

Environmental Foot Prints and Nutritional Life Cycle Assessment of Food Products: A Narrative Review

Review Article

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Abstract

Comprehensive assessment frameworks are required to measure both environmental effect (carbon footprint, greenhouse gas (GHG) emissions) and nutritional efficacy of foods. Nutritional Life Cycle Assessment (nLCA) is an imperative tool of assessment framework. The objective of this review was the synthesis of global nLCA literature to assess the existing methodologies and standards, the various tools utilized, and the outcome measures implemented to evaluate the environmental impact of various raw and packaged food products. We conducted a narrative review to synthesize the key findings from nLCA studies published between 2016 to 2020 using the PubMed database. The comparative reliability of nLCA was undermined by widespread methodological variations. The functional unit (FU) significantly determines ranking, which acts as a key and frequently contradictory conclusion. Reliance on FUs based on mass sometimes renders comparisons useless by neglecting to take nutrient profiling into account. Nutritional FUs show that products such as pulses, microbial proteins, and some intensive livestock systems can offer high nutrient delivery for a lower environmental burden, while beef and dairy consistently register as environmental hotspots. The high heterogeneity resulting from co-product allocation strategies and localized production efficiency (example: precision nutrition) was a major limitation to drawing broadly applicable findings. The nLCA community needs to get an agreement on globally standardized, nutritionally weighted FUs, prioritizing the development of public-health focused indicators such as the HENI score. Furthermore, systematic integration of social and economic factors into LCSA is required for converting complex data into holistic, region-specific actions.

Keywords: Nutritional life cycle assessment; Life cycle assessment; greenhouse gases; carbon footprint

Introduction

The environmental impact of human activities can be assessed using a quantitative measure called Life Cycle Assessment (LCA). The use of LCA methodology to assess the environmental impact of agri-food products is called nutritional LCA (nLCA). Opting for the appropriate nutritional functional unit to compare alternative food items is critical in nLCA. Most used functional units are based on either calories, proteins, mass of the product, or land occupied across the supply chain or a geographical area. [1]

LCA is a system analysis and operational unit analysis that studies the environmental aspects and potential impact throughout

the life cycle of a product (cradle-to-grave), which includes processes from acquiring the raw product to its production, use, and final disposal. The life cycle of a product includes the extraction of a raw material, including the energy carrier, followed by the production of an intermediate product and end-product, its use, and finally the disposal or recycling. [2]

It is critical to understand that the environment is affected by food production, processing, preservation, preparation, distribution, or disposal, in many ways, such as by the emission of greenhouse gases (GHG), use of land and water resources for the production or loss of biodiversity, etc. [3]. The level of environmental impact may vary depending upon the type of food, such as animal products may have a

higher impact compared to other food types because of greater energy use and GHG emissions. It has been suggested that GHG emissions should be one of the criteria to evaluate the environmental impact of foods, but not the only criterion. Water footprints, ammonia emissions, and primary energy use are the potential impacts on the environment. [4]

Furthermore, LCA has been complemented with costing and social life cycle assessment to constitute what is called life cycle sustainability assessment. It is the evaluation of performance of the sustainability of the product with its three dimensions, including environmental, economic, and social. The life cycle costing includes five major types of costing, i.e., initial cost, operation cost, maintenance cost, disposal cost, and residual cost. [5]

LCA has four steps, including the goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. The cradle-to-grave approach involves all the stages of the life cycle approach, i.e., from extraction of the raw material to the end of life of the packaging. [6] However, little is known about the LCA of multiple food products. Also, multiple studies have used different methods and standards to perform LCA. Considering the need to review the availability of literature on LCA of different food products, the tools used to Perform them, and the key-outcome measures applied, we performed a narrative review. The objective of the review was to assess the tools used to perform LCA of different raw and packaged foods globally.

Materials and Methods

Screening and extraction of studies

We used the PubMed database to find studies using the keywords, “Life Cycle Assessment, LCA, nLCA, Nutritional Life cycle Assessment.” The inclusion criteria were restricted to studies published in English between 2016 and 2020 that explicitly focused on the nutritional life cycle assessment of food products. Initial screening was based on the relevance of titles and abstracts to the review’s objectives, followed by a full-text evaluation of the selected articles. Data extracted included the author and year of publication, food items assessed, geographical context, functional unit, methodological tools used in the study and key outcomes measured. The conceptual grouping of the studies to synthesize the overarching themes in nLCA methodologies was performed. Consistent with the narrative review methodology, we did not perform a formal quality appraisal or systematic exclusion quantification.

