Combined nutritional and environmental assessment: a case study of alternatives to potato crisps

Article

Accepted Version

Bosseaux, J., Mohareb, E. ORCID: https://orcid.org/0000-0003-0344-2253, Sui, Y. and Wagstaff, C. ORCID: https://orcid.org/0000-0001-9400-8641 (2025) Combined nutritional and environmental assessment: a case study of alternatives to potato crisps. British Food Journal. ISSN 1758-4108 doi: 10.1108/bfj-09-2024-0886 Available at https://centaur.reading.ac.uk/125087/

To link to this article DOI: http://dx.doi.org/10.1108/bfj-09-2024-0886

Publisher: Emerald

Combined nutritional and environmental assessment: A case study of alternatives to potato crisps

Jessica Bosseaux, University of Reading, j.bosseaux@reading.ac.uk (Corresponding author)

Eugene Mohareb, University of Reading, e.mohareb@reading.ac.uk

Yiming Sui, University of Reading, y.sui@pgr.reading.ac.uk

Carol Wagstaff, University of Reading, c.wagstaff@reading.ac.uk

Abstract:

Purpose

Processed food products are often marketed as healthier alternatives by highlighting beneficial nutrient content or limiting unhealthy ingredients. This study evaluates and compares the nutritional and environmental impacts of three alternative snacks available on the market: Regular Potato Crisps, Lentil-Based Alternative, and Chickpea-Based Alternative.

Methodology

The CONE-LCA framework was applied by combining ELCA inventories, based on ingredient assumptions from product packaging, with nutritional risk factors derived from labelled values. DALYs were calculated for both environmental and nutritional impacts and integrated into a single assessment, using the recommended portion as the functional unit to reflect consumption reality.

Findings

The alternatives to potato crisps are not systematically healthier or more sustainable. The main drivers of health and environmental impacts are shared ingredients such as oils and sodium, as well as processing methods, which limits the benefits of simple substitution. More positive impacts can be achieved through recommending smaller portion sizes to consumers and encouraging industry to reformulate by substituting key ingredients.

Implications

CONE-LCA offers a more realistic view of health impacts and is applied here for the first time to processed snacks. Using portion size as the functional unit strengthens its relevance for consumers and policymakers, and supports better choices in product formulation and dietary guidance while acknowledging trade-offs.

Originality

This study extends CONE-LCA to processed snack foods, demonstrates its application at the product level, and introduces a portion-based functional unit that reflects real consumption behaviour.

Keywords

CONE-LCA; Life Cycle Assessment; environmental impact; nutritional impact; health assessment; food consumption; healthier food items; sustainable food choices; direct risk factors; DALYs; Agribalyse; ELCA methodology; life cycle impacts; decision-making; impact methodology; human health impacts

1. Introduction

Food systems must be addressed in their complexity, considering the multifaceted challenges across various dimensions. While scholarly discourse often focuses on the economic, environmental, and social aspects of food system sustainability (Sundin et al., 2023), while nutritional impact is frequently considered as a lower priority (Hospes & Brons, 2016). Environmental health issues stemming from food production represent a significant concern (Garnett, 2013) and the interconnections between agricultural practices and public health offer a platform for cross-sector collaboration to address these shared challenges (Hawkes & Ruel, 2006).

Notably, food-related diseases emerge as a paramount public concern within this discourse, which stands out as a primary contributor to the mortality and morbidity of UK residents, imposing a financial burden of £6.5B to the National Health Service in 2020/21 (Office for Health et al., 2023).

Meanwhile, the food system has been identified as a key contributor to human-induced climate change, with the agro-industrial food systems being identified as particularly problematic for its climate and other environmental impacts (Ritchie & Roser, 2023; Lal, 2021). Modern industrial food systems have been targeted for their damage to human life due to water, soil, and air contamination, as well as their contribution to global warming, eutrophication, and other long-term environmental impacts.

