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Birds of a feather: environmental insights from a review of global broiler chicken production

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Chicken is a high-quality protein source consumed globally, and as the global population grows, broiler chicken production will increase. A meta-analysis of 57 broiler chicken production life cycle assessments (LCA) (173 individual assessments) was conducted to compare environmental impact results by production type and across regions. Findings indicate no significant differences in global warming potential (GWP) between conventional and organic/free-range systems. However, acidification and eutrophication were significantly higher in the organic/free-range system compared to the conventional system. These results challenge the assumption that organic production is the least environmentally impactful system, at least according to standardized LCA impact metrics. Geographically, North and South American broiler chicken production had lower GWP than European broiler chicken production, and all outperformed Asian broiler chicken production. No studies examined broiler chicken production in mainland Africa. Additionally, inconsistent reporting of functional units and impact categories complicated comparisons. This study highlights sustainable agriculture's complexities and the need for a holistic approach to food systems.

KEYWORDS

chicken, environmental impact, Greenhous gas, LCA, organic

1 Introduction

Ending hunger is a critical United Nations Sustainable Development Goal (SDG), and ensuring access to sufficient protein is an important component of this target (United Nations, 2015). Meanwhile, population growth and economic development in developing countries drives an increasing demand for high quality protein sources, such as chicken, which is widely consumed globally (United Nations, 2024). Additionally, in high-income countries, demographics are predicted to shift toward an increase in elderly populations, who require higher protein intake to mitigate muscle loss (Smith et al., 2024). Worldwide, most of the protein consumed (~60%) comes from plant-based sources, which are less resource-intensive and environmentally impactful than animal-derived proteins (Poore and Nemecek, 2018; Smith et al., 2024). However, these proteins are generally considered lower quality due to their amino acid composition and digestibility, underscoring the need to access animal protein sources like

chicken, which has lower environmental impacts compared to other livestock (Poore and Nemecek, 2018; Smith et al., 2024). Regardless of protein source, increasing production to meet growing demand has the potential to conflict with other SDGs due to increased resource use and associated pollution to land, air, and water. These challenges emphasize the importance of assessing the environmental impacts of global agricultural practices, with chicken production being a particularly important due to its prominence in global the diet. Analyzing existing standardized environmental assessments is essential for identifying research coverage by region and production type, highlighting environmental “hot spots,” and determining best practices to minimize environmental impact.

Life cycle assessment (LCA) is a methodology often used to understand the environmental impacts of food production systems (Arvanitoyannis et al., 2014). LCAs are conducted utilizing the ISO 14040 series to standardize the process to enable comparable and repeatable results. Conducting LCAs on the protein-rich food systems is valuable for policymakers, environmentally conscious investors, and non-profit organizations seeking more sustainable food systems (Arvanitoyannis et al., 2014). However, interpretation of the results can vary significantly based on the LCA model design parameters, such as production type, location, system boundary, and functional unit. To address these challenges, we reviewed and analyzed over 150 LCAs of poultry systems.

Poultry production and consumption have increased since the 1960s, surpassing beef consumption in the 1990s and recently eclipsing pork consumption (Parlance and Qaim, 2022). Today, poultry is the most consumed meat worldwide (~40%), and 90% of poultry consumed is chicken (FAO, 2025; Parlance and Qaim, 2022). This increase in poultry production can be partially attributed to the chickens' ability to reach market weight quicker than other larger animals and their adaptability to various environments including small plots of land (Miller et al., 2022). These factors make poultry farming more attractive to farmers in developing nations (Miller et al., 2022). Additionally, poultry production provides the opportunity for egg production which is another valuable source of protein. Chicken is also less environmentally impactful than pork or beef on a protein basis (Poore and Nemecek, 2018). Due to poultry's versatile production systems and feed to protein conversion efficiency, increased chicken production can provide high-quality protein while minimizing environmental impacts, helping to achieve the United Nations' SDGs related to food and the environment.

Given the importance of chicken as a high-quality protein source, this study provides a detailed synthesis and analysis of the existing LCAs of chicken production systems to support improved environmental decision-making as chicken production is expanded. Additionally, we provide a discussion of the challenges of interpreting these results across a variety of studies and seek to elaborate recommendations for greater standardization of food-related LCAs.

2 Materials and methods

To conduct this review and analysis, 57 LCA/environmental assessments of chicken production were identified and inputted into an Excel database (see [Supplementary excel file](#)). These studies were identified utilizing Google Scholar in 2023–2024 with the following search terms: “lifecycle assessment of chicken,” “lifecycle assessment

of organic chicken,” “environmental assessment of chicken,” and “environmental assessment of organic chicken.” Additionally, only studies in the English language were considered. After initial consolidation of the studies, we identified papers that included multiple production scenarios and separated these analyses individually, totaling 173 assessments in all. Each database entry contained the following information when available: publication title, link to publication, functional unit (product identification and mass), other identifying information (ex. no litter flooring system vs. baseline), type (conventional, better welfare than conventional, free range, better welfare than free range, organic, and better welfare than organic), scope (start and end), impact assessment method utilized (e.g., TRACI and Eco-Indicator-99), location (continent, country, and region), and impact category (IC) results.

2.1 Functional unit conversion

The functional unit varied between studies with 25 types of functional units (e.g., carcass weight vs. live weight vs. fried chicken) identified in total. When utilizing a unit of mass (either as live chickens, carcass weight, processed meat, or other), the assessments were largely split between 1 metric ton and 1 kg (see [Supplementary material](#)). To enable a comparison between studies, the functional unit was converted to 1 kg to allow for impact category comparison. Studies that did not report a specific mass value were removed from the functional unit analysis. These studies reported 1,000 live chickens and a certain but unspecified quantity of broiler meat as their functional units (Bundgaard et al., 2014; Pishgar-Komleh et al., 2017). Additionally, a study that reported impact category results in units other than the initially stated functional unit (results were only reported per total broiler) was excluded from conversion (Suffian et al., 2018).

