sustainability assessments (McLaren et al. 2021). Despite this progress, the selection of appropriate nutritional functional units remains a critical decision during a study's Goal and Scope Definition.

Accurately defining a food's function is essential when expressing LCA results relative to nutrient composition (Ridoutt 2021). To address this issue, food-group-specific functional units, such as those based on protein, carbohydrates or fats, have been proposed to better reflect product functionality and facilitate meaningful comparisons (Ortenzi et al. 2025). To date, most n-LCA research has focused on protein-rich foods (Green et al. 2021; McAuliffe et al. 2023; Kyttä et al. 2023), with more recent extensions to carbohydrate sources, fruits, vegetables, milk and plant-based alternatives (Kyttä et al. 2023). In some cases, individual nutrients such as energy, protein, micronutrients or minerals have been used as denominators (Beal and Ortenzi 2022; Katz-Rosene et al. 2023; McAuliffe et al. 2023; Sonesson et al. 2017; Smith and Beal 2025), while other studies employ composite nutrient indices, such as the Nutrient-Rich Food index (NRFx.y), which combines nutrients to encourage and limit (Fulgoni et al. 2009; Kyttä, Ghani, et al. 2025; Kyttä, Kårlund, et al. 2025).

Despite these advances, comparatively little attention has been paid to dietary fats and oils within nutrient-specific n-LCA frameworks, particularly with respect to fatty acid composition. Dietary oils are primarily consumed as sources of fats, and their nutritional function is therefore more appropriately characterised by specific fatty acid delivery than by mass or energy alone. Extra virgin olive oil (EVOO), a central component of the Mediterranean diet, is characterised by a high proportion of monounsaturated fatty acids, particularly oleic acid (C18:1 n-9), alongside smaller contributions of polyunsaturated fatty acids and vitamin E. At the same time, EVOO production can impose notable environmental burdens (El Joumri et al. 2023), and numerous LCAs have identified environmental hotspots across the olive oil value chain (Salomone 2008; Salomone and Ioppolo 2012; Mohamad et al. 2014; Rajaeifar et al. 2014, 2016; Russo et al. 2015; El Hanandeh and Gharaibeh 2016; Parascanu et al. 2018; Duman et al. 2020; Fernández-Lobato et al. 2021; Ramos and Ferreira 2022; Rahmani et al. 2022). However, these studies have largely relied on mass- or volume-based functional units and have not explicitly linked environmental impacts to nutrient-specific functions.

The present study addresses this gap by applying a simple nutrient-specific enviro-nutritional LCA framework to dietary oils, using EVOO as a demonstrator system. Attributional LCA was first used to quantify environmental impacts across 14 Tuscan EVOO production systems. Carbon footprint results were then normalised to nutrient-specific functional units based on fatty acid composition and vitamin E content, enabling calculation of a nutritional carbon footprint (n-CF) expressed per unit nutrient. This approach facilitates comparison of dietary oils based on their efficiency in delivering specific nutritional functions and provides a transparent basis for evaluating trade-offs between environmental performance and nutritional composition.

2 | Materials and Methods

2.1 | Case Study

The companies analysed ($n = 14$) operate in Central Italy, between the Provinces of Siena and Grosseto (South-eastern Tuscany). Some companies are exclusively devoted to organic olive cultivation and EVOO production, whilst others have more diversified operational structures, including separate winemaking, cured meat or honey production facilities. These additional activities do not share material inputs (e.g., fertilisers) or natural resources (e.g., land) with olive cultivation. Two oil mills provided primary data for olive processing activities, which were used to represent the milling stage for the study area. The temporal boundary for olive cultivation and harvesting extended from February to October 2023.

The environmental performance of EVOO production was evaluated using an LCA framework in accordance with the Product Category Rules (PCR) 2010:07, Version 2.01 for EVOO (PCR 2010). These rules divide the olive-oil supply chain into three major phases: upstream (olive cultivation and harvesting), core (transport, milling and storage) and downstream (bottling, packaging, distribution, use and disposal). A cradle-to-processing-gate system boundary was applied, focusing exclusively on the upstream and core phases. Downstream processes were excluded because most participating producers sell their oil in bulk and the goal of the study was to assess environmental impacts associated with the production of bulk EVOO.

All participating companies followed comparable agronomic practices and processing techniques, resulting in limited variability across operations. Figure 1 presents a generalised schematic of EVOO production and highlights the activities included within the upstream and core phases, thereby defining the system boundary encompassing cultivation, transport, milling and storage. Due to the relative homogeneity of soil quality across the study area (Madiai et al. 2017), soil organic carbon stock changes were excluded to avoid diluting hotspot identification

