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Mitigating environmental impacts of chicken production – The role of Co-product valorisation

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ABSTRACT

Food loss and waste (FLW) has become a significant issue for mitigating environmental impacts in the food system. The global food system contributes substantially to climate change, eutrophication, and other environmental concerns, predominantly attributable to the rearing and processing of animal products. Despite these concerns, chicken production is increasing worldwide and is a key focal point for mitigating greenhouse gas emissions. However, in many countries, high-nutritional value chicken co-products such as feet, giblets, and other offal are still undervalued, often considered waste and sent for valorisation rather than being consumed, leading to a limited understanding within the literature of their environmental implications.

Life Cycle Assessment (LCA) studies in the agri-food sector typically allocate environmental burdens between main products and co-products based on economic value, resulting in a lower burden for chicken co-products due to their lower price compared to carcass meat. This study conducts an LCA on a typical tonne of chicken co-products in the UK to evaluate the environmental burdens of different treatment scenarios and analyse the impact of different allocation methods. It compares the current treatment with four scenarios: sending all to pet food, rendering, incineration, or anaerobic digestion, using system expansion to assess the influence of avoided products. Results show that economic allocation based on raw material price is on average 122 % lower than mass allocation, with the difference of global warming reaching 184 %, equivalent to 1953 kg CO_2 eq/tonne. Processing all co-products into pet food is the most environmentally friendly option, while incineration generates the largest impact. Outcomes under system expansion are highly sensitive to the choice of displaced products, with soybean meal and palm oil substitution yielding the greatest benefits. The findings highlight the overlooked role of edible co-products in sustainable food system. However, the "pet food only" scenario does not achieve absolute reductions, suggesting that further valorisation pathways of chicken giblets, including greater integration into human diets, warrant investigation.

1. Introduction

Food loss and waste (FLW) has become a critical global issue in recent decades, exerting negative influences on societal, economic, and environmental dimensions, and affecting both developed and developing countries (Zhu et al., 2023). It is estimated that approximately 14 % of food produced globally, equalling more than 1.3 billion tonnes, is wasted annually (FAO, 2011). FLW occurs at each stage of the food supply chain. For developed countries, the majority of FLW normally occurs at the consumption stage, whereas for developing countries, post-harvest losses dominate FLW due to inefficiency harvesting and inadequate storage conditions (Slorach et al., 2019). Remarkably, the total annual amount of FLW is comparable to China's annual food production, and could satisfy the food needs of at least 1 billion people in a given year (Hanson et al., 2016). What's more, FLW is considered to have a significant impact on global climate change. The global food system accounts for 19–29 % of total anthropogenic greenhouse gas (GHG) emissions, with FLW along the entire food supply chain estimated to represent one-third of these emissions (Crippa et al., 2021; FAO, 2015; Xue et al., 2019). This includes over 11 million tonnes (16 %) of

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anthropogenic ammonia (NH_3) emissions (Guo et al., 2023).

However, a unified standard for the definition of FLW remains elusive among researchers, leading to varied interpretations and applications of the term in studies (Xue et al., 2017). According to statistics from FUSIONS (Östergren, 2014), nearly 100 definitions of FLW are currently utilized across various organizations, studies, and literature. Despite major projects and organizations offering their definitions of FLW (e.g., FAO, USDA, WRAP, FUSIONS), the debate over which definition to use in research persists, including distinctions between what is considered edible versus inedible, and avoidable versus unavoidable waste. For example, the definition of FLW proposed by WRAP, which is widely accepted in the UK, emphasizes the edible portions of food not consumed by people as FLW (WRAP, 2018). Chicken co-products (also known as by-products or offal) are not automatically classified as FLW simply because they are not generally consumed by humans and either rendered or exported abroad. In fact, in the UK they are often not even categorised as "food" in the first place, and therefore fall outside the scope of what is defined as FLW. This discrepancy is observed in many other countries - e.g., US (Kafarakis, 2025), highlights the complexity and cultural variability inherent in defining FLW.

Poultry is the second most consumed type of meat globally after pork (14.99 kg per person vs 16.02 kg per person) and is anticipated to exceed the consumption of pork in the future (Skunca et al., 2018). Among poultry, chicken represents the largest component. The preference for chicken flavour and its nutritional benefits, including low fat and high protein content, has led to a steady increase in the raising and slaughtering of chickens in the UK, with over 1.17 billion chickens slaughtered in 2021 (Rumsey, 2023). The slaughtering process generates approximately 30 % of Category 3 (CAT.3) co-products, which are assessed as low-risk and free from infectious diseases (British Poultry Council, 2024). These co-products, which are potentially suitable for human consumption, are generally in pet food manufacturing and amounted to a total weight of 850,000 tonnes, including "potentially edible" parts such as chicken heads, giblets, feet, and bones (Rumsey, 2023). However, in the UK, these parts are usually not consumed (less than 1 %, based on the British Poultry Council (2024); instead, they are purchased for re-processing and valorisation, which is typically known as rendering.

Rendering is a valorisation process for animal co-products. Through high-temperature cooking followed by drying, rendering eliminates potential pathogens and maintains stable CAT.3 animal co-products. This process separates fat or oil from proteins to produce marketable products. Typically, the water content in the co-products is vaporized, usually accounting for 67 % of the wet weight (Fabra UK, 2023). In the remaining solids, the ratio of fat products to protein meal products is generally 1:2 (Fabra UK, 2023). In the rendering process of chicken co-products, usually chicken meal and chicken fat are produced, which are used primarily as animal feed, with a small portion converted into biodiesel. The substitution of traditionally high-carbon footprint products, such as palm oil, fish meal, and soybean meal, with chicken fat products and protein meal represents a significant environmental benefit (EFPRA, 2021).

Processing animal co-products into pet food is also a common disposal method. This processing can occur in rendering plants or in separate pet food manufacturing facilities. For example, pet food often contains a certain amount of bone paste, which offers natural texture and flavour, high protein content, low fat content, and rich minerals content, making it suitable for consumption by cats and dogs (Mosna et al., 2021). Furthermore, thoroughly dried products such as chicken feet, skin, and bones are commonly used as "chew toys" for larger pets, aiding in dental health, energy consumption, and nutritional supplementation (Ma, 2022).