To enable additional comparison, functional units were converted to live weight (LW) with the factors listed in [Table 1](#). To determine these factors, carcass weight (CW) was estimated to be 73% of the live weight (Park et al., 2021) and edible meat (EM) was estimated to be 65% of the carcass weight (Murawska and Murawska, 2017). Additionally, breast meat was estimated to be 24% of LW, and cooked meat was considered to have a 25% moisture loss (Pang et al., 2021; USDA, 2014). Raw chicken meat was also reported to have a protein content of 21% (USDA, 2018). The appropriate live weight factor was determined through industry definitions (live weight and carcass weight) and interpretation of the LCAs as needed. Once the factor was determined for each assessment (see [Table 1](#) for summary of conversion factors), the converted value (1 kg) was divided by the live weight factor.

3 Results

This analysis of broiler chicken production (BCP) LCAs was conducted from two distinct perspectives. The first perspective is from a standard meta-analysis of BCP LCAs that involved the cataloging of the BCP LCA in a standardized format. This approach provides insights into “hot spots” of environmental impact in the chicken production process that are consistently reported throughout the studies and conversely, to identify best environmental practices from the least impactful production systems.

TABLE 1 Functional units and live weight conversion factors.

Unit	Factor code	Live weight factor	Assessments
Boneless chicken	E	2.11	Wiedemann et al. (2017)
Boneless chicken portion	E	2.11	Copley and Wiedemann (2022)
Breast filets	B	4.17	Bengtsson and Seddon (2013)
Broiler chicken meat at point of sale	C	1.37	González-García et al. (2014)
Broilers	L	1	Oxenboll et al. (2011)
Carcass weight	C	1.37	dos Araújo Santos et al. (2023) , Cesari et al. (2017) , Jones et al. (2006) , Leinonen et al. (2016) , Leinonen et al. (2014) , Leinonen and Kyriazakis (2013) , Leinonen and Williams (2015) , López-Andrés et al. (2018) , Nicolaj et al. (2011) , Theresa et al. (2026) , Usva et al. (2023) , and Wiedemann et al. (2012)
Chicken cooled packed and delivered to France	C	1.37	da Prudencio Silva Junior et al. (2012)
Chicken meat	E	2.11	Yayli and Kilic (2023)
Chicken meat for one year of breeding	E	2.11	Boggia et al. (2019)
Chicken meat products	E	2.11	Copley and Wiedemann (2022)
Chilled Cobb breed chicken with 74% moisture, 9% total fat and 15% protein	C	1.37	Giusti et al. (2022)
Consumed chicken meat and chicken meat products	E	2.11, Moisture loss = 25%	Skunca et al. (2018)
Cooled and packaged chicken	C	1.37	Prudêncio da Silva et al. (2014)
Edible carcass weight	E	2.11	Leinonen et al. (2013) and Leinonen et al. (2012)
Fried Chicken	E	2.11, Moisture loss = 25%	Azmi et al. (2023)
Frozen chicken delivered to port of Itajai	C	1.37	da Prudencio Silva Junior et al. (2008)
Honey marinated sliced broiler chicken filet produced and packed by Ruokatalo and purchased by consumers in retail shops	B	4.17	Katajajuuri et al. (2008)
live mass of broiler	L	1	Beal et al. (2023) , da Duarte Silva Lima et al. (2019) , Giannenas et al. (2017) ; Kiss N. et al. (2022) , Kiss N. E. et al. (2022) , Martinelli et al. (2020) , Mostert et al. (2022) , Ogino et al. (2021) , Payandeh et al. (2017) , Pelletier (2008) , Putman et al. (2017) , Ramedani et al. (2019) , Tallentire et al. (2017) , Thoma and Putman (2020) , and Wicaksono and Kaswara (2021)
Meat	E	2.11	Paolotti et al. (2016)
Packed meat	C	1.37	Kalhor et al. (2016)
Poultry meat	E	E2.11	Boggia et al. (2010) , Castellini et al. (2012a, 2012b) , and Rocchi et al. (2019)
Poultry protein	P	10.05	Heines et al. (2022)
Roast chicken	C	1.37	Bengtsson and Seddon (2013)
Whole packaged chicken	C	1.37	Thévenot et al. (2013)

L = Live weight = 1 kg LW. C = Carcass weight to live weight conversion = 1 kg LW = 0.73 kg CW, Live weight factor = 1.37. E = Edible meat to live weight conversion = 1 kg CW = 0.65 kg EM, Live weight factor = 2.11. B = Breast meat to live weight conversion = 1 kg LW = 0.24 kg breast meat, Live weight factor 4.17. P = Protein conversion to live weight = 1 kg EM = 0.21 kg protein, Live weight factor = 10.05.

The other key perspective involves examining how BCP LCA results are reported. Importantly, as the LCAs were cataloged, the authors noticed inconsistencies in the reporting of key components like the functional unit, which makes direct comparison more

difficult. These inconsistencies likely exist in other compendiums of agricultural LCAs, suggesting that there is opportunity to improve standardization across LCA studies of food systems. This issue is most likely due the ISO 14040 series framework, given it is a broad standard

designed to cover a variety of production systems. From the authors' perspective, additional standardization of LCA methodology across agricultural and food production would provide value both to practitioners and other stakeholders.

3.1 Consolidated LCA results

After normalization of the functional unit to 1 kg live weight, the distribution of the category indicator results for global warming, acidification, and eutrophication show a right skewed normal distribution (Figure 1). This distribution is expected, given these values are bound by zero and most values are closer to zero when compared to outliers.

Global warming, acidification and eutrophication category indicators results were selected for statistical analysis to assess due to their greater frequency of reporting throughout the LCA studies. Studies that utilized cradle-to-farmgate were chosen for comparison for an "apples to apples" comparison and because it was the most consistently applied system boundary across studies. Conventional, free-range, and organic BCP LCA were compared utilizing univariate data analysis.