Snacks, and more particularly crisps, are widely consumed in the United Kingdom. The fried slim slices of the cheap and abundant crop is historically very popular in the country (Bevan, 1974). The consumption and expenditure have increased since the early 2000's according to the Family Food Dataset (Department for Environment, Food & Rural Affairs, 2023). There is a potential trade-offs between fresh and processed potatoes that can have nutritional implications in the country (Dogbe & Revoredo-Giha, 2021).

Crisps are not likely to be compensated in consumption by another food product (Wilson et al., 2023), except maybe another type of savoury snacks. The past decade, supposedly healthier alternatives have gradually started appearing in stores and raised some interest as direct replacement of potato crisps (Dady, 2021; Hawthorne, 2018).

Recent interest has surged in understanding the combined environmental and nutritional impacts, providing a more comprehensive perspective on the repercussions associated with food systems, particularly concerning the potential harm to human health from food products. This paper employs the Combined Environmental and Nutritional Life Cycle Assessment (CONE-LCA) framework (Stylianou, Fantke, et al., 2016), mostly focusing on their impact on human health measured through Disability Adjusted Life Years (DALYs). Three snack food items have been selected, including potato crisps, due to their significant consumption, and two alternative products that are gaining growing consumer interest (IBISWorld, 2024). This study presents three innovative applications of the CONE-LCA framework. Firstly, we selected processed food items, necessitating the breakdown of ingredients and nutrients into diet risk factors (DRF) and DALYs. Secondly, the analysis is conducted at the food product level rather than the diet level, acknowledging the complexity of consumption habits. Lastly, the selected functional unit (FU) is a single recommended portion of each product, reflecting the packaging available in the market and the assumed real intake.

2. Literature review

2.1. Snack consumption: spotted problems and potential solutions

Potato Crisps are a popular snack in the United Kingdom, even qualified as a "national obsession" by the Guardian (Henley, 2010), despite being heavily salted and high-fat food items. According to the British Family Food Dataset (Department for Environment Food & Rural Affairs, 2024), british people spent £0.58 per week on 68 grammes of crisps and potato snacks in 2022. Potato crisps are available in the famous UK meal deals, and are on of the most calorific items available, which contribute to verconsumption (Leek & Afoakwah, 2023).

Crisps and other savoury snacks are usually targeted by nutritional recommendation as non-core food, and it is recommended to limit their intake (*The Eatwell Guide*, 2024). Numerous studies have focused on health impacts of snack consumption, nostly to understand how consumption frequency can contribute to overweight and obesity, and therefore to human health threats (Cooke et al., 2024). It has been observed that subjects that are overweight or obese had a higher consumption of crisps that people having a normal-weight, and was also associated to a lower consumption of nuts and yogurt, that are considered core food items (O'Connor et al., 2015). Contradictory results have been published concerning the portion size was not a explaining factor to overweight adolescent (Kerr et al., 2008). Nevertheless, it is noted that the method shows misreporting biases and inconsistency between the two main data collections.

Beyond the harms caused by energy (kilocalories) overconsumption, previous research, and national data reveal a complex interplay of dietary factors contributing to adverse health outcomes; the immoderate intake of some nutrients (saturated fat, sugar, and salt), and deficiency of other nutrients and food groups (low polyunsaturated fat intake, fibre fruits, and vegetables) lead to higher disease mortality and morbidity (Afshin et al., 2019).

The average British diet profile contributes to nutrient deficiency and obesity and increases the risk of type 2 diabetes, diarrhoeal disease, cancer, cardiovascular disease, and dental caries (Rayner & Scarborough, 2005). Several countries' dietary guidelines recommend restricting food products with high levels of salt, fat, and sugar content. This recommendation is particularly pertinent to snacks, designated as "energy-dense, nutrient-poor foods high in sodium, sugar, and/or fat such as biscuits, cakes, sugar-sweetened beverages, and crisps" (Hess et al., 2016, p. 467).