Rendering, as an environmentally friendly method for processing animal co-products, has been extensively studied using the Life Cycle Assessment (LCA) framework to assess its environmental impacts (Xue et al., 2017). LCA is widely used for assessing the environmental impacts generated throughout the lifecycle of a product or system and has been broadly applied in research on FLW as well as the treatment of animal co-products (Bakkaloglu et al., 2022; Skunca et al., 2018; Slorach et al., 2019; Xu et al., 2015; Xue et al., 2021). For example, Campos et al. (2020) conducted a comparative analysis of the production scenarios of poultry fat, poultry co-product meal, and feather meal at a rendering company in Portugal, revealing that the production of 1 tonne of each product could cause 666, 726, and 597 kg of CO_2e, respectively. Al-Zohairi et al. (2023) evaluated the slaughter and subsequent processing of pork co-products in four European countries (Denmark, Germany, Sweden, and Poland), demonstrating that the treatment of animal co-products has significant potential to reduce the environmental impact of pork consumption.

Despite nearly a million tonnes of chicken co-products being generated annually in the UK, their environmental impacts and valorisation pathways have received limited systematic attention. Most existing research has focused on rendering or on aggregated categories of animal co-products, without fully examining alternative treatment routes within a consistent framework. This lack of comprehensive analysis makes it difficult to identify which options are genuinely the most environmentally favourable, and understanding the implications of various disposal methods is, therefore, essential for identifying more sustainable solutions. Furthermore, in previous studies on the assessment of rendering, animal co-products were technically categorised as waste, and thus no burden was allocated to them, which is in line with the ISO standard (ISO, 2006). While consistent with earlier practice, this approach no longer reflects current realities, as animal co-products are nowadays not simply wastes, but are increasingly recognised and used as raw materials for value-added products. The traditional zero burden allocation method is therefore no longer justified, and continued reliance on it risks underestimating their true environmental relevance. A critical gap remains around how different allocation choices - economic versus mass-based - reshape the perceived impacts of chicken co-products, and how these methodological decisions influence conclusions about their role in sustainable food systems. The decision on whether to allocate based on economic value or physical characteristics (such as mass, volume, etc.) of the different products needs to be carefully discussed and analysed by researchers before establishing LCA models.

Hence, this study assessed gap of inconsistent allocation approaches and limited analysis of co-product usage by applying LCA to evaluate the current treatment options and four alternative treatment scenarios for chicken co-products in the UK. To achieve more accurate results, system expansion was employed to account for the environmental impacts of avoided products. A scenario analysis of system expansion was conducted to evaluate the selection of avoided products. In addition, different allocation methods were applied and the appropriateness of each allocation method in an LCA study of animal co-products is discussed. Furthermore, the impacts of defining chicken offal as FLW on its disposal and associated environmental benefits are discussed.

2. Methods

2.1. System definition

The objective of this study is to conduct an LCA of the valorisation process for chicken co-products currently produced in the UK and then compare it with four more simulation scenarios. The functional unit (FU) is defined as 1 tonne of chicken co-product produced from the slaughterhouse. The scope of the study starts with the chicken raising and ends at the point where chicken co-products experienced one type of valorisation or disposal process, depending on the scenario, which is detailed in chapter 2.4. Ancillary processes such as infrastructure construction and capital goods were excluded, as their contribution was assumed to be negligible compared with operational impacts.

The calculation of the Life Cycle Inventory (LCI) and Life Cycle

Impact Assessment (LCIA) was conducted using SimaPro 9.4.0.1 with the ReCiPe 2016 methodology selected for the analysis. Eight environmental impact categories were chosen: global warming, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, and land use. These categories were chosen based on their demonstrated significance in previous studies on animal co-products and the rendering process (e.g. Al-Zohairi et al., 2023; Campos et al., 2020).

Due to the inherent complexity of environmental impact analysis, where different scenarios or allocation methods may result in trade-offs across multiple impact categories, a direct comparison between impact categories becomes challenging. To address this issue, the endpoint method was applied, following the ReCiPe 2016 model, to aggregate various impact categories into a common unit. This approach improves comparability and facilitates the interpretation of results by converting mid-point indicators into endpoint indicators, such as damage to human health (measured in disability-adjusted life years, DALYs), ecosystem quality, and resource availability. By using this method, the issue of incomparable impact categories is mitigated, allowing for a more holistic assessment of the environmental burdens and benefits associated with different valorisation scenarios.

2.2. Data collection and processing

The construction of the LCI involves the processing of rendering, the production of pet food, as well as the transportation of chicken co-products. Primary data on co-product composition, slaughterhouse outputs, and transportation routes were obtained through communication with the British Poultry Council (2024) and Google Maps (2024). Secondary data for processing stages were drawn from peer-reviewed literature and established LCI databases. For rendering processing, the main parameters were adapted from Campos et al. (2020), which provides detailed energy and material balances for poultry co-product processing. Typically, grinding and milling are first required to reduce the size of co-products, allowing for more uniform handling during following cooking and processing. Subsequently, high-temperature cooking is conducted to sterilise bacteria and melt lipids, facilitating their separation from other mixtures. This usually requires heating to temperatures above 115 °C. After the separation of lipids by high-speed centrifugation, the remaining mixture will be dried to produce powdered chicken meal, with a large amount of water being lost as steam. All the data related to power and electricity consumption are shown in SI Table A1.

The data for pet food production was adapted from Al-Zohairi et al. (2023) and the Ecoinvent 3.7.1 database (Wernet et al., 2016). Similar to the rendering process, the production of pet food also requires high-temperature cooking and sterilization for the raw chicken co-products. However, certain types of pet food need to ensure the integrity of the chicken co-products (e.g., chewable chicken feet) as well as their moisture (e.g., canned pet food), making grinding, cutting, or drying optional. Additionally, approximately 10 % of waste may be generated during production, such as inedible bones. These wastes will be disposed of by incineration as biowaste. The LCI for this process is shown in Table A.2.

Furthermore, the transportation distance for raw chicken co-products was modelled as 127 km, calculated based on the distance from several representative UK slaughterhouses to their nearest rendering factories (Google Maps, 2024). As rendering factories typically produce pet food as well, the distance to a pet food company was similarly modelled as 127 km. The LCI data for incineration and anaerobic digestion process were obtained from Ecoinvent 3.7.1 database (Wernet et al., 2016).