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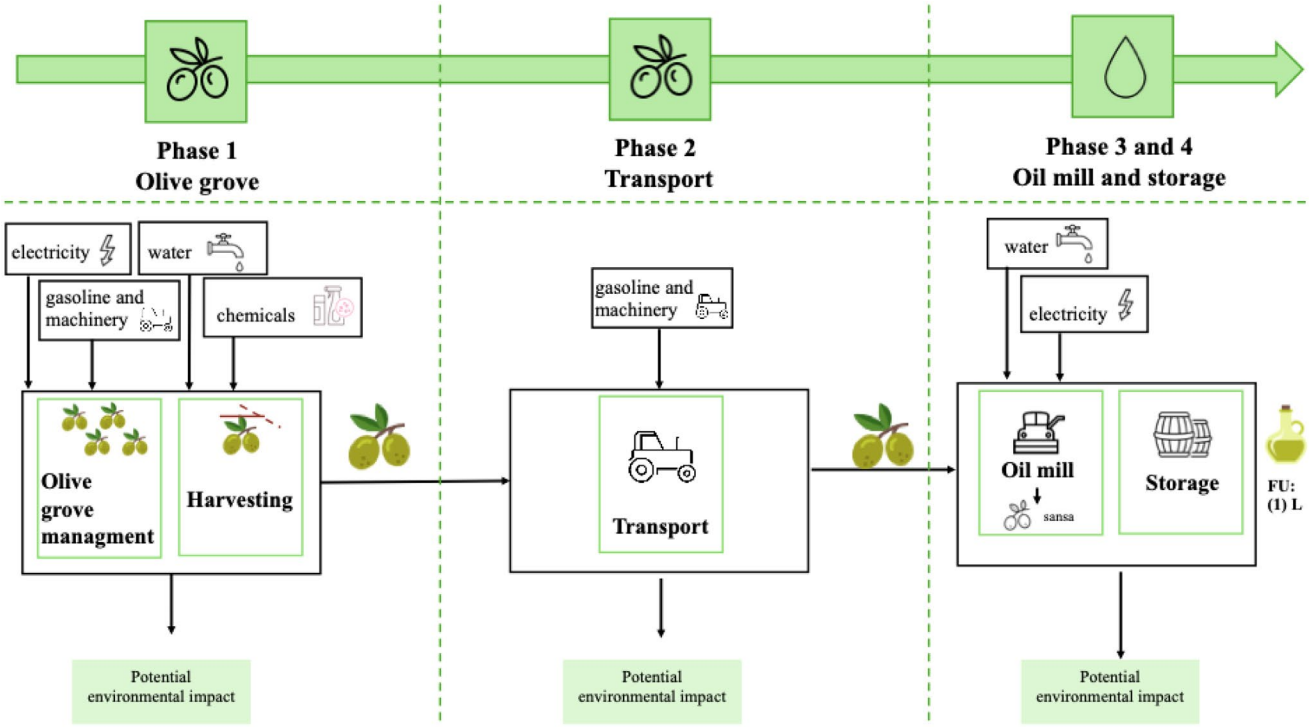


FIGURE 1 | System boundary and process flow for extra virgin olive oil (EVOO) production in Tuscany. The assessment covers four primary phases: (1) olive grove management and harvesting; (2) transport; (3) oil milling; and (4) storage. Inputs include electricity, water, fuel and agrochemicals, each contributing to potential environmental impacts. The baseline, or pre-nutrient-adjusted functional unit, is 1 L of bulk processed oil.

with highly uncertain parameters. The primary data collected for this study were not sufficient to support a reliable estimation of soil organic carbon change, and for this reason soil carbon was not included in any of the comparative calculations. Including such poorly constrained values would introduce more noise than insight. As a result, their omission is unlikely to influence the relative ranking of oils or the interpretation of n-CF outcomes.

The baseline functional unit (FU) was defined as 1 L of bulk EVOO. Primary data from the participating companies were collected and used to conduct a Life Cycle Inventory Analysis (LCI). The LCI includes all inputs and outputs required to quantify environmental emissions and resource use across the defined system boundary (Proietti et al. 2017). Data were collected using standardised quantitative questionnaires and supplemented by in-person interviews with producers. Table 1 summarises the inventory data associated with the functional unit.

The LCA was conducted using SimaPro software (PRé Consultants 2016) and the Environmental Footprint 3.1 Life Cycle Impact Assessment method. Direct emissions related to agricultural operations, transport and machinery use were calculated following the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019). Default IPCC emission factors were adopted for CO_2, CH_4, CO and N_2O, while emission factors for NO_2, NO_x and NH_3 were sourced from the EMEP/EEA Air Pollutant Emission Inventory Guidebook (EMEP/EEA 2016). Detailed equations, parameters and assumptions are provided in the Supplementary File S1. Climate-related indicators are utilised solely herein to demonstrate the importance of functional unit choice, though a broader indicator LCA will be presented in due course.

For cross-oil comparison, environmental impact data for non-EVOO vegetable oils were sourced from the Agribalyse 3.1 database, which provides harmonised LCI data for food products at the European level. Agribalyse values were used to represent average production conditions for coconut, corn, peanut, soybean, sunflower and EVOO, enabling contextualisation of the Tuscan EVOO case study within the wider dietary oils landscape.

2.2 | Fatty Acid Composition of Extra Virgin Olive Oil

The fatty acid composition of EVOO was characterised using primary analytical data derived from wet-chemistry nutritional analyses conducted for quality reporting purposes by participating producers. These values were sense-checked with two reference sources: the United States Department of Agriculture FoodData Central database (USDA 2019) and the Council for Agricultural Research and Economics (CREA), which serves as the official nutritional reference for Italy. An average composition was calculated based on company quality certificates to assess representativeness and variability across data sources.

Vegetable oils consist predominantly of triglycerides (98%–99% by mass), whose fatty acid chains vary in degree of saturation and chain length (Tian et al. 2023). Rather than aggregating

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TABLE 1 | Inventory data for the functional unit of 1 L of bulked extra virgin olive oil (EVOO), including system-level characteristics and inputs across agricultural, transport, milling and storage phases.