Alternatives to snacks, and more specifically to industrially produced crisps, have dragged attention in research, from crisps production to consumer experience understanding (Balan et al., 2021; Escobedo & Mojica, 2021). Balan et al. (2021) in particular emphasise the need to substitute starchy snacks, which are potentially considered harming individuals with diabetes, with non-starchy alternatives. It has been stated that the promotion of healthy snack choices could contribute to anti-obesity public health initiatives (O'Connor et al., 2015), and the market has to offer such alternatives.

New food products are becoming available as alternatives to potato crisps, with similarly packaged crispy snacks. They are marketed as healthier than Potato Crisps and most of them include nutrient content claims, such as "high source of protein". According to the industrial report on potato crisps and snacks in the UK (IBISWorld, 2024), consumers are shifting to healthier snack alternatives, which have pushed the industry to create and introduce new recipes. More and more pulse-based snacks are available in store as potato crisps alternatives. Despite their health claims such as 'vegan', 'less fat' and 'no added preservatives', these highly processed alternatives contain some other ingredients such as salt that raise concerns (Action on Salt, 2021; Blood Pressure UK, 2021).

Food choice and consumption are influenced by a range of factors beyond nutrient content alone. These factors include hunger, location, social and cultural environment, as well as distracted and hedonic eating, all of which shape the type and frequency of eating behaviours. Literature in food science and nutrition has conducted in-depth assessments of the impacts of various food groups and nutrients on overconsumption, highlighting the oversimplified categorization of 'healthy' and 'unhealthy' products (Visioli et al., 2022). It's imperative to note that relying solely on the dichotomy of healthy and unhealthy products is insufficient for categorizing them. Rather, they must be considered in light of their potential to influence long-term food choices and subsequently modify dietary intake.

Food choice is a complex, multifactorial process that cannot be captured by a single model (Sobal & Bisogni, 2009). Dietary patterns emerge from a series of such choices over time, shaped by a range of determinants: economic factors (cost, income) (Drewnowski & Specter, 2004), and marketing (price, brand) (Beharrell & Denison, 1991), health motivations and weight-control concerns (Steptoe et al., 1995), and sensory attributes like taste and texture (Raghunathan et al., 2006). Social context, such as eating occasions and family or peer influence and cultural background, also plays a key role (Sobal & Bisogni, 2009). Interventions aimed at dietary change have shown that improving the availability and accessibility of healthier alternatives, often supported by “nudge” strategies, can positively shift consumer behaviour (Leng et al., 2017). Consequently, manufacturers now offer reformulated products marketed as healthier options, although the actual nutritional improvements of these alternatives vary considerably.

This complex interplay of variables can either have detrimental or beneficial effects on consumers' health. Nutrient-poor and energy-dense food products may be associated with high body mass index, potentially eaten in the absence of hunger (Hess et al., 2016), and therefore cause food-related diseases.

2.2. Environmental concerns of food systems

Crippa et al. (2021) developed a global food emissions database (EDGAR-FOOD) covering emissions from 1990 to 2015, and their results indicate that food systems contribute roughly one third of global anthropogenic greenhouse gas emissions, a figure that underpins policy development based on detailed emission inventories to inform more effective climate change targets (Crippa et al., 2022). Beyond greenhouse gas emissions, climate change will damage soils and water, which are essential for carbon storage, climate regulation and supporting plant growth, and will therefore reduce food production (Wijerathna-Yapa & Pathirana, 2022).

Environmental Life Cycle Assessment (ELCA) addresses the environmental aspects and potential environmental impacts throughout a product's life cycle considering factors that affect resources, ecosystems, and human health. However, for some products, human health damage cannot be limited to ELCA but must integrate the effects related to their use. For example, the production of items dedicated to saving lives (e.g., airbag systems, studded tyres, medicine, etc.) must combine the assessment of the risks and benefits of both their production and use (Furberg et al., 2018). In the previous research, health risk assessment of food products is generally limited to the food production impacts (e.g., Environmental-LCA, Social-LCA) or the nutritional impact (e.g., nutrient profile). In this paper, we combine food production and nutritional impacts to evaluate the disease burden attributable to specific three substitutable crisps food items.