Our analysis indicates that there is no significant difference in global warming category indicator results for conventional, free range and organic BCP. This result falls in line with other meta-analysis study's findings (Kyriazakis et al., 2025). That said, it is important to note that the use of an organic BCP has been shown to increase the welfare of the animals within the system (Göransson and Lundmark Hedman, 2024). Other analysis has demonstrated that some increases in animal welfare such as decreasing stocking density have minimal impact on BCP's carbon footprint (Karlsson et al., 2025). This suggests that a more humane production system could be utilized for chicken production while having no significant impact on global warming.

Our analysis indicates that the category indicator results for acidification and eutrophication were significantly higher when comparing free range and organic BCP to conventional BCP studies (see Figure 2). This difference in acidification and eutrophication can be attributed to organic crop production, which generally has lower yields since cultivation of nitrogen-fixing and cover crops are required to manage soil quality, leading to greater emissions per mass of product (Leinonen and Kyriazakis, 2013). Feed consumption was also greater in the free range and organic BCP systems, which can be

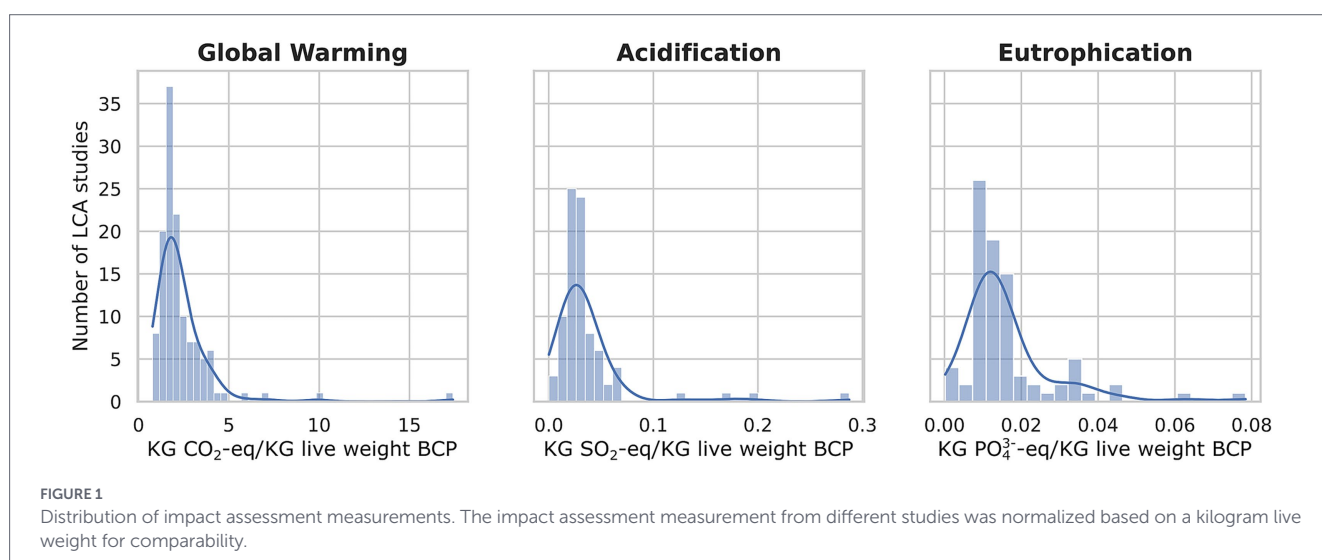
attributed to slower weight gain and a higher feed conversion ratio (Leinonen et al., 2012). Increased chicken manure production is also a contributor to environmental acidification and eutrophication with ammonia emissions contributing to both category indicators with nitrogen leaching after land application contributing to eutrophication only (Leinonen et al., 2012). It is worth noting the distinction that nitrogen inputs to organic systems represent recycled nitrogen, as opposed to synthetic nitrogen for conventional systems, so while eutrophication may increase, less nitrogen is added to the total global pool of reactive nitrogen in organic systems (Cattell Noll et al., 2020).