System data	Unit	Average	SD
Field extension	ha	19.7	33.5
Olive production	kg	2.88×10^4	6.00×10^4
Oil production	L	5.84×10^3	8.18×10^3
Input data agricultural phase			
Copper-based fertiliser	kg	0.00877	0.00458
PET	kg	0.116	0.202
PVC	kg	0.00272	0.00188
Diesel	kg	0.133	0.187
Nitrogen-based fertiliser	kg	0.102	0.0488
Manure	kg	0.968	1.39
P_2O_5-based fertiliser	kg	0.0639	0.0120
K_2O-based fertiliser	kg	0.111	0.0318
Fosmet (insecticide)	kg	0.00866	0.00452
Electricity	kWh	1.76	3.74
Clinoplinolite/zeolite	kg	0.315	0.531
Organic fertilisers	kg	0.0102	0.0130
Boron-based fertiliser	kg	0.0121	0.0103
Water	L	601	905
Ox blood	kg	0.145	0.0633
Generic insecticide	L	0.0257	0.0335
Generic fungicide	L	0.000810	0
Steel	kg	0.00170	0
Input data transport			
—	kg km	163	261
Input data oil mill phase			
Electricity	kWh	0.306	0.330
Water	L	0.0354	0.00467
Diesel	kg	0.0800	0.0566
Input data oil storage phase			
Washing water	L	0.664	0.491
Steel	kg	0.0246	0.0460
Nitrogen	L	0.00360	0.00439
Electricity	kWh	3.25	3.41

Note: All values derive from primary data.

fatty acids into broad classes (e.g., saturated, monounsaturated or polyunsaturated fatty acids), the present analysis focuses on individual nutritionally relevant fatty acids that characterise dietary oils and enable meaningful cross-product comparison. Specifically, oleic acid (C18:1 n-9), linoleic acid (C18:2 n-6) and α-linolenic acid (ALA, C18:3 n-3) were selected as nutrient-specific descriptors of oil composition.

In addition to fatty acids, vitamin E (α-tocopherol) content was included due to its recognised nutritional relevance as an antioxidant and its consistent reporting across data sources. Supplementary Table S1 provides the detailed composition of EVOO for selected nutrients across primary data and reference databases, with analysis focusing on variability and representativeness of nutrient values used in the subsequent enviro-nutritional LCA. For the comparative analysis, Table 2 in Section 3.3 provides simplified nutritional values for all oils considered.

2.3 | n-LCA of Extra Virgin Olive Oil Production

A n-LCA was conducted to integrate nutritional information into the attributional LCA framework. Although n-LCA methodologies are still evolving and lack formal standardisation, nutritional properties are commonly integrated either by modifying the functional unit (Phase 1) or during the impact assessment stage (Phase 3) (Ridoutt 2021; Niccolucci et al. 2024). Similarly, McAuliffe et al. (2020) proposed a three-tier system whereby single nutrient(s) consideration is Tier 1, composite indicators/profiles which account for recommended daily values used as functional units fall under Tier 2, with impact assessment adjustments to account for health implications as Tier 3. Under these categorisation suggestions, the n-LCA conducted herein would align with Tier 1.

The present analysis applies a nutrient-specific functional unit approach to dietary oils. Carbon footprint results (kg CO_2-eq per litre of bulk oil) were normalised to the content of selected nutrients, enabling calculation of a n-CF expressed per unit nutrient. Nutrient-specific n-CF values were calculated for oleic acid (C18:1 n-9), linoleic acid (C18:2 n-6), α-linolenic acid (ALA, C18:3 n-3) and vitamin E (α-tocopherol), reflecting nutritionally relevant components of dietary oils and enabling cross-oil comparison within the fats and oils food group.

For each oil i and nutrient j, n-CF was calculated as:

$$\text{n-CF}_{i,j} = \frac{\text{CF}_i}{\text{Nutrient content}_{i,j}}$$

where CF_i is the carbon footprint per litre of oil and $\text{Nutrient content}_{i,j}$ is the amount of nutrient j present in oil i (expressed in g/100 g for fatty acids and mg/100 g for vitamin E). Nutrient-specific n-CF values were then ranked across oils to support comparative interpretation.

For cross-oil comparisons, a single shared nutritional profile was applied to EVOO. Primary analytical data from Tuscan producers were used to derive representative values for fatty acid composition and vitamin E content. These values were applied both to the Tuscan EVOO systems and to the Agribalyse EVOO comparator, for which independent nutritional composition data were not available. This approach ensures consistency in nutrient-specific functional units while avoiding artificial

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TABLE 2 | Input data used to calculate nutrient-specific carbon footprint values for dietary oils.