Recent studies have investigated ways to achieve more environmentally sustainable and healthier diets in industrialized countries, trying to combine the nutritional benefits with different scores such as the nutrient-rich food score, to the environmental impact, such as CO_2 emissions (de Jong et al., 2024). The effects of environmental factors on nutrition and health are attracting growing attention, uniting research across nutrition, environmental science and public policy to inform more effective food policies (Fanzo et al., 2021).The combination of favouring locally grown crops and incorporating plant-based proteins into cereal-based foods such as pasta and bread can benefit both national diets and human health (Chaudhary et al., 2018). The concern for micro- and macro-nutrition is related to nutritional security, an important issue that concerns business stakeholders, public authorities, and consumers (Ebert, 2014). Additionally, shifting from one product to another can have indirect effects through substitution. For example, transitioning from animal protein to plant-based protein products can simultaneously benefit nutritional and environmental impacts (Saget et al., 2020).

Fernández-Ríos et al. (2022) conducted a study on processed snacks combining a full ISO 14040 ELCA WEF (water–energy–food) nexus with the Nutrient-Rich Food 9.3 index to evaluate both environmental burdens and nutritional quality of a 50 g bag of potato chips. This case study on potato crisps confirms that life cycle assessment, while essential for uncovering environmental hotspots in food systems, must be complemented by a parallel appraisal of nutritional impacts.

To capture both the harm to human health arising from poor dietary quality and the harm arising from environmental burdens, a methodology named Combined Nutritional and Environmental LCA (CONE-LCA) has been first proposed by Stylianou et al. (2016), evaluates environmental and nutritional health impacts of food items in parallel rather than in isolation.

Its innovation lies in translating both environmental burdens and nutritional outcomes into a common human-health damage metric, namely disability-adjusted life years (DALYs). In environmental LCA, DALYs are obtained via end-point impact indicators, whereas in the nutritional assessment they are derived by first converting nutrient profiles into dietary risk factors and then into DALYs. To date, the method has been applied to a variety of products, notably milk (Stylianou, Heller, et al., 2016), fruits and vegetables (Stylianou, Fantke, et al., 2016), both of which are defined as dietary risk factor categories. In this study, we extend the method to processed food items, demonstrating its applicability across a broader range of products.

3. Material and methods

The methodology in this study follows the CONE-LCA framework to evaluate and compare the environmental and nutritional impacts of regular potato crisps and two substitute food items (Stylianou, Heller, et al., 2016). The procedure comprises four main steps. First, we present the goal and scope of the assessment, followed by the life cycle inventory data. Next, we conduct the environmental impact assessment and the nutritional damage-to-human-health assessment. Finally, we integrate both sets of metrics into a combined human-health damage indicator.

3.1. Goal and scope definition

The ELCA is typically conducted at the product level, whereas nutritional impacts should be considered at the diet level as it results from a complex combinations of nutrients and other compounds that act synergistically within the food and across food combinations (Tapsell et al., 2016). Nonetheless, a product-level focus remains valuable because consumers frequently repeat purchases of the same item, thereby shaping broader dietary patterns over time (Liu et al., 2019). By comparing substitutable snacks, this study demonstrates how switching products can alter overall diet patterns. Assessing nutritional impacts at the product level can also guide social marketing strategies that encourage healthier, long-term dietary shifts.

In accordance with the methodological framework of ELCA, the FU is chosen to represent the product’s functional output, ensuring comparability across systems (Reap et al., 2008). The mass unit is often used in agriculture because the main function lies in the agricultural stages of the life cycle, and it allows comparing yield variations or sold quantities (Vinyes et al., 2015). Nutrient-based FUs have been used on the premise that the role of food is to supply specific nutrients (McAuliffe et al., 2020). However, for consumers the function of food also involves social, psychological and practical dimensions as described earlier. Applying this to crisps is challenging since snacks have no precise definition and may be viewed as either a small quantity eaten between meals or a light meal in their own right (Hess et al., 2016). In this study we consider crisps to be a small portion intended for individual consumption between meals, purchased on the go or as part of a meal deal, common in the UK. Consequently, the FU is the weight of a standard individual sold portion rather than a measure based on a similar weight (e.g. 1kg) or nutrient content (e.g. 1g of protein).