Results and Discussion

Evidence from studies

Dietary Impact Assessments: The evaluation of environmental impacts across whole diets reveals significant variations based on dietary composition and the chosen functional units. Heller et al. highlighted the absence of standardized nutritional quality metrics in LCA frameworks, noting the use of indices like the Healthy Eating Index (HEI), Nutrient Rich Foods Index (NRF), and Overall Nutritional Quality Index (ONQI) [7]. Building on dietary modeling, Coelho et al. estimated that shifting from an average French diet to a vegetarian diet significantly lowers the environmental footprint

[8]. Similarly, sustainable dietary models demonstrate comparable efficiencies; the New Nordic Diet and the Mediterranean Diet yield comparable weekly GHG emissions of 25.8 Kg CO₂ eq and 23.6 Kg CO₂ eq, respectively [9]. Demographic factors also influence dietary footprints, as Balter et al. observed that men in Sweden generate higher median daily CO₂ emissions (5.3 kg) than women (4.4 kg), primarily driven by a higher intake of meat and dairy products [10].

Livestock, Dairy, and Processed Food Metrics

When evaluating specific animal products, transitioning from a mass-based metric to a nutrient-based functional unit becomes critical to successfully integrate meat quality and nutritional outcomes into environmental assessments [11]. This need for precise metrics extends to dairy products; for instance, Bava et al. evaluated Italy’s Grana Padano cheese across multiple environmental categories, identifying impacts including 3.26 m³ of water use, a carbon footprint of 98.2 g CO₂ eq, and 1.44 MJ for resource use [12]. The environmental impact of processed products also varies widely depending on the ingredients. Sietiti et al. showed that among children’s ready-made foods, heavy lunch meals like spaghetti Bolognese and salmon risotto produce the highest environmental impact, whereas dry porridge and fruit-based desserts produce the lowest [13].

Farm Management and Crop Production Interventions

Addressing environmental burdens effectively often requires direct agricultural interventions. Ibidhi and Calsamiglia demonstrated that optimizing farm management to reduce milk’s footprint (0.67–0.98 Kg CO₂ eq/Kg) is a more efficient mitigation strategy than changing consumer diets [14]. Crop production faces specific pollution hotspots despite multiple agricultural stages. For Galician wheat, the primary pollutants are nitrogen fertilizers, field emissions, and transport fuel, leading to European bread environmental impacts ranging from 0.5 to 6.6 kg CO₂ eq/kg [15]. Similarly, evaluating resilient quinoa production across direct and indirect inputs, Lotfalian Dekhordi and Forootan found that producing 1 ton generates 354 kg CO₂ equivalents, with phosphorus identified as the primary contributor to toxicity impacts [16]. Shifting diets and optimizing farm production are key to reducing environmental impacts (Figure 1).

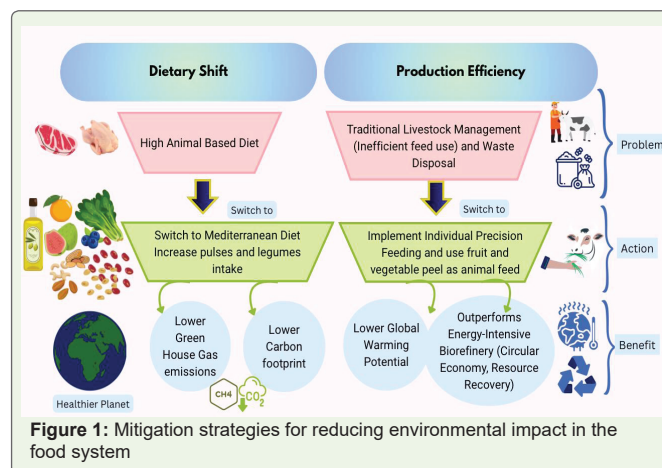


Table 1:

S. No	Author and year of publication	Food items assessed	Country or continent	Functional unit	Methodology and tools used	Outcome measures	Results
1.	Heller <i>et al.</i> 2013 [7]	Food consumption patterns	Sweden, Netherlands, Switzerland, Italy, US, Spain, India, Finland, Norway, Austria, UK, France, Denmark, Germany	Mean adequacy ratio; Recommended dietary intake; mean excess ratio, and Energy density Nutrient-Rich Foods Index; Overall Nutritional Quality Index; Alternate Healthy Eating Index; composite NRF scores	Life cycle inventory databases for food and agriculture	GHG, MI, CED, EP, AP, POCP, Land use, NH3, Water, primary energy use, P use	Improved human health, ecosystem quality, and resources and ecosystem services
2.	Coelho <i>et al.</i> , 2016 [8]	105 foods (French diet profiles)	France	Average daily kcal-adjusted food ingestion for one person in a French two-person urban household (adjusted to 2300 kcal/person/day).	LCA using the cradle-to-mouth method. Data from AGRIBALYSE database	GWP, GWP including land use change (GWP-LUC), acidification (AC), eutrophication (EU), land occupation (LO), total cumulative energy demand (CED), biotic natural resource-depletion species (BNR-spe), and biotic natural resource-depletion ecosystems (BNR-eco). EPA and DHA intake.	Vegetarian diets yield the lowest environmental impact. Avoidable food waste is a primary impact contributor
3.	Ulaszewska MW <i>et al.</i> 2017 [9]	Two dietary models: Mediterranean diet and the New Nordic diet	Italy	Food consumption in kg/week	Environmental hourglass approach	GHG emissions (Kg of Co2 eq per week)	New Nordic diet: 25.8 kg CO ₂ eq/week; Mediterranean diet: 23.6 kg CO ₂ eq/week
4.	Balter <i>et al.</i> 2017 [10]	102–174 food items (Swedish food)	Sweden	kg carbon dioxide equivalents (CO ₂ e) per kg of food product.	LCA data linked to a food frequency questionnaire (FFQ) from the Swedish LifeGene study (Meal-Q). NutriCalc program used to link dietary data to a national food composition table.	Daily emission of CO ₂ e; intake of nutrients (β-carotene, carbohydrates, polyunsaturated fat, fiber, vitamin B12, zinc, vitamin D, retinol equivalents, calcium, fat, saturated total fat, protein, iron, folate, vitamin C). Adherence to Nordic Nutrition Recommendations (NNR).	daily diet emissions average 4.7 Kg CO ₂ e per person men generate higher emissions due to meat/dairy intake.
5.	McAulliffe <i>et al.</i> , 2018 [11]	Meat products from cattle, sheep, pigs, and poultry.	UK	1. Total mass of omega-3 polyunsaturated fatty acids (PUFA). 2. Combined mass of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). A standard mass-based functional unit (kg deboned meat) was also used for comparison. Additionally, four nutrient indices (UKNIprot, UKNIprot, UKNIprot, UKNIprot10-2) were used.	LCA was used to estimate the environmental footprints (e.g. global warming potential) of different livestock production systems. Data from various studies combined to link environmental footprint, kill-out percentage, meat yield, and nutrient content.	GWP initially per kg of deboned meat, then per unit of omega-3 PUFA, EPA+DHA, and finally per 1% of Recommended Daily Intake (RDI) using the nutrient indices. Fatty acid profiles (omega-3, omega-6, EPA, DHA, etc.) were also analyzed.	Shifting from mass to nutrition FUs reverses environmental rankings. Pasture-fed-beef has lower GWP by mass, but higher omega-3 FU
6.	Bava L <i>et al.</i> (2018b) [12]	Grana Padano cheese	Italy	1 kg of fat and protein-corrected milk 12-month ripened	Dry matter, nutritive value, and economic allocation methods	Emissions of nitrogen compounds, phosphates, fuel consumption, equipment use, soil and working conditions, pesticide derived emissions,	Milk production drives 93.5–99.6% of total cheese impacts. Emissions vary significantly based on co-product allocation methods.
7.	Sieti <i>et al.</i> 2019 [13]	12 ready-made baby foods	UK		ISO 14040/14044 methodology, using Gabi LCA software and the CML 2001 method; ecoinvent v3.1	Environmental impacts. GWP, ADPe, ADPf, AP, EP, FAETP, HTP, MAETP, ODP, POCP, TETP	Lunch meals, particularly spaghetti Bolognese and salmon risotto carry the highest environmental burden. Pescatarian diets showed the lowest environmental impact.