Product	Carbon footprint (kg CO_2-eq/L)	Oleic acid (C18:1n-9) (g/100 g)	Linoleic acid (C18:2n-6) (g/100 g)	α-Linolenic acid (ALA, C18:3n-3) (g/100 g)	Vitamin E (α-tocopherol) (mg/100 g)
Coconut oil	4.01	6.25	1.68	0.02	0.11
Corn oil	3.51	27.2	51.9	1.04	22.6
Extra virgin olive oil	1.61	73.7	7.19	0.65	27.4
Peanut oil	4.26	55.4	19.6	0.31	15.2
Soybean oil	3.71	21.4	50.9	6.62	12.2
Sunflower oil	2.34	62.9	20.6	0.10	68.5

Note: Carbon footprint values (kg CO_2 eq per litre) are paired with nutrient composition data for oleic acid (C18:1 n-9), linoleic acid (C18:2 n-6), α-linolenic acid (ALA, C18:3 n-3) and vitamin E (α-tocopherol).

differentiation between EVOO systems based solely on data source rather than composition.

To distinguish between system-level environmental performance and category-level nutrient delivery efficiency, two analytical layers were applied in the present study. Primary LCA results for the 14 Tuscan EVOO production systems were analysed at the foreground level to characterise variability, hotspots and mitigation opportunities. Nutrient-specific carbon footprint comparisons across dietary oils were subsequently conducted at the background level using harmonised environmental data (Agribalyse 3.1), enabling category-level comparison within the fats and oils food group without conflating system-specific variability with differences in nutritional function.

3 | Results

3.1 | Attributional Carbon Footprint of Extra Virgin Olive Oil Production

The attributional LCA revealed substantial variability in the carbon footprint associated with the production of EVOO across the 14 Tuscan production systems analysed. When expressed per litre of bulk EVOO, carbon footprint values ranged from 0.62 to 4.24 kg CO_2 eq L^{-1}, with a mean value of 1.88 kg CO_2 eq L^{-1}. This variability reflects differences in agronomic practices, energy use and processing configurations across producers operating within a broadly comparable geographical and climatic context.

To contextualise these findings, carbon footprint values from the present case study were compared with published Italian and European literature. As shown in Figure 2, the mean carbon footprint derived from the present Tuscan case study aligns closely with values reported for Italian and European EVOO production systems, which exhibit mean values of 1.72 and 1.62 kg CO_2 eq L^{-1}, respectively. Across all datasets, carbon footprint distributions display marked variability, with median values generally lower than corresponding means, indicating right-skewed distributions driven by a subset of higher-impact production systems.

Comparison with other vegetable oils, expressed on a mass-based functional unit of 1 L of bulk oil, further illustrates the relative position of EVOO within the wider dietary oil landscape. Carbon footprint values across oils ranged from 2.36 kg CO_2 eq L^{-1} for sunflower oil to 4.27 kg CO_2 eq L^{-1} for peanut oil. Within this comparison, EVOO from the present case study ranked among the lower-impact oils, although substantial overlap exists across oil types, reflecting differences in cultivation systems, yields and processing efficiencies.

3.2 | Phase-Level Contributions to Carbon Footprint

The relative contribution of individual production phases to the overall carbon footprint of EVOO is illustrated in Figure 3. Across all companies, direct field emissions and agricultural inputs consistently accounted for the largest shares of total carbon footprint, while transport, oil milling and oil storage contributed smaller proportions. The violin plots highlight both the central tendency and variability of percentage contributions associated with each phase. Direct field emissions exhibited the highest median contribution, with a relatively wide distribution, indicating substantial inter-company variability. Agricultural inputs also showed consistently high contributions, though with a narrower distribution relative to direct emissions. In contrast, downstream core processes such as milling and storage displayed lower median contributions and more constrained variability.

Phase-level contributions disaggregated by company (anonymised) are presented in Figure 4. The graph illustrates heterogeneity in the relative importance of individual phases across producers, particularly within the agricultural phase, where differences in input intensity and management practices result in pronounced variation in carbon footprint contributions. Despite this variability, the dominance of upstream processes remains consistent across the dataset, indicating that mitigation opportunities are most likely to be realised

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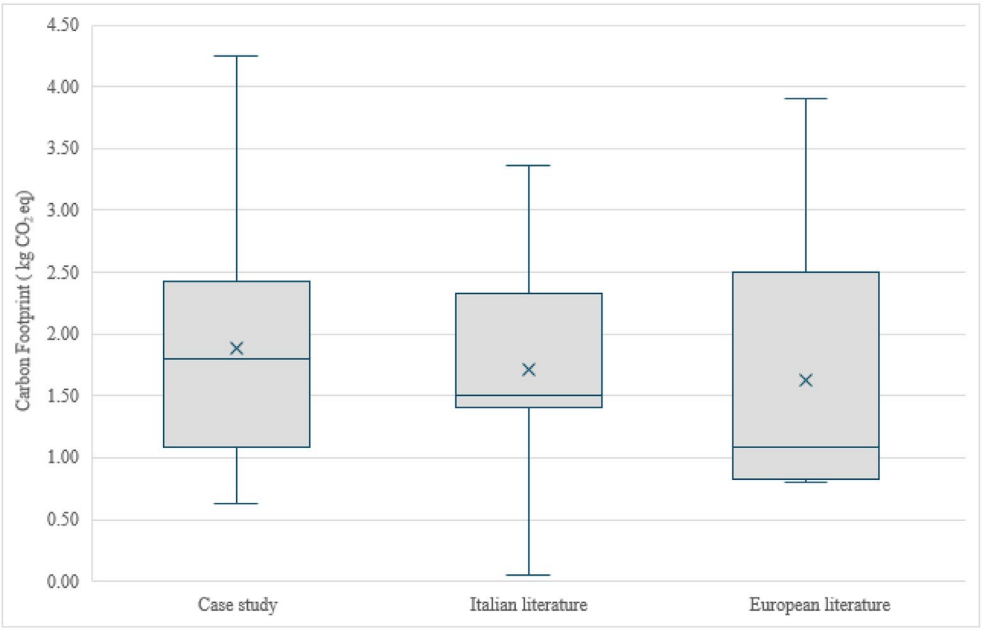