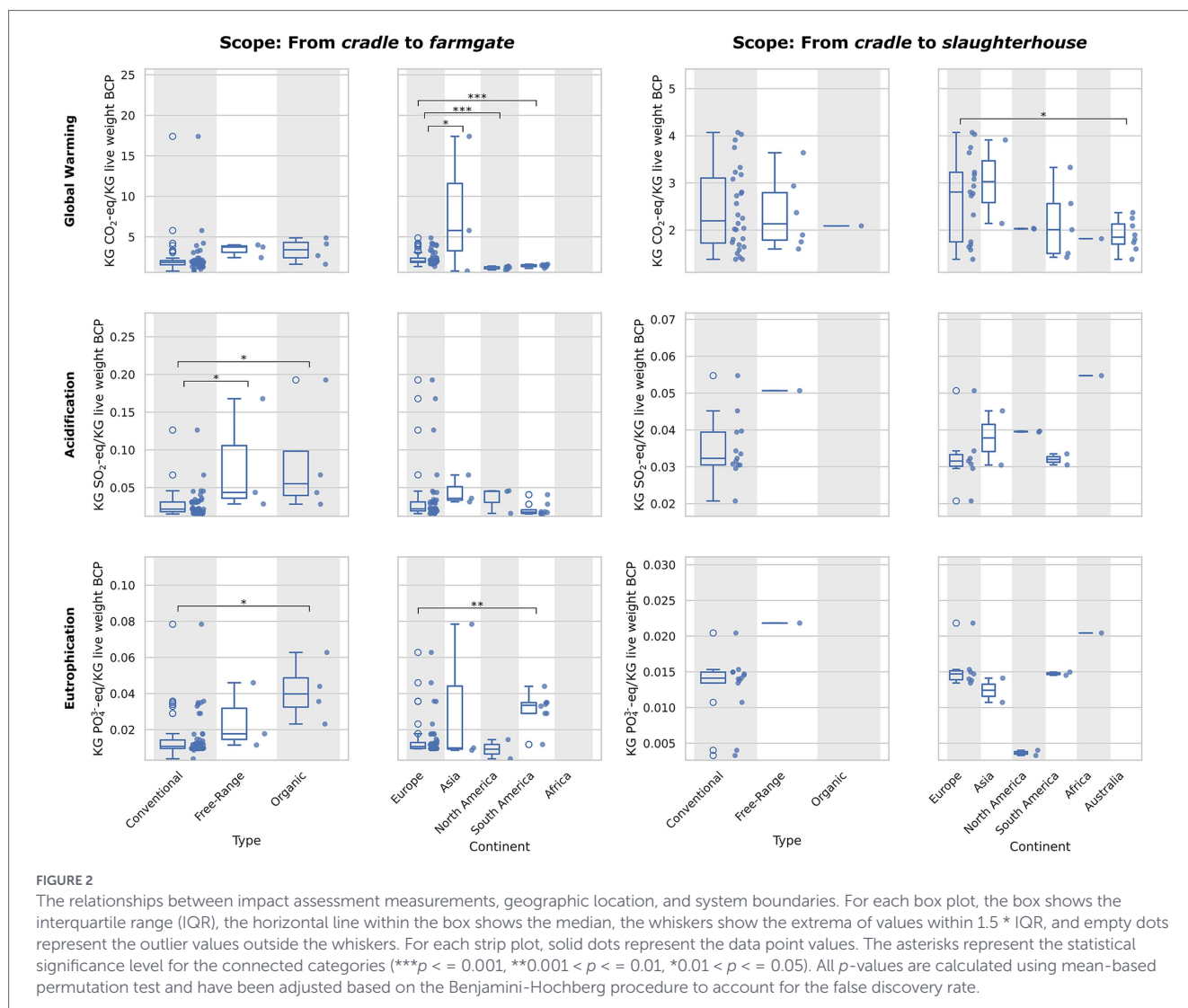
The higher eutrophication and acidification impact results indicate that organic and free-range chicken producers with environmental objectives could incorporate strategies such as proper litter management to slow uric acid breakdown into acidifying emissions or buffering strips of vegetation to trap nutrients before they reach bodies of water (Patterson and Adrizal, 2005; Wang et al., 2021). It should also be noted that there were fewer LCAs with data on free range or organic BCP systems compared to conventional BCP system LCAs. This provides an example of where meta-analysis of LCA data can be utilized to highlight hotspots for environmental impacts and identify areas where additional work is needed.

3.2 Spatial coverage of LCA studies

The examined LCAs were most commonly from Europe, with 91 of the 173 analyses representing the region. The United Kingdom had the greatest number of environmental assessments (42) related to BCP, more than double the United States and Brazil, each of which had 19 BCP LCAs conducted. The bulk of the research was carried out by a small number of people despite the high output (Jones et al., 2006; Leinonen et al., 2016; Leinonen et al., 2014; Leinonen et al., 2013; Leinonen et al., 2012; Leinonen and Kyriazakis, 2013; Leinonen and Williams, 2015; Tallentire et al., 2017). Figure 3 presents a summary of the number of BCP LCA studies conducted by country.

The vast majority of the North American BCP LCAs (19) were conducted in the United States (Beal et al., 2023; Bundgaard et al., 2014; da Prudencio Silva Junior et al., 2008; Putman et al., 2017; Thoma and Putman, 2020), with two being conducted in Mexico (López-Andrés et al., 2018) and no peer-reviewed studies were identified for Canada. The Canadian chicken production system produced





over 1.34 billion kilograms of carcass weight chicken in 2022, and a peer-reviewed LCA of Canadian BCP would likely be informative for both producers and consumers (Agriculture and Agri-Food Canada, 2022). All South American assessments were conducted in Brazil (dos Araújo Santos et al., 2023; da Duarte Silva Lima et al., 2019; Giusti et al., 2022; Martinelli et al., 2020; da Prudencio Silva Junior et al., 2012; da Prudencio Silva Junior et al., 2008; Prudêncio da Silva et al., 2014) or simply stated as representing South America as a region (Kebreab et al., 2016). South American researcher focus on Brazilian chicken production likely stems from the fact that Brazil is the second-highest chicken producer in the world with production expected to reach 15.1 million metric tons in 2024 (USDA, 2023).

Fifteen BCP LCAs were conducted in Australia, with a focus on Queensland and South Australia (Bengtsson and Seddon, 2013; Copley and Wiedemann, 2022; Wiedemann et al., 2012, 2017). In Asia, researchers in Iran conducted the most BCP LCAs (Kalhor et al., 2016; Payandeh et al., 2017; Pishgar-Komleh et al., 2017; Ramedani et al., 2019). Iranian interest in agricultural LCAs may be due to the country's environmental challenges such as desertification, unsustainable livestock production, and water limitations (Madani, 2021). The only broiler chicken production LCA we identified in Africa was on the Réunion Island, which is a department of France (Thévenot et al., 2013). This is likely because LCAs, in

general, have been conducted far less frequently in Africa than other continents with several countries producing more LCA product studies than the entire continent (Karkour et al., 2021). This indicates that there is need for agricultural LCAs on the African continent particularly as countries modernize their agricultural systems.