The FU used is a single recommended portion of each product, as presented in Table 1. Indeed, a pack is supposed to fulfil the same function, which is snacking, and these are typically purchased in individual packs. Also, the literature that deals with snacking look at portions of food consumed as well as the frequency of consumption (Kerr et al., 2008). A study by Raynor and Wing (2007) demonstrated that crisp consumption is driven by the total amount of food available rather than by package size. When the quantity of snacks provided was doubled, energy intake rose by 81 percent, yet changing the size of each individual package had no significant effect. In other words, people tend to eat in proportion to the overall amount on offer, regardless of how those snacks are divided into packets. Also, in the absence of clear serving-size labels, people use pack size as a cue for how much to eat (Rippin et al., 2018).

The system boundaries for each product cover the cultivation stage, including seeds and farming practices, and extend to processing. They also encompass transport, packaging, energy use, and on-site storage. Further details are provided in the data collection section. The ELCA covers the supply chain until the factory gate, as from this point all products are distributed, purchased, and consumed in the same conditions.

3.2. Data inventory

The CONE-LCA framework enables the environmental life cycle assessment with nutritional health risk modelling to evaluate the impacts of replacing potato crisps with alternative products. Three products available nationally in most UK stores in May 2023 were selected for comparison: regular potato crisps (RPC), a lentil-based alternative (L-BA), and a chickpea-based alternative (C-BA). Table 1 presents key product information derived from market data, including declared ingredients (excluding seasoning), portion size per pack, and retail price. The reported price corresponds to the cost of a single one-person pack within a multi-pack bundle. The alternatives were chosen because they feature a distinct primary ingredient, as advertised, and are marketed on the basis of a healthier nutritional profile (e.g. gluten free, vegan, less than 100 Kcal a pack).

The data collection includes the information on the packages of each individual portion bag, including the list of the ingredients for each product, the weight of each individual portion, the quantity of each ingredient in each pack, and the nutritional content as advertised on the packaging (Table 1).

Full name	**RPC**	**L-BA**	**C-BA**
Portion (grams)	25	14	23
Price per portion (£)	1.95	1.90	1.4
Ingredients			
List*	Potatoes, Sunflower oil, Rapeseed oil, salt	Potato starch, Lentil flour, Rice flour, Corn flour, Sunflower oil,	Chickpea flour, Rice flour, Tapioca starch,

		Rapeseed oil, Coconut oil, Sugar, Salt	Sunflower oil, Black-eyed peas, Sugar, Salt
Nutritional value per portion			
kcal	130.25	65.66	99.13
Total fat (g)	7.75	2.716	3.45
Saturated fat (g)	0.625	0.406	0.391
Total carbohydrates (g)	13.25	8.904	13.57
Sugar (g)	0.1	0.63	1.702
Dietary fiber (g)	0.925	0.126	1.978
Protein (g)	1.525	1.33	2.76
Sodium (g)	0.35	0.357	0.391

**Spices/seasonings have not been considered.*

*Table 1. Nutritional value per portion per selected products (*Source: Authors' own work)

From here, we collected other data to enable the Environmental Impact Assessment on SIMApro, including Agribalyse (ADEME, 2022), EcoInvent (Wernet et al., 2016) and confidential information provided by industrial partners and experts to approximate ingredient quantities. For reasons of confidentiality, the precise values obtained from industrial partners cannot be disclosed; however, the methodological approach and relative contributions are transparently presented, and assumptions are detailed in the supplementary material where possible (Table 2).