To address data quality, care was taken to ensure that the sources used were as recent and relevant as possible. Most foreground data for rendering and pet food were taken from recent peer-reviewed studies (Al-Zohairi et al., 2023; Campos et al., 2020), which describe modern industrial practices. Background processes such as electricity supply, transport, and waste treatment were obtained from the Ecoinvent 3.7.1 database (Wernet et al., 2016), which represents European averages. The transport distance (127 km) was directly calculated from several major UK slaughterhouses to their nearest rendering plant using Google Maps (2024), which provides a reasonable approximation of real logistics.

2.3. Allocation for environmental impact analysis of chicken co-product

In addition, four different allocation methods were tested to distribute the environmental burdens generated during the raising phase between chicken meat products and chicken co-products. These include:

1) Zero Burden Allocation: allocating all burden solely to chicken meat products, with no burdens allocated to chicken co-products;
2) Raw Material Price (RMP) Allocation: allocating based on the sale price at the slaughterhouse (i.e., raw material price, RMP) (average £ 2420/tonne for chicken meat products versus £ 34/tonne for chicken co-products) (Campos et al., 2020);
3) Product Price (PP) Allocation: allocating based on the price of the final product (i.e., product price, PP) (average £ 3911/tonne for chicken meat products versus £ 2820/tonne for chicken co-products) (Campos et al., 2020); and
4) Mass Allocation: allocating based on the mass at the slaughterhouse (70 % versus 30 %). The waste generated at slaughterhouse is considered as "waste" rather than "product" according to ISO standard, and thus does not assign any environmental burden (Dominguez Aldama et al., 2023). Besides, the total amount of slaughterhouse waste is less than 1 %, which is deemed negligible (British Poultry Council, 2024).

From an agricultural perspective, mass allocation may be more easily justified than economic allocation. In poultry farming, every unit of feed, water, energy, and electricity is evenly applied to the entire chicken - including carcass meat, offal, head, feet, etc. This means that for the same weight of chicken meat and co-products, the input is the same. Consequently, it is inequitable to allocate less environmental burden to chicken co-products simply based on their lower price as would happen in economic allocation, which is decided by traditional consumption habits. Further, the benefits of chicken offal consumption are not well captured by their market price (e.g. iron, protein, B12, values which are comparable to carcass meat (U.S. Department of Agriculture, 2025). Moreover, when comparing LCA results across different countries, economic allocation can lead to significant discrepancies.

Therefore, after the analysis of the allocation methods, the mass allocation method was selected for further research, as it better reflects the biological reality of poultry production. Price data were sourced from peer-reviewed literature (Campos et al., 2020), while mass ratios were based on UK slaughter statistics (British Poultry Council, 2024). Nevertheless, the results of alternative allocation methods are also reported for comparison, acknowledging that allocation remains a key source of methodological uncertainty in LCA.

2.4. Scenario development

Five scenarios are considered in this study. Specifically, baseline and scenarios 1 and 2 involve the breeding of chickens, the slaughtering process, the transportation of chicken co-products, the rendering or pet food processing, as well as the disposal of waste generated during the pet food processing. Conversely, scenarios 3 and 4 similarly involve the breeding of chickens, processing, and the transportation of chicken co-products, but include additional disposal processes through incineration or anaerobic digestion. The scope of the five scenarios is shown in Supporting Information (SI) Fig. A.1.

Baseline: This scenario represents the current method for processing chicken co-products in the UK. 67 % of chicken co-products are directed to pet food factories for processing into pet food products, while the remaining 33 % are sent to rendering factories for processing into rendering products (British Poultry Council, 2024).

Scenario 1 - All Pet food: This scenario assumes that all chicken co-products produced from slaughterhouse will be processed by pet food factories into pet food products.

Scenario 2 - All Rendering: This scenario assumes that all chicken co-products produced from slaughterhouse will be processed by rendering factories into rendering products.

Scenario 3 - All Incineration: This scenario assumes that all chicken co-products produced from slaughterhouse are disposed as municipal solid waste through incineration, with electricity generation being offset from this process.

Scenario 4 - All Anaerobic Digestion: This scenario assumes that all chicken co-products produced from slaughterhouse are disposed as municipal solid waste through anaerobic digestion, with biomethane production being offset from this process.

Moreover, analyses of different system expansion approaches were conducted on the baseline co-product treatment options, as well as scenarios 1 and 2, to evaluate the impact of various combinations of avoided products on the LCA results. No products are substituted for scenarios 3 and 4 as all co-products are disposed of through incineration or anaerobic digestion. Avoided products were categorised into two groups based on their solid-liquid states: soybean meal and fish meal for solid products, and palm oil and biodiesel for liquid products, as shown in Table 1. As previously mentioned, the baseline scenario assumed that the chicken meal produced by the rendering process substitutes the equivalent mass of soybean meal and fish meal in a 1:1 ratio, while the chicken fat is assumed to be substituted for an equivalent mass of biodiesel. Similarly, the protein meal produced by the pet food process substitutes an equivalent mass of soybean meal, while animal fat substitutes an equivalent mass of palm oil. Moreover, four combinations were set for the equivalent mass of avoided products: soybean meal + palm oil (Combination 1, C1), soybean meal + biodiesel (Combination 2, C2), fish meal + palm oil (Combination 3, C3), and fish meal + biodiesel (Combination 4, C4). The corresponding changes in environmental impact were recorded for each combination.

3. Result and discussion

3.1. Environmental burden of different allocation methods

3.1.1. Result comparation under different allocation methods

As illustrated in Fig. 1, when applying the zero burden allocation method as well as the economic allocation method to the processing system of chicken co-products in the UK, the results of various environmental impacts of these co-products are significantly lower than the results calculated by mass allocation. Of the two economic allocation methods, the results based on the RMP are substantially smaller than those based on the product price, given that the latter has a higher price from the valorisation processing. On average, economic allocation results are 122 % lower than those from mass allocation, with the global warming being 184 % less, equivalent to 1953 kg CO_2e. This indicates that under the RMP allocation method, the current processing of chicken co-products in the UK is net absorptive, i.e. positive environmental impacts, in absolute terms.