Data analysis of cradle-to-farmgate LCA was conducted by continent. This analysis indicates that North and South America BCP LCA reported that the category indicator results for global warming were significantly less those in Europe. Europe had significantly less global warming impact per unit than Asia. All right-skewed outliers for the reported category indicators result for global warming were from Asia, which likely shaped these results. Additionally, none of the identified Australian BCP LCAs were cradle to farmgate with the majority being cradle-to-slaughterhouse. No significant difference in acidification were identified between the continents. Our analysis indicates that the reported category indicator results for eutrophication were significantly lower for Europe when compared to South America. This may be due to the stricter environmental regulations such as the European Union's 1991 Nitrate Directive being enacted in Europe (European Union, 1991). Additionally, studies were examined that utilized a cradle-to-slaughterhouse scope however no significant difference was found in the category indicator results for

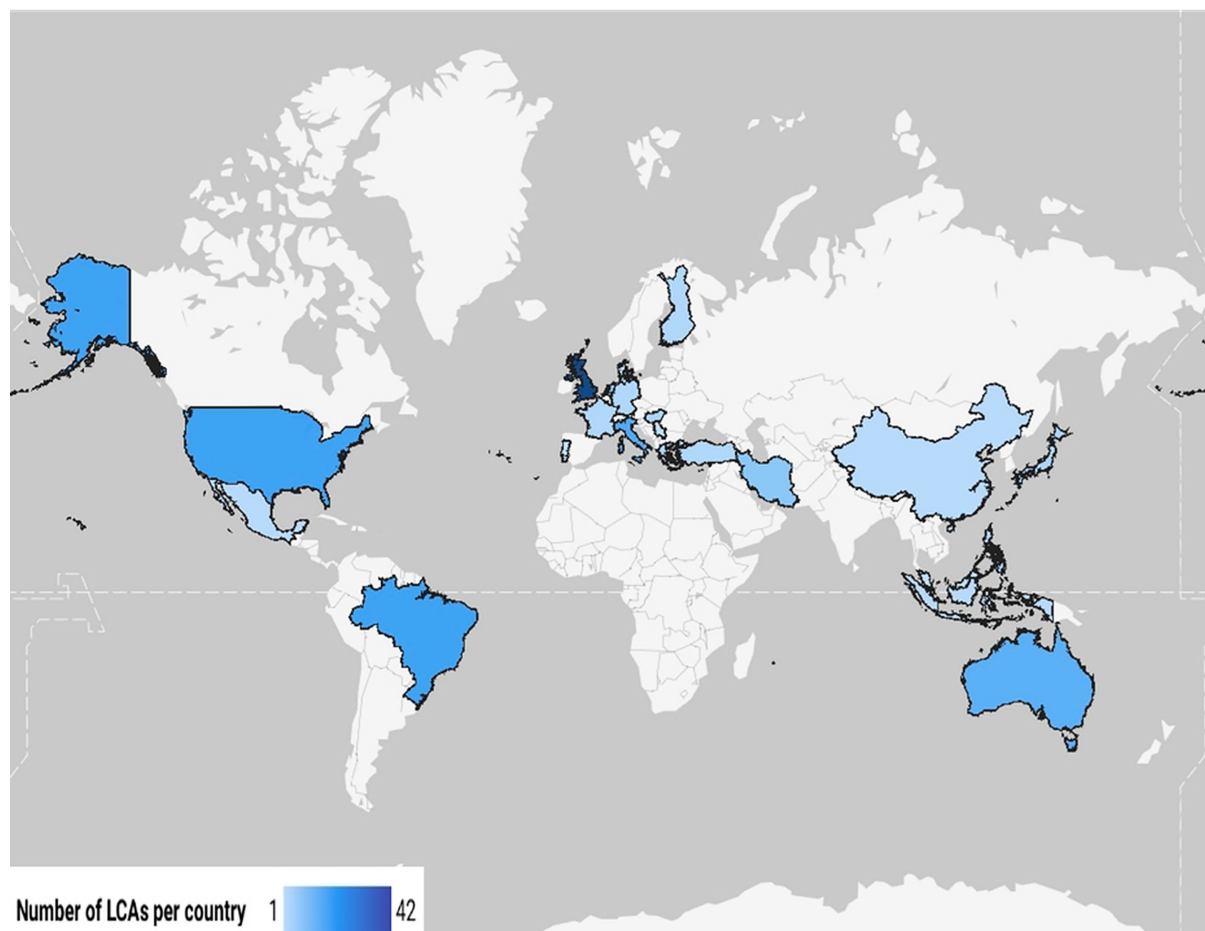


FIGURE 3

Map of broiler chicken production LCA quantity by country. white areas represent a lack BCP LCA in the country, whereas colored areas indicate at least one BCP LCA.

global warming and acidification. There were significant differences in the category indicator results of eutrophication, but those conclusions were drawn from continents with only 2 studies, and more data would likely be necessary to draw meaningful conclusions. This analysis should aid global food suppliers in determining the environmental impact of chicken products and products containing chicken.

4 Discussion

Defining the functional unit is an important part of any LCA. By the ISO 14040 definition, the functional unit is the “quantified performance of a product system for use as a reference unit” (International Organization for Standardization, 2006).

The use of a standard functional unit enables comparison across distinct production systems, such as organic vs. conventional food production. For BCP, reporting results with a standard functional unit of kg live weight (kg LW) of broiler chicken would streamline comparison between studies and product systems. A kg LW of chicken also allows conversion to other functional units such as carcass weight or protein. This variance in functional unit also seen in the LCAs of other livestock (de Vries et al., 2015; McAuliffe et al., 2016). Utilizing a

standard functional unit of kg LW would allow for comparison of studies from farmgate onwards and facilitates easier comparison of BCP as the scope is expanded (i.e., easier for the interested party to understand the additional impacts that are added via slaughterhouse, travel, etc....).

Over 90 impact categories were reported for the 57 published assessments. Throughout all the assessments, global warming (kg of CO₂) was the most highly reported metric with over 120 values reported, followed by acidification (kg of SO₂e) and eutrophication (kg of PO₄³⁻) each with approximately 80 reported values. After cumulative energy demand (24 reported values), all other impact categories were reported fewer than 20 times. The top 20 impact categories were reported 9 or more times (see Figure 4). Additionally, some impact categories were reported with multiple variations. For example, abiotic resource depletion was reported across a variety of resources (minerals and non-renewable fossil fuels, elements and reserves, and fossil fuels) and units (kg of Sb, kg of Sb, MJ, respectively). Similarly, an impact category (IC) such as land occupation may be reported in different units (e.g., ha, m²a, m² organic arable, and m² year), which may be easier to normalize.