Ingredients	**RPC**	**L-BA**	**C-BA**
Potatoes	0.925[1]		
Potato Starch		0.175[2]	
Lentil Flour		0.28[3]	
Chickpea flour			0.36[3]
Rice flour		0.075[2]	0.15[2]
Corn Flour		0.075[2]	
Tapioca Starch			0.15[2]
Sunflower oil	0.28[2]	0.1[2]	0.15[2]
Rapeseed oil	0.06[2]	0.075[2]	
Coconut oil		0.075[2]	
Black Eyed Peas			0.08[3]
Sugar		0.045[2]	0.074[2]
Salt	0.01[1]	0.255[2]	0.017[2]

[1]Based on Inventory of AGRIBALYSE v3.0.1, 2020. Potato crisps, at plant/FR U
[2]Based on industrial partners and experts.
[3]Based on the label of each product in table 1

*Table 2. Ingredient composition of products used for ELCA modelling (kg per kg of product) (*Source: Authors' own work)

The life cycle inventory is based on the AGRIBALYSE® 3.1 LCA Database and adapted with EcoInvent (v.3 – Allocation, cut-off by classification - system). AGRIBALYSE® (v.3) is a free dataset that delves into the entire journey of agricultural products, starting from farming and extending to distribution and disposal. Metaphorically speaking, the processes within AGRIBALYSE® are built as a set of nesting dolls, with each layer revealing different aspects and stages of the process; this offers a holistic approach for including key resource flows (e.g., energy use, pollution, land, and water consumption) throughout the life cycle. We selected pre-developed AGRIBALYSE® products as proxies for the products chosen above and adapted them according to these specifications (Appendix 1). The assumptions for cultivation, transport, processing, energy, and storage, have been developed using previous publications including Frankowka et al. (2019) and Goffart et al. (2022). The LCA has been conducted on SimaPro, and the results have been verified with Python (v.3.10.9) programming language by aggregating categories, for example, the category 'Plant Production Products' includes pesticides, herbicides, and insecticides (Appendix 2).

The AGRIBALYSE® dataset gives a very detailed inventory that can sometimes require further investigation before its application. For example, the category of "Transport, Lorry" is detailed per type of lorry (e.g. 16-32 metric tonnes, Municipal waste collection service) and geographic regions (e.g. global, Europe, Germany). The list of processes is extensive, with more than 800 impact categories.

While the environmental life cycle inventory was constructed by modelling the ingredient composition required to produce 1 kg of each product, the nutritional inventory was developed through post-processing of labelled nutritional values, packaging information, and expert-based conversions.

To calculate the DALYs for RPC, L-BA, and C-BA, we first must calculate the direct risk factors (DRFs) (Stylianou, Heller, et al., 2016; Stylianou, Fantke, et al., 2016). This was done using a combination of labelled product information, including nutritional values and ingredient lists (Table 1), together with expert-based estimates (Appendix 3). When no direct nutritional equivalent was available, values were extracted from ingredient declarations or estimated using industrial insights and expert judgement. The nutritional composition of each product was disaggregated into its constituent ingredients, which were then mapped to DRFs using nutritional values from USDA and Calorie Chart (*Calorie-Charts.Info*, 2023; USDA, 2023).

From this step, we calculated the DRFs, which capture both positive and negative health outcomes associated with dietary intake, since under- or overconsumption of nutrients can contribute to the onset of disease and influence life expectancy. Following the Global Burden of Disease framework, nine food groups (milk, nuts and seeds, processed meat, red meat, sugar-sweetened beverages, non-starchy vegetables, legumes, fruits, and whole grains) and six nutrients (calcium, fibre, seafood omega-3 fatty acids, sodium, trans fatty acids, and polyunsaturated fatty acids) were included (Gakidou et al., 2017) (Figure 1). The DRFs were quantified using mean, lower, and upper bound values, aggregated by category, and linked to disease outcomes through Relative Risk (RR) and Attributable Fraction (AF) values (Walker et al., 2019) (Appendix 4 and 5).

The healthiness of each food item was then expressed in µDALYs, reflecting the relatively minor contributions of individual products. This enabled the nutritional impacts to be assessed in a manner consistent with the environmental impacts, thereby supporting their integration within the CONE-LCA framework.