FIGURE 2 | Comparison of carbon footprint values (kg CO_2 eq) per functional unit of 1 L of bulk extra virgin olive oil. Box plots represent the distribution of results for the present case study ($n = 14$), Italian literature ($n = 10$) and European literature ($n = 6$). Where relevant, literature values were harmonised to exclude downstream processes for consistent comparison (e.g., cradle-to-consumer impacts in Agribalyse were truncated at processing).

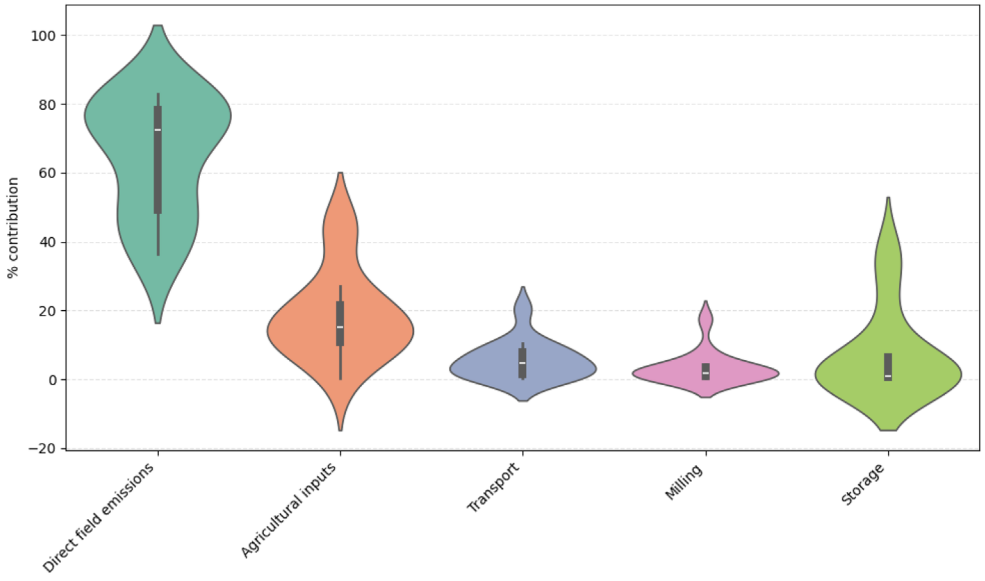


FIGURE 3 | Distribution of carbon footprint contributions (%) by life-cycle phase for 1 L of bulk extra virgin olive oil, calculated using the Environmental Footprint 3.1 (adapted) V1.01/EF 3.1 method. Violin plots illustrate the density of data across percentage ranges, with wider sections indicating a higher concentration of observations within that range.

through interventions targeting field-level emissions and agricultural input use.

3.3 | Nutrient-Specific Carbon Footprint Results

To enable category-level comparison of dietary oils based on nutrient delivery (key fatty acids and vitamin E) efficiency, carbon footprint results from background production systems were normalised to nutrient-specific functional units to derive n-CF values for selected fatty acids and vitamin E. This analysis builds on the system-level results presented above by shifting the interpretive focus from production variability to functional nutrient provision within the fats and oils food group. Nutrient-specific n-CF values were calculated for oleic acid (C18:1 n-9), linoleic acid (C18:2 n-6), α-linolenic acid (ALA, C18:3 n-3) and vitamin E (α-tocopherol), reflecting nutritionally relevant components of dietary oils.

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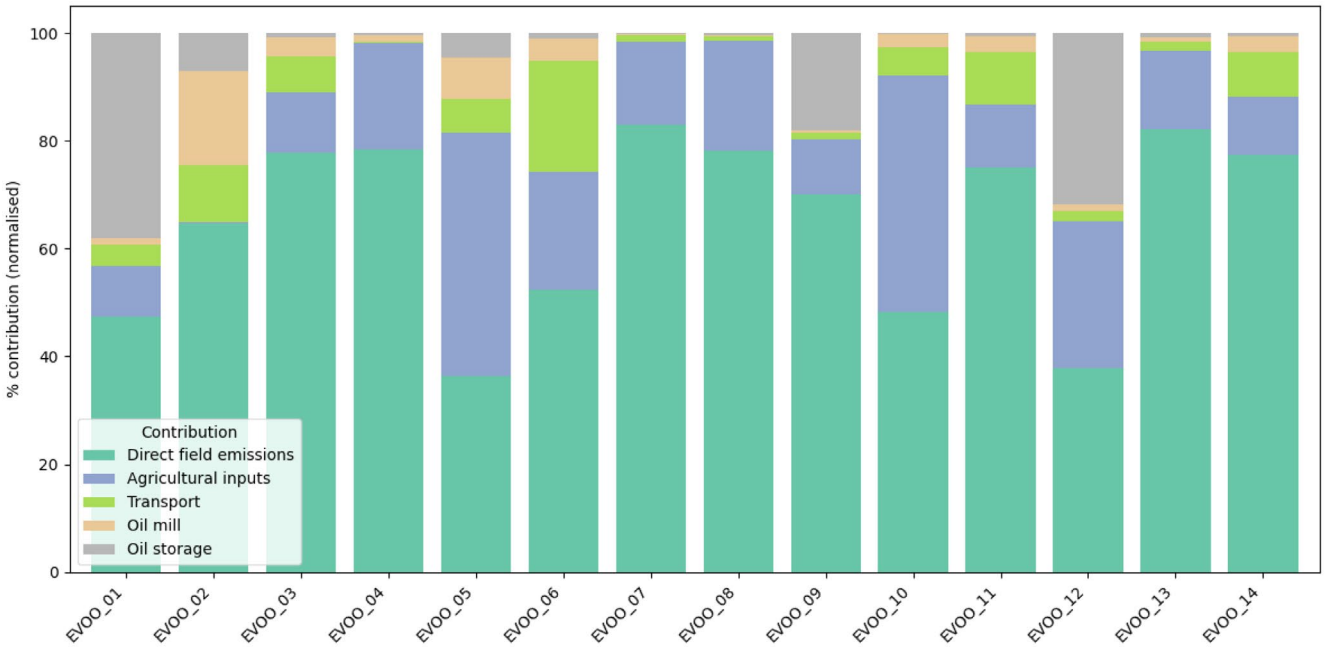