This diversity of reporting complicates system comparisons. This is especially true when the results are reported as category indicator results (e.g., kg of CO₂ eq per functional unit) since these types of

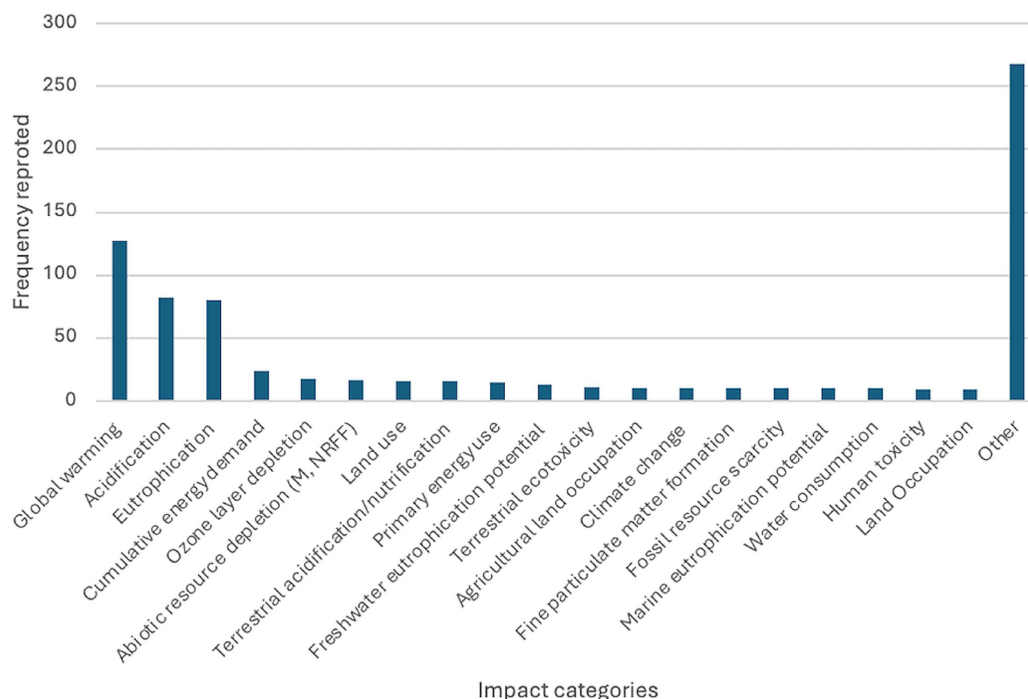


FIGURE 4

Top 20 reported impact categories reported in BCP LCA and a combined other category. M, NRFF, minerals and non-renewable fossil fuels, see supplemental for all individual categories not shown on the bar graph.

results mean little more to the reader than “more is bad.” When LCA results show trade-offs between category indicator results then interpreting those findings ultimately becomes a value judgment for the interested party.

This issue can be seen in microcosm with global warming/climate change being the most reported category indicator result in our examination of BCP LCAs. This has been identified as an issue for livestock LCAs with categories such as biodiversity and particulate matter being reported less than other categories such as global warming (McClelland et al., 2018). This disproportionate focus on CO₂ emissions is likely the result of the scale and scope of climate change as a dominant environmental issue, underscored by initiatives like the Kyoto Protocol and the Paris Agreement (Baiardi, 2023). Public climate awareness is also influenced by opinion leaders, such as Greta Thunberg or Andrew Bolt on social media (Baiardi, 2023), leading to the simplification of complex environmental issues being reduced to a singular focus on CO₂ emissions as an all-encompassing environmental metric for the public. This likely has increased the “value” of lowering kg of CO₂ eq per functional unit compared to another impact category. Some impact categories have the potential to be more tangible than global warming. For example, eutrophication can be a very tangible for waterfront communities’ due to the development of algal blooms which remove oxygen from the water and cause the death of fish and other aquatic species (Nematchoua, 2022). However, if only global warming is reported or if the reader does not understand the consequences of the other impact categories, then there is potential for uninformed interpretation of LCA results. Over 90 impact categories were reported, with some impact categories

having different category indicator results (e.g., abiotic resource depletion). This diversity of reporting can make it difficult to compare similar studies and can potentially cause information overload for stakeholders (Bawden and Robinson, 2020). Figure 4 demonstrates the diversity in reporting, showing that while global warming was the most reported specific category, the combined “Other” impact categories were reported even more frequently.

To further simplify, the reported impact categories were grouped into general categories of acidification, aquatic toxicity, eutrophication, global warming, human health, land, ozone layer depletion, particulate matter formation, resource/energy use, smog production, terrestrial toxicity, and water use (see Table 2). Utilizing these groupings and a common reporting unit would help standardize agricultural LCAs. However, impact assessment methodologies are geographic in nature, which poses challenges to standardization (Bare, 2011; CML-Department of Industrial Ecology, 2016).

From this examination, utilizing the frequency of reported LCA impact categories provides guidance for standardizing reported category indicator results. While other results could still be reported, standardization of agricultural, or even just BCP LCAs, with common category indicator results reported would be helpful. To increase standardization across BCP LCAs, we propose three recommendations. First, studies should adopt a standard functional unit of 1 kg live weight to allow for consistent comparisons across production systems. Second, initial results should be reported a on cradle-to-farmgate basis, with additional downstream results reported separately. Finally, LCAs should utilize the impact categories described in Table 2 and provide clear descriptions of each impact category. In summation,

TABLE 2 Reported impact categories, category indicator units, frequency, and environmental relevance by group.