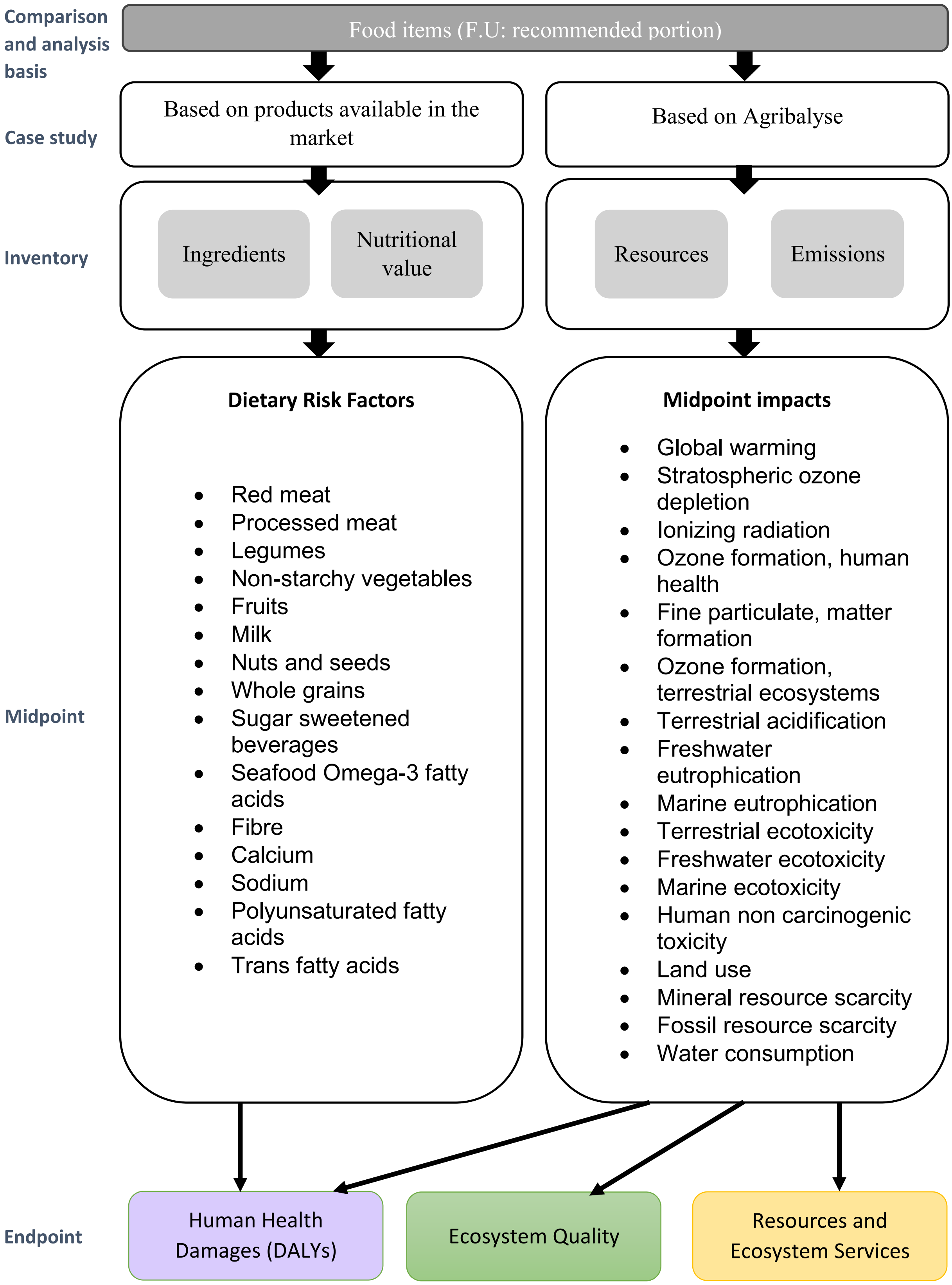


***Figure 1.** Graphical representation of the combined nutritional and environmental health impact LCA framework. Dashed lines represent links between midpoint and endpoint categories that are useful to interpret impact scores, but whose quantification is also associated with a high degree of uncertainty (Source: Authors' own work)*