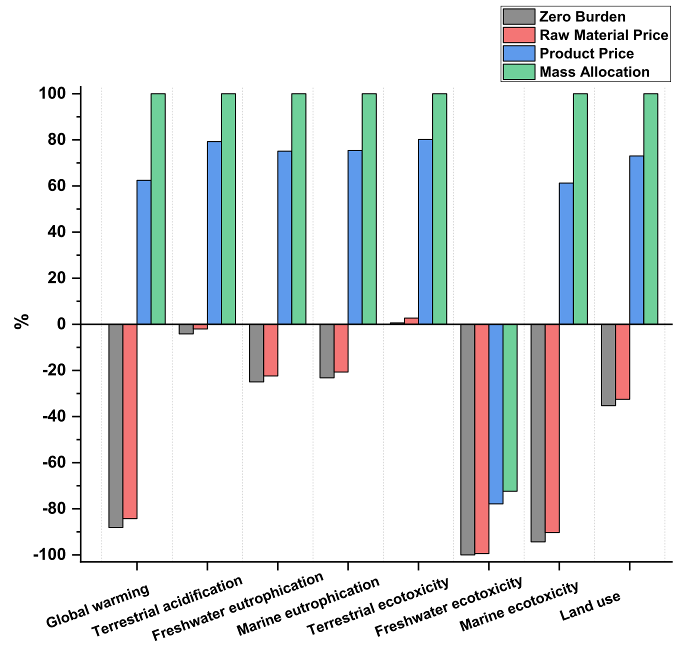

Fig. 1. Comparation of environmental impact results of baseline between different allocated methods; negative percentages indication a net reduction in environmental burden.

The reason of this situation is that, in the UK and many advanced economies, chicken co-products are generally not considered edible in most people's perspectives. According to the British Poultry Council (2024), only 1 % of chicken co-products enter the human food chain and consumed by people, while the rest is all valorised waste. As a result, the price of chicken co-products at the slaughterhouse is quite low, accounting for only 1 % of the price of chicken meat products.

Table 1
Different combinations of avoided products.

Scenario	Process	Avoided product	Initial Analysis	Combination 1	Combination 2	Combination 3	Combination 4
Baseline	Rendering	Soybean meal	✓ (50 %)	✓	✓		
		Fish meal	✓ (50 %)			✓	✓
		Palm oil		✓		✓	
		Biodiesel	✓		✓		✓
	Pet food	Soybean meal	✓	✓	✓		
		Fish meal				✓	✓
		Palm oil	✓	✓		✓	
		Biodiesel			✓		✓
S1	Pet food	Soybean meal	✓	✓	✓		
		Fish meal				✓	✓
		Palm oil	✓	✓		✓	
		Biodiesel			✓		✓
S2	Rendering	Soybean meal	✓ (50 %)	✓	✓		
		Fish meal	✓ (50 %)			✓	✓
		Palm oil		✓		✓	
		Biodiesel	✓		✓		✓

Consequently, only 1 % of the environmental burden created during chicken raising process is allocated to co-products, with the remaining majority allocated to chicken meat. Moreover, because the system expansion is included in the system boundary, the rendering products and pet food products could consequently offset environmental burdens caused by a certain number of high-emission products such as soybean meal and palm oil. Therefore, the net environmental burden could be negative.

However, this relatively low environmental impact is contradicted by the LCA results obtained through mass allocation. As shown in Fig. 1, when allocating environmental burden based on the mass ratio between chicken carcass meat and chicken co-product (which more closely aligns with nutritional value), the environmental benefits derived from offsetting high-emission avoided products no longer completely counteract the environmental burden caused by raising chickens, with the exception of freshwater ecotoxicity category. This is because the cultivation of avoided products - such as soybeans - does not require as much land use change, electricity, and energy as chicken raising (e.g., maintaining lighting and temperature in chicken coops). However, the irrigation of soybeans consumes more freshwater, and its wastewater includes toxic substances such as pesticides and fertilizers, which results in the category of freshwater ecotoxicity remaining negative.

3.1.2. Discussion of impacts between allocation methods

As mentioned in the introduction, it is crucial to allocate environmental burdens reasonably when assessing a product or system by LCA, especially when one or more co-products/wastes are generated simultaneously, as different allocation methods will directly influence LCA results. This issue is particularly prevalent in agri-food production systems, where production processes often generate co-products or valorisable wastes. Therefore, rational allocation decisions need to be made to determine the allocation ratio between the main product (e.g., chicken carcass meat) and co-products (e.g., giblets, necks, feet) (Rice et al., 2017). According to ISO standards, wastes are not required to allocate burdens, and due to this, more unambiguous and detailed boundaries need to be defined between co-products and wastes, to ensure the fairness of the allocation. However, the distinction between co-products and wastes is currently vague and unclear, especially in determining whether the coproduction exists or whether additional outputs are reusable co-products or wastes (Bava et al., 2019). Moreover, the use of the terms "co-product" and "by-product" adds confusion. The former is the term used in ISO standards for describing the product produced simultaneously with the main product, while the latter is not. Nonetheless, a large number of researchers are still confused about the use of two terms (CDM, 2008).

Employing strategies to avoid allocation is one of the most recommended approaches in ISO standards, but it is challenging to completely avoid it in agri-food system, as there is always co-product produced (Wilfart et al., 2021). Therefore, ISO suggests initially using the physical relationship between inputs and outputs as the allocation method. Only when the physical allocation method can’t be achieved, will the economic allocation method be applied. As mentioned in section 2.2, it is reasonable and objective to allocate chicken meat products and co-products according to mass. All of the inputs during chicken raising phase are distributed equally to each gram of chicken meat/co-product, and this allocation isn’t and shouldn’t be affected by prices simply determined by subjective factors such as dietary habits.

Moreover, this comparison in the baseline scenario is sufficient to illustrate the differences and implications of using different allocation methods. When extending from the baseline scenario to the other alternative treatment scenarios, the allocation method affects only the absolute magnitude of the environmental impact results but does not change the relative ranking/ratio of different scenarios. Therefore, conducting an economic allocation comparison for all scenarios would not yield additional insights beyond what has already been demonstrated in the baseline scenario.

For this reason, after determining that mass allocation provides a more appropriate representation of environmental burden distribution, we consistently applied mass allocation to all scenarios for comparability and methodological consistency.