FIGURE 4 | Normalised percentage contribution of life-cycle phases to the carbon footprint (kg CO_2 eq) per functional unit (FU) of 1 L of bulk extra virgin olive oil (EVOO), calculated using the environmental footprint 3.1 (adapted) V1.01/EF 3.1 method. Each bar represents one production system, showing the relative share of emissions from direct field activities, agricultural inputs, transport, milling and storage.

The associated nutrient-specific n-CF values, as well as related nutritional values, are reported in Table 2, which provides quantitative detail underlying the rankings shown in Figure 5. Together, these results demonstrate that the environmental efficiency of dietary oils is strongly dependent on the nutritional function under consideration, and that mass-based carbon footprint metrics alone do not fully capture differences in nutrient delivery efficiency across oils. In this context, EVOO is represented by a single category-level nutritional profile derived from primary Tuscan data, with nutrient-specific rankings reflecting compositional characteristics rather than variability across individual production systems.

4 | Discussion

4.1 | Reframing Environmental Performance Through Nutrient-Specific Functional Units

The results of this study reinforce a central methodological point in food LCA: expressing environmental impacts per unit mass or volume can provide only a partial representation of the environmental efficiency of foods whose primary function is nutritional provision (McAuliffe et al. 2020; Ridoutt 2021; McLaren et al. 2021). When carbon footprint values are normalised to nutrient-specific functional units, substantial changes in relative performance can emerge across foods, illustrating how strongly interpretation depends on the functional unit selected (Ridoutt 2021; McLaren et al. 2021). In the present study, this reframing is operationalised by separating system-level environmental performance from category-level nutrient delivery efficiency, allowing nutrient-specific interpretation (ranking) without conflating production variability with compositional function.

Using EVOO as a demonstrator system, system-level mass-based carbon footprint position EVOO among the lower impact vegetable oils when expressed per litre, consistent with the spread of values reported across published studies and product declarations for EVOO production systems (Proietti et al. 2014; Proietti et al. 2017; Stillitano et al. 2019; Navarro et al. 2018; Poore and Nemecek 2018; Reinhardt et al. 2020). However, nutrient-specific normalisation reveals a more nuanced picture. Oils that appear environmentally favourable on a volumetric basis do not necessarily deliver key nutrients with comparable efficiency, while oils with higher mass-based impacts may perform more favourably when expressed per unit of specific fatty acid or vitamin (micronutrient). This divergence reflects well-recognised challenges in defining food function and designing nutritional functional units that support meaningful comparisons (McAuliffe et al. 2020; Ridoutt 2021; McLaren et al. 2021).

The nutrient-specific carbon footprint heatmap illustrates how the environmental efficiency of oils varies depending on the nutrient considered. For EVOO, the high proportion of oleic acid and the presence of vitamin E contribute to comparatively favourable nutrient-specific performance for these components, while performance for polyunsaturated fatty acids reflects the lower absolute content of these nutrients in olive oil relative to some seed oils (Tripoli et al. 2005; Tian et al. 2023). This is aligned with the broader principle that environmental comparisons can change materially when the denominator is shifted from product quantity to nutrient delivery (Saarinen et al. 2017; Katz-Rosene et al. 2023). In this context, the nutrient-specific heatmap reflects category-level efficiency ranking in delivering individual nutrients, rather than performance differences among individual EVOO production systems.