Group	Listed impact categories	Category indicator units	Frequency reported	Environmental relevance
Acidification	Acidification, Terrestrial acidification/nutrication, Terrestrial acidification potential	kg SO ₂ eq, kg SO ₂ eq, kg SO ₂ eq	82 + 16 + 2 = 100 total	- Biodiversity loss - Creation of acid rain. Acidification can affect soil chemistry and plant growth. In aquatic environments, it can harm aquatic life and disrupt reproductive processes(United States EPA, 2024a).
Aquatic toxicity	Freshwater aquatic ecotoxicity, Freshwater ecotoxicity potential, Marine ecotoxicity, Aquatic ecotoxicity	kg 1,4 DCB- eq, CTUe, kg 1,4 DCB eq, kg TEG water	4 + 3 + 3 + 2 = 12 total	- Biodiversity loss - Ecosystem disruption Toxic chemicals can harm aquatic life and disrupt reproductive processes. Can change ecosystem composition and disrupt nutrient cycling dynamics (ISO, 2003).
Eutrophication	Eutrophication, Freshwater eutrophication potential, Marine eutrophication potential, Eutrophication, Phosphorus excretion, N2O - > N, NH3 - > N, NO3 - > N, Ammonia Ammonia	kg PO ₄ ³⁻ eq, kg P eq, kg N eq, kg N eq, g P excreted, kg, kg, kg, g, Average kg	80 + 13 + 10 + 8 + 6 + 3 + 3 + 3 + 2 + 2 = 130 total	- Creation of toxins - Creation of dead zones in waters ways Excessive nutrients in water ways can cause the formation algal blooms which can create toxins which move up the food supply chain. Algal blooms cause dead zones with little or no oxygen (United States EPA, 2024b).
Global warming	Global warming, Climate change, Climate change Land Use Change, Climate change Greenhouse gasses excluding Land use and direct land change use, Greenhouse gases with land use and direct land use change	kg CO ₂ eq, kg CO ₂ eq, kg CO ₂ eq, DALY x10 ³ kg, CO ₂ eq, kg CO ₂ eq	127 + 10 + 8 + 3 + 3 + 3 = 154 total	- Increased global temperatures - Ocean acidification Increases in global temperatures can affect weather patterns and cause rise in sea levels due the melting of ice. Ocean acidification can harm marine life especially those with calcium carbonate shells (United States EPA, 2023).
Human health	Human toxicity, Carcinogens, Non-carcinogens, Human toxicity potential, Human toxicity potential, Carcinogens, Heavy metals, Human health, Ionizing radiation, Respiratory organics	kg 1,4 DCB- eq, kg C ₂ H ₃ Cl eq, kg C ₂ H ₃ Cl eq, cancer CTUh, non-cancer CTUh, kg B (a) P, kg Pb, DALY, Bq C-14 eq, kg C ₂ H ₄ eq	9 + 5 + 5 + 3 + 3 + 2 + 2 + 2 + 2 + 2 = 35 total	- Acute health effects - Chronic health effects Toxic emissions to air, land and water can led to variety of negative human health outcomes. Exposure can from inhalation, ingestion and/or skin contact. Chronic exposure to toxic substances can cause a variety of health issues including cancer, respiratory conditions and neurological disorders.

(Continued)

TABLE 2 (Continued)

Group	Listed impact categories	Category indicator units	Frequency reported	Environmental relevance
Land	Land use, Agricultural land occupation, Land occupation, Arable land, Land occupation, Land occupation, Ecological footprint, Land use, Natural land transformation, Agricultural land use, Ecosystem quality, Land occupation, Ag. Land, Land use—competition	m ² a crop eq, m ² year, ha, m ² , m ² org arable, m ² year, gm ² *year, PDF m ² *year, m ² , m ² , PDF m ² yr., m ² a, m ² a, m ² a	16 + 10 + 9 + 7 + 5 + 4 + 3 + 3 + 3 + 2 + 2 + 2 + 1 + 1 = 71	• Biodiversity loss • Ecosystem and soil degradation Development of agricultural lands can lead to the loss in biodiversity, soil erosion and loss of soil fertility. It also has the potential to affect carbon sequestration, water filtration and pollination (Foley et al., 2005).
Ozone layer depletion	Ozone layer depletion	kg CFC-11 eq	18 total	• Increased rates of cancer and cataracts • Detrimental effects to plants, marine life and human built materials UV radiation breaks down ozone depleting substances (ex. chlorofluorocarbons) which release chlorine and bromine atoms which convert ozone (O ₃) into O ₂ . The thinning of the allows more UV-B radiation to reach earth which can be deleterious to human health (United States EPA, 2024c)
Particulate matter formation	Fine particulate matter formation, Respiratory effects, Respiratory inorganics, Particulate matter formation	kg PM 2.5 eq, kg PM 2.5 eq, kg PM 2.5 eq, kg PM10 eq	10 + 7 + 5 + 2 = 24 total	• Respiratory illness • Increased mortality rate Particulate matter are microscopic solids or liquids that can inhaled. Particles less than 10 micrometers can enter your lings and possibly enter the blood stream. Particles less than 2.5 micrometers (fine particles) have the greatest health risk (United States EPA, 2024d).