3.2. Scenarios for the environmental impacts of chicken co-products treatment

Based on section 3.1, this study applies mass allocation as the method for distributing environmental burdens for the remainder of the analysis, determining the environmental impacts of processing chicken co-products in five different scenarios within the UK. The specific results are illustrated in Figs. 2–4. Using the eight environmental categories selected, scenario 1 - where all chicken co-products are processed as pet food - provides the lowest score in all categories, indicating that it is the most beneficial scenario among the five scenarios, although the degree of impact varies. For example, in the Freshwater Ecotoxicity of characterisation result shown in Fig. 2a–S1 exhibits a 140 % lower impact than the highest (S3), while the difference is not significant in the terrestrial acidification, with only 6 % lower than S3.

Each stage of the chicken co-product processing contributes differently to the environmental impacts across categories. Examining terrestrial acidification as an example, this impact category is primarily influenced by emissions of nitrogen and sulphur oxides (NOx and SOx) as well as nitrogen compounds associated with chicken feed production and manure, which are key pollutants causing terrestrial acidification. Therefore, the stage of chicken raising has the greatest impact on terrestrial acidification. Additionally, since the functional unit of each scenario is set as 1 tonne of chicken co-products produced from the slaughterhouse, the total environmental impact generated during the raising process is the same across scenarios. The incineration process in S3 also generates emissions of NOx and SOx, although such emissions are minimised in incineration plants. Therefore, the results of terrestrial acidification between scenarios are close, with S3 marginally leading.

In terms of freshwater ecotoxicity, impacts may come from the washing of chicken coops at farms, the rinsing of live chickens at slaughterhouses, and the cultivation process of soybeans (Wernet et al., 2016). Generally, soybean cultivation requires extensive freshwater irrigation, which consumes significant amounts of fresh water. Furthermore, the application of phosphorous fertilizer and pesticides, which dissolve in the wastewater with irrigation, increases freshwater toxicity. Consequently, the freshwater ecotoxicity impacts for soybean products (e.g., soybean meal) are quite high, whereas 60 % of the pet food product is protein meal, which can replace soybean meal at 100 % (Al-Zohairi et al., 2023), making the impacts for scenarios involving pet food treatment (baseline and S1) low for the freshwater category, while S3 has the highest impact. Similarly, the substitution of soybean meal for chicken co-products in pet food also offsets substantial greenhouse gas emissions from soybean cultivation, the land use change from forests to arable land, the manufacturing and application of chemical fertilisers and pesticides, and the fossil fuels consumed during planting and harvesting processes.

Fig. 3 demonstrates that when categorising process contributions to global warming by their occurrence stages, both the rendering process and pet food process are environmentally beneficial due to the avoided products. In the baseline, S1, and S2, the environmental benefits derived from the valorisation process reach −85 %, −130 %, and −30 %, respectively. In contrast, the incineration process in S3 generates significant environmental impacts, despite the consideration of heat recovery and reuse during the disposal phase, still accounting for 20 % of the total emissions. Meanwhile, the anaerobic digestion process in S4 is much milder, accounting for approximately 5 % of the environmental impacts, primarily due to methane capture and recycling. However, the main emissions are still attributed to chicken raising and the processing at slaughterhouses. Therefore, among all five scenarios, S1 - where all chicken co-products are processed as pet food - is comparatively the

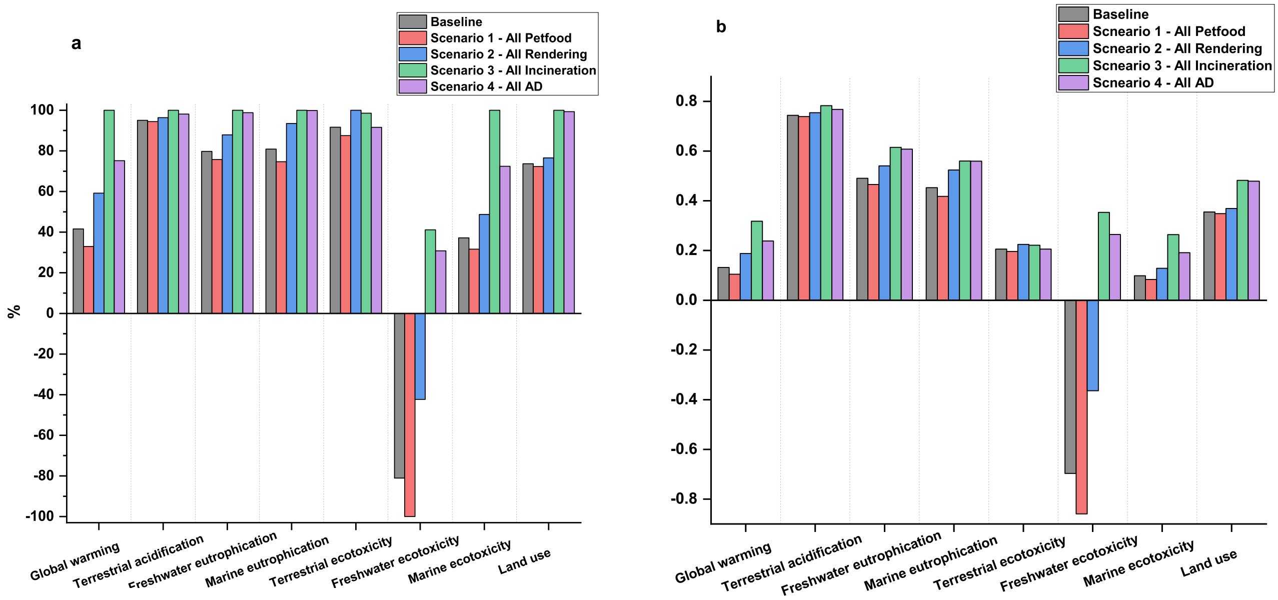

Fig. 2. ReCiPe 2016 midpoint results of each scenario.
a. Characterisation result; b. Normalisation result.

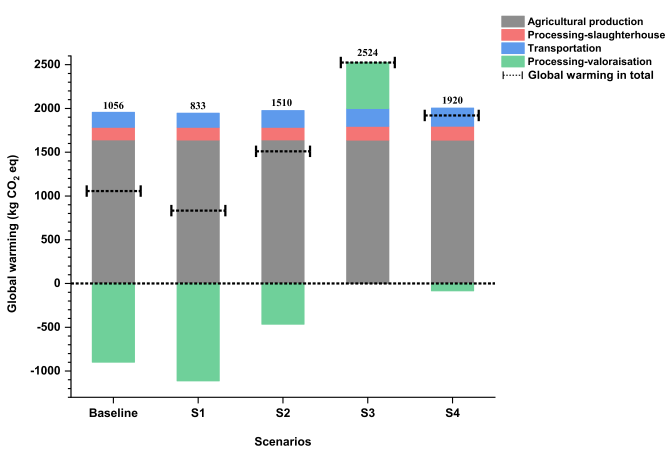

Fig. 3. Bar chart of processing contributions about global warming across different scenarios.

most environmentally benign option.