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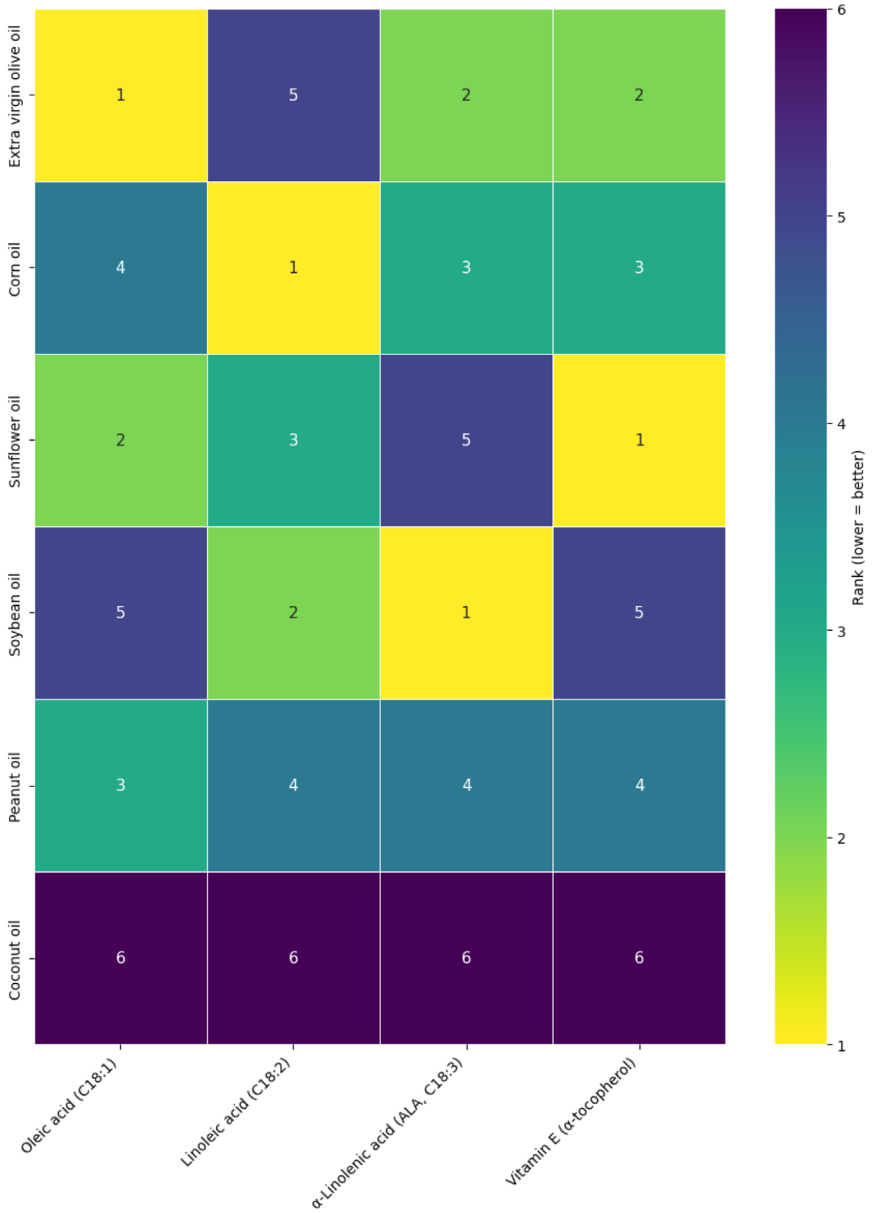


FIGURE 5 | Nutritional carbon footprint heatmap showing category-level carbon footprint rankings normalised to selected nutrients across dietary oils. Rankings are based on background production data and expressed relative to oleic acid (C18:1), linoleic acid (C18:2), α-linolenic acid (ALA, C18:3) and vitamin E (α-tocopherol) content.

4.2 | Implications for Comparing Dietary Oils Within the Fats and Oils Food Group

Dietary oils differ markedly in fatty acid composition, micronutrient profiles, agronomic requirements, yields and processing intensity, all of which influence both environmental impacts and nutritional outcomes (Tian et al. 2023). As a result, rankings based solely on mass-based carbon footprint metrics risk obscuring trade-offs between environmental performance and nutrient delivery. This is particularly salient for within-group comparisons where products may be nutritionally similar in broad terms (all 'oils') but functionally distinct in the nutrients they deliver (McLaren et al. 2021; Ridoutt 2021). Category-level comparison is therefore essential to avoid attributing differences in nutrient delivery efficiency to production systems when they primarily arise from compositional characteristics.

The nutrient-specific approach adopted here provides a more functionally relevant (nutrition) basis for category-level comparison within the fats and oils food group by shifting the interpretive focus from 'impact per litre' to 'impact per unit nutrient delivered' (McAuliffe et al. 2020; Saarinen et al. 2017). Rather than identifying a single 'best' oil, the results show that relative performance is contingent on the nutrient under consideration. Oils richer in polyunsaturated fatty acids may perform more favourably when assessed per unit linoleic acid or α-linolenic acid, while oils characterised by high monounsaturated fatty acid content or antioxidant content may exhibit advantages when assessed per unit oleic acid or vitamin E (Tripoli et al. 2005; Tian et al. 2023).

In the present analysis, EVOO is represented by a single, empirically grounded nutritional profile, such that nutrient-specific performance reflects compositional function rather than

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variability across individual production systems. For EVOO specifically, its nutritional and culinary role within dietary patterns such as the Mediterranean diet, and its compositional distinction from many refined seed oils (food dressing versus cooking food), necessitate cautious generalisation beyond the demonstrator case. EVOO is typically characterised by high monounsaturated fatty acid content and bioactive compounds, and it is often consumed raw as well as used in cooking (Tripoli et al. 2005; Lozano-Castellon et al. 2022; Pattara et al. 2016; Tome-Carneiro et al. 2020). Moreover, oil use is context dependent: heating and frying can alter oil composition and degrade nutritional attributes, with degradation pathways influenced by the initial fatty acid profile and antioxidant content (Guillaume et al. 2018; Kmiecik et al. 2023; Abrante-Pascual et al. 2024). These considerations emphasise that nutrient-specific rankings should be treated as indicative of nutrient delivery efficiency under the assumptions applied, rather than as prescriptive substitution guidance.