8.	ibidhi et al. 2020 [14]	Dairy cattle farms	Spain	1 kg energy-corrected milk	Integrated farm system model	GHG emissions (carbon footprints)	Carbon footprint: 0.98 kg-eq/ of energy-corrected milk for Mediterranean dairy farm; 0.84 for central region dairy farm; 0.67 for Canta baric dairy farm
9.	Salim et al. , 2020 [15]	Galician bread and wheat	Galicia, Spain	1 kg of wheat grain transported to the milling facility; 1 kg of Galician bread.	LCA following ISO 14040 and 14044 standards.	Climate change (kg CO ₂ -eq), terrestrial acidification (kg SO ₂ -eq), freshwater eutrophication (kg P-eq), human toxicity (kg 1,4-DCB), fossil depletion (kg oil-eq).	Wheat cultivation (fertilizer use) is the primary environmental hotspot of bread production, Galician bread had a lower environmental impact than many staple foods in Europe.
10.	Dehkordi et al. , 2020 [16]	Quinoa grain and crop residues	Isfahan province, Iran	1 tonne of quinoa grain; 1 ha of area under cultivation	LCA methodology using Simapro V. 8.2.3 software and the CML-IA baseline V3.01/ EU25 modeling ap	Energy ratio (ER), energy productivity (EP), specific energy (SE), net energy gain (NEG), GWP, abiotic depletion (AD), fossil fuels abiotic depletion (FAD), eutrophication (EU), ozone layer depletion (OLD), human toxicity potential (HTP), terrestrial ecotoxicity (TE), freshwater aquatic ecotoxicity (FAE), marine aquatic ecotoxicity (MAE), photochemical oxidation (PhO), and acidification potential (ACP).	global warming potential (GWP) is 354 kg CO ₂ eq. per tonne of quinoa. Irrigation and nitrate fertilizers drive the highest energy consumption.
11.	Mc. Auliffe et al. ; 2020 [17]	16 various food items.	Global-Australia, Spain, France, Italy, Belgium, UK, China, etc.	Mass-based (g or kg of product), energy (kcal or GJ), nutrients- based (protein, specific amino acids), composite indicators (nutrient density scores) or a combination of these.	LCA, linear programming, endpoint modeling, nutrient density scoring (NDS) using various nutrient profiling models (e.g. NRF9.3), and the CONE-LC	Environmental impacts (climate change-GWP, water footprint, land use, energy use), nutritional quality (nutrient density scores, individual nutrient content, protein quality index), and health impacts (DALYs).	incorporating nutritional factors drastically alters traditional mass-based environmental rankings.
12.	Halloran et al. ; 2016 [18]	Edible insects: Mealworms (<i>Tenebrio molitor</i>), black soldier flies (<i>Hermetia illucens</i>). The review also mentions crickets and other insect species generally.	Primarily Europe with mention of production in Thailand, South Africa, China, Canada, and USA.	Mass-based (kg of fresh or dry weight), nutrient-based (protein content), and economic-based (dollar value) units	LCA methodology, following ISO 14040:2006 and ISO 14044:2006 standards. Data collected from both commercial producers and experimental trials.	Climate change, resource consumption, nutrient enrichment potential, acidification potential, and impacts on land and water consumption.	Insects show lower feed efficiency than livestock. Insects outperform livestock in lower land, water, and GHG requirements.
13.	Cancino-Espinoza et al. ; 2018 [19]	Organic quinoa (<i>Chenopodium quinoa L.</i>) production.	Peru (Huancavelica and Ayacucho)	One 500 g packet of organic quinoa ready for retail sale in Lima or export to the US or EU. A nutritional-based FU was also used for comparison with other protein-rich foods.	LCA methodology following the ISO 14040 standard. Data collected from 14 farms (63.5 ha) Ayacucho. IPCC 2013 and ReCiPe 2008 to estimate environmental impacts with SimaPro 8.3 software for calculations. Monte Carlo Simulation used	GHG emissions GWP, terrestrial acidification (TA), particulate matter formation (PMF), photochemical oxidant formation & edible protein Energy Return on Investment (ep-EROI).	Quinoa yields lower GHG emissions per protein unit than animal sources. Field fertilizers act as the dominant emission source.
14.	Weber et al. ; 2018 [20]	Animal food products including meat, eggs, milk, and fish.	Germany	Not mentioned	Literature reviews and data analysis.	Polychlorinated biphenyl (PCB) contamination levels in food products, soil, and air.	persistent PCB contamination remains a significant issue in food products of animal origin. †