Normalisation was conducted using the Recipe 2016 method. This involves converting characterisation results by dividing each environmental category's result by a specific normalisation score, based on the average annual emissions for each impact category, to obtain a ratio of a product or system's emissions (PRé Sustainability, 2022). A value greater than 1 indicates that the production of the product or system exceeds the average annual global emissions in 2010 for the impact category. Values between 0 and 1 indicate that the emissions are below the average annual emissions, while values less than 0 indicate that the production has a net positive impact, representing as environmental benefit. Normalisation allows for comparisons across different environmental categories, as shown in Fig. 2b. All categories' maximum values are less than 1, demonstrating that the environmental burden caused by chicken co-products is lower than the global average regardless of the scenario in which they are treated. However, it is also evident that the terrestrial acidification, which shows minimal differences among scenarios, is the closet to the average value (i.e., closest to 1), indicating that this category should receive focused attention during chicken co-product processing, as varying the processing scenarios does not significantly reduce its environmental impact. Conversely, for categories like global warming and marine ecotoxicity, even the most severe scenario (S3) only reaches about 40 % of the global average emissions, indicating a relatively lower environmental impact.

The endpoint results of five scenarios are derived through transformation and calculation based on the midpoint results, as illustrated in Fig. 4. The impact on human health significantly exceeds that on ecosystems and resources throughout the chicken co-product processing, with the average scores of 82, 9.5, and 0.78, respectively (Fig. 4a). Human health is predominantly influenced by the global warming category within the human health branch, measured in Disability-adjusted Life Years (DALYs) (Stylianou et al., 2021). It is also evident that the variations in endpoint results among scenarios are primarily concentrated on human health. Moreover, Fig. 4b integrates scores from different scenarios and presents a total score. It is observed that S1 (pet food only) has the lowest total score among five scenarios, indicating it has the lowest environmental impact, while S3 (incineration only) has the highest total score. This further proves that the valorisation of chicken co-products is desirable, raising their economic value while reducing environmental impacts. However, even though the S1 has the lowest score, it is only 5 points (6 %) lower than the baseline, suggesting that further improvement to the valorisation process may have limited significance on the existing basis. Alternative treatment methods such as direct human consumption, might bring unexpected environmental benefits and warrant further research.

3.3. System expansion scenario analysis of combinations of avoided products

Utilizing the parameter setting function in SimaPro, the potential avoided products replaced byproducts from rendering or pet food manufacture were varied separately using a one-factor-at-a-time approach (Fig. 5). The assumed combination for the substitution quantities and ratios of avoided products used in this study - i.e., soybean meal, fish meal, and biodiesel - are set as baseline and represented by black lines, while the percentage values indicate the extent to which the maximum (or minimum) emissions for a scenario in a given classification differ from the baseline emissions. Values above the baseline suggest improved environmental performance, while those below suggests poorer performance.

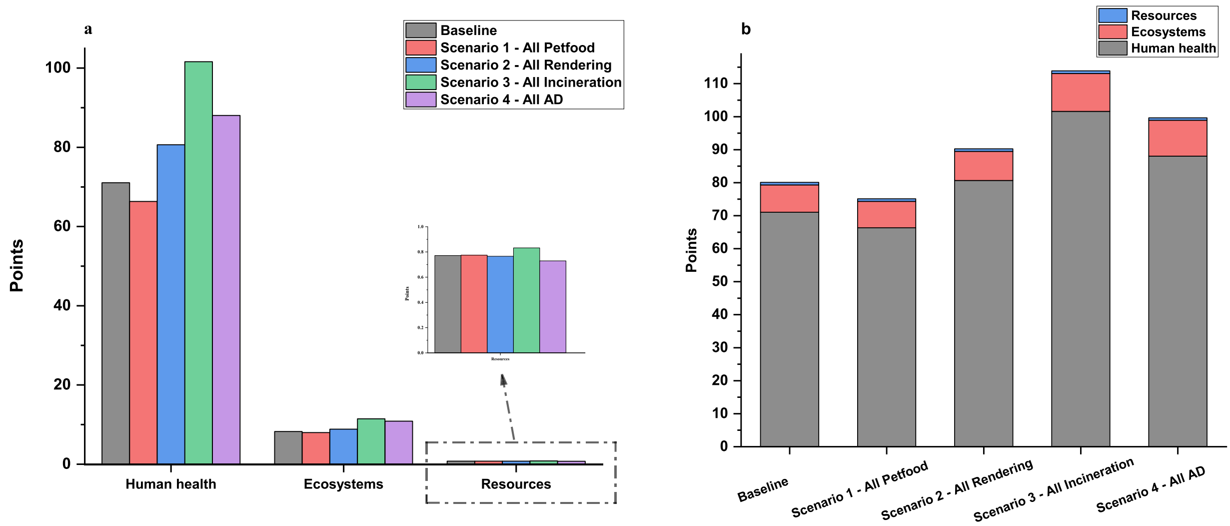

Fig. 4. ReCiPe 2016 endpoint results of each scenario.
a. Endpoint weighting; b. Endpoint scoring.

The selection of avoided product types significantly impacts the overall environmental outcomes of the chicken co-product treatment process. This variation is due to the partial of offsetting the overall environmental impacts by different avoided products. For example, in the global warming category, the difference between the highest (C4) and lowest (C1) total emissions in S1 is relatively large at 985 kg CO_2 eq, which represents a 118 % increase over C1. A similar difference of 860 kg CO_2 eq is observed between C1 and C4 in the baseline scenario. The combinations of avoided products also impact freshwater ecotoxicity. In the baseline scenario, the highest scenario (C4) emits 137 % more, totalling 24 kg 1,4-DCB. Similarly, in S1, the greatest differential is 28 kg 1,4-DCB, 130 % above the baseline combination. Moreover, in marine ecotoxicity, the highest emissions exceed the lowest by 5 kg 1,4-DCB, which is 137 % of the minimal emissions. In land use, the highest emission is 874 m^2a crop eq more than the lowest, corresponding to a 47 % increase over the minimal value. However, in some impact categories, the variation between combinations is not significant. For example, in the terrestrial acidification category for S1, the difference between the maximum and minimum values is merely 0.65 kg CO2 eq, accounting for a 2 % increase relative to the baseline. The differences in other categories generally range from 10 to 30 %.