4.3 | Methodological Considerations and Limitations

Several methodological considerations should be acknowledged. First, carbon footprint was selected as the *focal* indicator due to its widespread use in food LCA and its relevance to climate change mitigation, enabling comparison with existing EVOO and vegetable oil literature (Poore and Nemecek 2018; Reinhardt et al. 2020; Proietti et al. 2017; Schmidt 2015; Stillitano et al. 2019; Navarro et al. 2018). Whilst the broader environmental profile of oils should include additional impact categories, the nutrient-specific framework presented here is conceptually extensible to other indicators where robust impact assessment methods and inventories are available (Ridoutt 2021; McLaren et al. 2021). That said, it should not be assumed that a lower carbon footprint equates to a lower holistic environmental footprint. The separation of foreground system, or primary-data-driven, analysis from background category-level nutrient comparison was adopted deliberately to improve interpretability and avoid artefacts arising from mixed data provenance.

Second, nutrient composition values for EVOO were derived from averaged compositional data rather than producer-specific nutritional analyses. This approach supports comparability and reflects the practical constraints often encountered in n-LCA studies, but it does not capture within-product variability arising from cultivar, geography, processing conditions or storage (Ridoutt 2021). Where producer-specific compositional data are available, future applications could examine how nutrient variability interacts with environmental variability to influence nutrient-specific rankings. This limitation is common to many n-LCA applications and reflects current data availability rather than a conceptual constraint of the framework.

Third, the selection of nutrients as functional units necessarily involves judgement about what constitutes 'function' for a given food group. Tier-1 nutrient-specific approaches can improve transparency by avoiding composite indices, but they still require careful justification of nutrient choice and clear statements about interpretation limits (McAuliffe et al. 2020; Ridoutt 2021; Niccolucci et al. 2024). In this study, key fatty acids and vitamin E were selected to reflect nutritionally relevant components that distinguish oils and are consistently reported across sources, but other functional attributes (e.g., polyphenols for EVOO) may be important in specific contexts (Tripoli et al. 2005; Flynn et al. 2023; Guarino et al. 2019; Bongiorno et al. 2023; Tsarouhas et al. 2015; Venn-Watson et al. 2020).

4.4 | Implications for Enviro-Nutritional Life Cycle Assessment

Overall, the findings support the argument that nutrient-specific functional units can improve the interpretability and policy relevance of environmental assessments of foods by aligning the denominator with nutritional function (Saarinen et al. 2017; McAuliffe et al. 2020; McLaren et al. 2021; Katz-Rosene et al. 2023). Using EVOO as a demonstrator system, the nutrient-specific carbon footprint framework presented here provides a transparent basis for exploring how sustainability conclusions change when oils are compared on the basis of nutrient delivery rather than mass or volume. Applied judiciously, such approaches can help communicate trade-offs more clearly and support the development of enviro-nutritional assessments that better reflect the dual objectives of environmental protection and human nutrition (McLaren et al. 2021; Ridoutt 2021). Importantly, such frameworks are intended to support interpretation of nutrient-environment trade-offs rather than to identify universally optimal foods or production systems.

5 | Conclusion

This study demonstrates the value of applying nutrient-specific functional units within an enviro-nutritional LCA framework to improve the interpretability of environmental assessments of dietary oils. Using EVOO as a demonstrator food category, carbon footprint results were normalised to selected key fatty acids and vitamin E, illustrating how sustainability conclusions can change when environmental impacts are expressed relative to nutrient delivery rather than mass or volume alone.

The findings highlight that comparisons among dietary oils are highly sensitive to the nutritional function under consideration. Oils that perform favourably on a mass-based basis do not necessarily deliver specific nutrients with comparable environmental efficiency, underscoring the importance of aligning functional units with clearly defined nutritional roles. By focusing on individual nutrients rather than composite indices, the approach adopted here provides a transparent basis for exploring trade-offs without imposing value judgements about overall nutritional quality.

While EVOO was used as a case study, the nutrient-specific framework presented is applicable to other dietary oils and, more broadly, to food groups where nutritional function is not adequately captured by conventional functional units. Applied cautiously, nutrient-specific n-LCA can support more nuanced

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sustainability assessments and contribute to clearer communication of the environmental implications of food choices aligned to nutritional need.

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The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supplementary File S1:** Direct emissions related to agricultural operations, transport and machinery use. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019) emission factors were applied for CO_2, CH_4, CO and N_2O, while emission factors for NO_2, NO_x and NH_3 were sourced from the EMEP/EEA Air Pollutant Emission Inventory Guidebook (EMEP/EEA 2016). **Supplementary Table S1:** Detailed composition of EVOO for selected nutrients across primary data and reference databases, with analysis focusing on variability and representativeness of nutrient values used in the subsequent enviro-nutritional LCA.

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