Refined Functional Units, Novel Proteins, and Contaminants

The critical role of functional units is further emphasized by McAuliffe et al., who highlighted that shifting from mass-based to nutrient-based units can significantly alter environmental rankings for foods, underscoring the need to link farm-level management directly to a product’s nutritional quality to ensure realistic sustainability assessments [17]. Alternative protein sources present unique sustainability metrics in this context; Halloran et al. found that edible insects, such as mealworms, outperform conventional livestock by requiring less land and water and producing fewer GHG emissions, despite possessing lower feed efficiency [18]. Nutrient-dense crops also exhibit specific emissions profiles; an LCA of a 500g functional unit of quinoa identified nitrogen-based gases from field operations, alongside machinery, transport, and resource use as key emissions [19]. Finally, comprehensive impact assessments must also consider pollutants; polychlorinated biphenyls (PCBs), measured using toxic equivalency factors, are persistent organic pollutants formed in combustion and noted in fish, poultry, dairy, and eggs [20].

However, the current nLCA landscape is hindered by widespread methodological heterogeneity. Inconsistencies across databases, software, and co-product allocation strategies severely complicate comparative meta-analyses, and the heavy geographic skew toward North American and European data leaves critical knowledge gaps regarding developing economies [12, 23].

The Way Forward

To ensure nLCA effectively drives global food policy, future research must urgently prioritize: International Standardization: Achieving global consensus on nutritionally weighted FUs, with a priority on validating and standardizing public health-focused indicators like the HENI score across diverse food groups. Holistic LCSA Expansion: Systematically integrating social and economic impact criteria into broader Life Cycle Sustainability Assessment (LCSA) frameworks to capture the full reality of food systems. Closing the Global Data Gap: Developing robust, localized LCA inventories for emerging markets across Asia, Africa, and South America to accurately reflect their distinct agricultural practices and nutritional challenges.

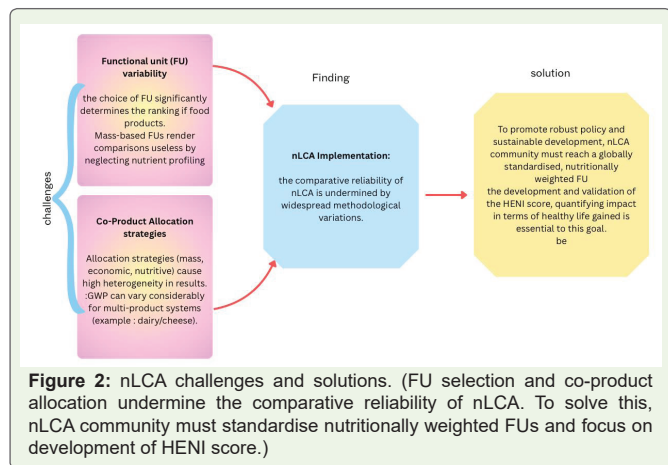


Figure 2: nLCA challenges and solutions. (FU selection and co-product allocation undermine the comparative reliability of nLCA. To solve this, nLCA community must standardise nutritionally weighted FUs and focus on development of HENI score.)

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Conclusions

Transitioning to sustainable food systems is an urgent global imperative that requires measuring both environmental damage and nutritional efficacy. This narrative review affirms that while Life Cycle Assessment (LCA) is a vital tool, its traditional reliance on mass- and energy-based functional units (FUs) is fundamentally inadequate, as these metrics fail to capture true nutritional density and bioavailability [17]. The selection of the FU dictates a food product’s environmental ranking; therefore, shifting toward nutritionally weighted FUs such as DIAAS, NRF9.3, and particularly the Health Nutritional Index (HENI) is not just a methodological upgrade, but a necessity (Figure 2) [22, 1].

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