The relative magnitude of emissions for different combinations varies across impact categories. As shown in Table A.3, for the categories of global warming, freshwater eutrophication, freshwater ecotoxicity, and marine ecotoxicity, the order of combinations from highest to lowest emissions is C4 (fishmeal + biodiesel), C3 (fishmeal + palm oil), C2 (soybean meal + biodiesel), and C1 (soybean meal + palm oil), respectively. In contrast, for categories like terrestrial acidification, marine eutrophication, and terrestrial ecotoxicity, combination C3 outperforms C2 with lower environmental burdens, but their values are still between C1 and C4. However, in the category of land use, the sequence of total emissions changes to C3, C4, C1, and C2, indicating that the avoided product combination of soybean meal + biodiesel is more effective in mitigating the environmental burden on the land use in chicken co-product treatment.

Overall, regardless of the avoided product combination applied, S1 generally exhibits a lower environmental impact than the baseline, with both the maximum and minimum environmental impacts of S1 being lower across all eight impact categories separately, despite a significant overlap between baseline and S1. This suggests that processing all chicken co-products into pet food, as proposed in S1, might achieve greater emissions reductions than the current treatment scenario when the same avoided product combination is selected. Furthermore, no matter which avoided product combination is selected, the environmental impact of S2 tends to exceed other two scenarios. This indicates that improvements are needed in the rendering process to reduce emissions. For example, efficient boilers and heat recovery systems used during the cooking and drying processes could reduce energy consumption. Additionally, the high demand for freshwater in the rinsing process suggests that biological treatment or membrane filtration might be helpful in minimising water pollution.

3.4. Discussion of impacts on FLW definitions

As discussed in the previous section, there are currently approximately 100 different definitions of FLW utilized by various organizations, studies, and literature globally (Östergren, 2014). These varying definitions result in subjective inclusion or exclusion of the same waste types in different studies, leading to inconsistent research outcomes, particularly prevalent in LCA studies. This issue is further compounded by cultural differences in determining what constitutes edible versus inedible items. Consequently, a significant portion of high-yield, high-quality, and nutrient-rich food, including certain chicken co-products considered in this study, is overlooked in the UK, North America, and many other Western European countries.

For future LCA research, it is imperative to clearly specify the FLW definition being employed and the scope of FLW encompassed by this definition. Such clarity will greatly contribute to the standardization of FLW research and facilitate more accurate cross-comparisons in FLW-LCA studies. For the general public, standardized FLW definitions can enhance the understanding of proper food utilization, reduce food waste generated during food preparation and consumption, and ensure that the associated energy inputs are not wasted.

3.5. Comparison with prior LCA studies

Our ranking of scenarios, with pet food showing the lowest impacts and incineration the highest, is consistent with previous LCA studies of animal co-products. Al-Zohairi et al. (2023) reported that processing pork co-product into pet food reduced the carbon footprint of the meat chain more effectively than rendering. Similarly, Campos et al. (2020) further showed that when system expansion is applied to include the effects of displaced products, the use of poultry co-products to substitute other feed ingredients leads to reductions in the environmental impacts of animal feed production. Our sensitivity analysis reinforces this substitution effect, as the combination of soybean meal and palm oil