(Continued)

TABLE 2 (Continued)

Group	Listed impact categories	Category indicator units	Frequency reported	Environmental relevance
Resource/energy use	Cumulative energy demand, Abiotic resource depletion (minerals and non-renewable fossil fuel), Primary energy use, Fossil resource scarcity, Non-renewable fossil energy, Abiotic resource depletion (elements, reserves), Energy consumption, Primary energy demand, Abiotic resource use, Fossil fuel energy demand, Fossil fuels, Resources, Abiotic resource depletion (fossil fuels), Energy resources, Fossil fuel depletion, Mineral extraction, Non-renewable energy use, Solid waste, Fossil energy	MJ eq, kg Sb, GJ, kg oil eq, MJ, kg ant, MJ, GJ, kg antimony eq, MJ, MJ surplus, MJ primary, MJ, MJ low voltage, kg oil eq, MJ surplus, MJ, kg, MJ	24 + 17 + 15 + 10 + 7 + 4 + 4 + 3 + 3 + 3 + 3 + 2 + 2 + 2 + 2 + 2 + 2 + 1 = 108 total	• Potential energy crisis • Diverse set of problems related to resource depletion Energy and resource use diminishes non-renewable sources of energy and resources which has a wide variety of implications including economic, geopolitical, social and environmental impacts.
Smog production	Photochemical oxidation, Photochemical Ozone formation potential, Photo-oxidant formation potential, Photochemical oxidant formation	kg Ethylene eq, kg NMVOC eq, g C ₂ H ₄ eq, kg NMVOC	7 + 3 + 1 + 1 = 12 total	• Respiratory illness • Damage to crops and ecosystems Ground level ozone (smog) is produced by chemical reactions between nitrogen oxides and volatile organic compounds. Exposure to smog can have deleterious effects to respiratory and cardiovascular system. Smog can alter soil and plant biochemistry which can be harmful for plant and animal life (United States EPA, 2024e).
Terrestrial toxicity	Terrestrial ecotoxicity, Pesticide use, Terrestrial ecotoxicity, Ecotoxicity, Pesticides	kg 1,4 DCB- eq, dose-ha, kg TEG soil, PAF*m ² * year, kg Active substance	11 + 6 + 5 + 3 + 2 = 27 total	• Food web contamination • Ecosystem disruption Pollutants enter a terrestrial system and organisms are exposed to them via dermal, oral, inhalation or food chain exposure. These pollutants can spread thorough the ecosystem via the web or other means potentially causing species the inability to sustain themselves (Fairbrother and Hope, 2005).

(Continued)

TABLE 2 (Continued)

Group	Listed impact categories	Category indicator units	Frequency reported	Environmental relevance
Water use	Water consumption, Water scarcity impact (AWARE), Fresh water consumption, Street weighted water, Water depletion, Water depletion potential, Water scarcity ABS, Water use, Consumptive fresh water use, Water depletion index, Blue water footprint, Water	m ³ , m ³ eq, L, L H ₂ O eq, L, m ³ , L, L ABS eq, L, m ³ , L, m ³	10 + 8 + 7 + 7 + 7 + 6 + 4 + 4 + 3 + 3 + 1 = 67 total	• Water scarcity • Water Quality Fresh water use has the potential to lead to water scarcity if demand exceeds supply.

The units and frequency are listed in the order of the listed impact category.

additional standardization of agricultural LCAs could help reduce some of the “black box” issues which can be a criticism of LCAs despite the methodology outlined in the ISO 14040 series (Klöpper, 2012).

5 Conclusion

This examination of BCP LCAs provides insights for environmentalists and LCA practitioners. A major insight for LCA practitioners is the evident need for standardization of the methodology as the reporting of functional units, and impact categories varies widely within and across sectors. Standardization of a functional unit and impact categories would benefit BCP LCA assessment and broader agricultural LCA studies by enabling greater comparability of results and identification of best practices to improve performance.

This examination of BCP LCAs also stresses the need to broaden geographic representation of agricultural LCAs. Given broiler chicken is a product consumed on all continents, our study indicates that BCP LCA research is highly concentrated in Europe, North America and Brazil, with limited to no representation in highly populous countries in Asia and Africa. Expanding the geographic range of LCA studies will be essential to address interconnecting global environmental and economic issues.

Furthermore, this study highlights a disproportionate focus on certain impact categories, particularly global warming within the agriculture sector, while other categories, such as smog or particulate matter emissions, are underreported. This narrow focus may lead to ill-informed policy decisions and hinder the development of more comprehensive sustainability strategies which account for a broader suite of impact categories. Clear and complete elaboration of the broader range of impact categories is essential, because LCA are often used to guide resource allocation and inform policy.

Another important insight from this study is that organic products, which are commonly perceived as environmentally friendly may not necessarily have less of an environmental impact than their conventionally produced counterpart. The USDA National Organic program is part of the Agricultural Marketing Service, and its certification does not necessarily convey that a product has a lower environmental impact. In the case of BCP, adhering to many of the tenets of the organic program could lead to a higher quality of life for the birds, while utilizing a conventionally produced feed could lower the impact of the final product. That said, this result also exposes the limitations of standard LCA impact metrics to provide a more holistic assessment of agricultural production processes that may be of interest to the consumer, including animal welfare (Lanzoni et al., 2023) as we have discussed, but also soil health, (Vidal Legaz et al., 2017) organic versus synthetic nitrogen utilization (Cattell Noll et al., 2020) and biodiversity (Gabel et al., 2016). In sum, our findings highlight the complexities of implementing “sustainable” agriculture and emphasize the necessity of understanding the critical environmental tradeoffs between production regimes, some of which are well captured in the application of LCA and others which are not.

By examining BCP LCAs, this study highlights valuable environmental insights into BCP production and exposes key inconsistencies

in LCA reporting. Greater standardization and more comprehensive LCA reporting practices would allow for easier comparison across studies and facilitate improved environmental optimization. This, in turn, would empower stakeholders to make more informed decisions and promote the best sustainable practices across the global food system.

Author contributions

DR: Methodology, Conceptualization, Visualization, Data curation, Writing – original draft, Writing – review & editing, Investigation. FL: Visualization, Writing – original draft, Methodology, Formal analysis, Data curation. JS: Writing – review & editing, Conceptualization, Supervision, Funding acquisition, Resources, Project administration. IT: Resources, Formal analysis, Writing – review & editing, Conceptualization, Visualization, Project administration, Funding acquisition, Supervision. MB: Funding acquisition, Resources, Conceptualization, Supervision, Project administration, Writing – review & editing. ES: Conceptualization, Resources, Investigation, Project administration, Supervision, Writing – review & editing.

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Supplementary material

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