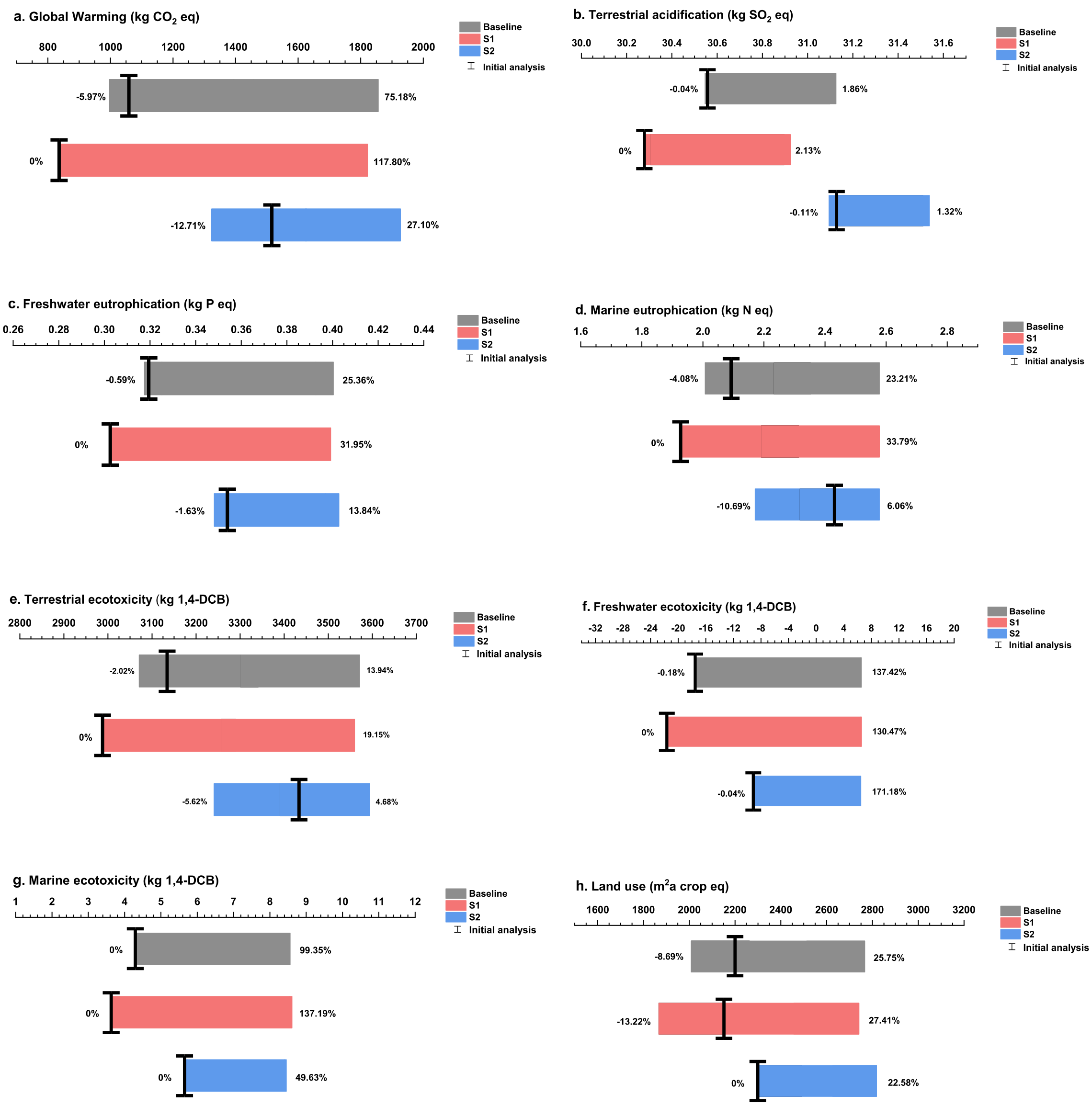

Fig. 5. System expansion scenario analysis of different combination of avoided products; coloured bars represent the range of impacts from different combinations, while the solid vertical line indicates the initial analysis combination.

produced the largest benefits, in line with earlier studies.

At the same time, this study extends the literature in several important ways. Whereas most previous assessments have concentrated on pork or aggregated categories of animal co-products, our analysis focuses specifically on chicken co-products, a large segment of the animal product market that remains underexploited in many advanced economies despite its considerable scale. Moreover, by explicitly testing different allocation approaches, this study demonstrates how methodological choices can substantially reshape the contribution of co-products, which were often overlooked in prior analyses. In addition, by linking chicken offal to debates on food loss and waste definitions, our analysis introduces a perspective that connects environmental assessment with cultural perceptions of edibility. Taken together, these contributions highlight both the continuity of our findings with existing evidence and the novel insights that this study brings to the LCA of edible co-products.

4. Limitations and implications

This study applied environmental LCA to evaluate the environmental impacts of chicken co-product valorisation in the UK and compared the results under different allocation methods and other scenarios. However, several limitations should be acknowledged.

In terms of methodological choices, the primary focus was on assessing the environmental impacts of chicken co-product valorisation using LCA, which is the most established method for evaluating environmental sustainability in agri-food systems. While alternative approaches, such as Social Life Cycle Assessment (S-LCA) and Environmental Input-Output Life Cycle Assessment (EIO-LCA), provide valuable perspectives, their application requires distinct datasets and methodologies that extend beyond the scope of this study. Future research could incorporate these methods to examine the socio-economic implications of increasing co-product valorisation, particularly in relation to pet food production and potential human consumption.

Regarding the selection of environmental impact categories, only eight categories were included in the analysis. These categories were selected based on their demonstrated significance in previous studies on animal co-products and the rendering process (Al-Zohairi et al., 2023; Campos et al., 2020). While additional impact categories, such as biodiversity loss, are highly relevant, they are often challenging to quantify within standard LCA methodologies due to data limitations and the complexity of ecological interactions. Similarly, resource depletion is an important factor, but it was indirectly addressed through land use and marine ecotoxicity. Future studies could explore these additional impact categories in greater depth, potentially through expanded system boundaries or hybrid LCA approaches, to enhance the comprehensiveness of the assessment.

Beyond these methodological limitations, the findings also have wider implications. They provide evidence that valorising edible co-products, particularly through pet food and rendering pathways, can support both waste reduction and resource efficiency strategies in the UK food system and other food systems where animal co-products are underutilised. At the same time, they also point to opportunities for further research, including cross-country comparisons to reflect cultural differences in co-product use, broader consideration of additional impact categories, and integration with consumer behaviour studies (i.e., promoting greater human consumption of offal). Addressing these aspects would further strengthen the role of edible co-products in reducing FLW and in lowering the environmental footprint of animal production.

5. Conclusion

Due to the subjective nature of FLW definitions, a large amount of waste generated from the agri-food system is currently not considered as FLW, and their environmental impacts do not receive sufficient attention. This study applies LCA to evaluate the environmental impacts of chicken co-product processing, a substantial component of FLW in many developed nations. This study compares the results of different allocation methods, processing scenarios, and products avoided by the processing to identify differences in environmental impacts. The results indicate that the significant discrepancy between the sale prices of raw chicken meat and raw chicken co-products (attributable to differing consumer preferences) leads to the LCA results based on economic allocation minimising the contribution of chicken co-products to the environmental burden generated during the chicken raising process. In contrast, the impacts are more substantial when applying mass allocation. Moreover, comparing current processing methods with simulated scenarios, it is evident that although the total emissions after valorisation (the baseline, rendering processing, and pet food processing) are already lower than the global annual emission per capita, Scenario 1 - where all co-products are processed into pet food - remains the relatively more environmentally friendly option. Conversely, treating co-products as biowaste and disposing by incineration is the scenario with the highest environmental impact.

System expansion scenario analysis also shows that regardless of the avoided product combination used, S1 consistently scores the lowest across all eight impact categories. The avoided product combination of soybean meal and palm oil is seen as the most substitutable combination, as those avoided products caused the highest environmental impact. Ultimately, this study suggests processing all chicken co-products into pet food (S1), is the optimal treatment for chicken co-products when pet food products replace an equivalent mass of soybean meal and palm oil. However, S1 is only 5 points (6 %) lower than the baseline (in the endpoint), indicating a marginal reduction in environmental impact. Ultimately, this suggests that the current approach is only slightly more impactful than directing all chicken co-products to pet food. Therefore, future research should explore and develop new processing methods for chicken co-products, as well as investigate the potential benefits of incorporating more co-products into the human food supply.

CRediT authorship contribution statement

Yiming Sui: Writing – original draft, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Eugene Mohareb:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Li Xue:** Writing – review & editing, Methodology, Conceptualization. **Gang Liu:** Writing – review & editing, Methodology, Conceptualization. **Stefán Thor Smith:** Writing – review & editing, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146750.

Data availability

Data will be made available on request.

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