3.3. Environmental Impact Calculation

The ReCiPe 2016 method, applied with its hierarchist perspective, enables the generation of results for all relevant impacts and areas of interest based on the most common policy principles (National Institute for public health and environment, 2016; Andersson & Listén, 2014).

The ELCA is conducted using the traditional ISO 14040/14044 approach (ISO, 2018), which allows for the inclusion of both midpoint and endpoint categories. Midpoints represent intermediate environmental changes resulting from emissions to the natural environment (for example, increased atmospheric greenhouse gas concentrations and radiative forcing), whereas endpoints represent the damage to sensitive receptors (for example, sea-level rise or human health impacts) (Matthews et al., 2015). Midpoint impact categories and endpoint areas of protection, as defined by the National Institute for Public Health and the Environment (2016), are considered in this analysis.

Literature was used to select specific processes and impact categories for a more thorough analysis. A study conducted in the UK by Frankowska et. al (2019) concludes that the processing stage and storage of the crisps LC are the largest contributors to emissions. Also, the land use occupation is largely attributed to the secondary ingredients of the products (e.g., edible oils), in this case, rapeseed oil, and confirmed in another study with palm oil (Nilsson, 2011). These previous studies highlight some important impacts to consider in the crop sector, including emissions and natural resources. These are then linked using damage pathways (Figure 2) to relevant endpoint categories. The three endpoint analysis areas, Human Health Damages, Ecosystem Damages, and Resources Damages are also considered in the analysis, with a focus on human health damage as, anthropocentrically speaking, it is the key area for combining nutrition and environmental impacts. In ELCA, damage to human health gathers several problems related to environmental impacts. Direct and indirect effects are considered. For example, stratospheric ozone depletion generates three types of skin cancer and cataracts due to UVB exposure, and water consumption has impacts on malnutrition due to water shortage (Huijbregts et al., 2017).

An overview of all midpoint results was first produced using a 1% cut-off analysis. Four midpoints were selected for detailed investigation due to their prominence in the literature and their strong association with the human health endpoint: freshwater ecotoxicity (FE), water consumption (WC), human carcinogenic toxicity (HCT), and ionising radiation (IR). The latter two show substantial impacts with clear connections to human health damage and were therefore included in the detailed analysis (Figure 2).

3.4. Nutritional Damage to Human Health Assessment

In the second step of the analysis, the contribution of each product to dietary risk was assessed by translating its ingredient composition into Dietary Risk Factors (DRFs). DRFs quantify the health burden, expressed in disability-adjusted life years (DALYs), associated with a marginal intake shift standardised per gram of a given dietary risk component (Stylianou et al., 2021). Positive DRFs indicate detrimental effects, whereas negative DRFs reflect protective or beneficial effects.

In the second step, we assess the contribution of each food item to dietary risk by translating each ingredient into the Dietary Risk Factors (DRF). DRF measures the health burden (disease morbidity and mortality) that an individual would have experienced with a marginal intake shift standardized for 1 g of dietary risk, expressed in DALYs, per gramme consumed of a given risk component (Stylianou et al., 2021) with positive DRFs that have a detrimental effect, and negative DRFs that have a beneficial effect. Finally, we consider the average UK diet and convert it into DRF and DALYs to assess the potential change that would imply several scenarios at population-scale health effects.

3.5. Combining Nutritional and Environmental Scores

As outlined in Sections 3.3 and 3.4, the unified health metric expressed in disability-adjusted life years (DALYs) are integrated from the environmental and the nutritional impact assessments (Stylianou, Fantke, et al., 2016; Stylianou, Heller, et al., 2016). DALYs capture the years of life lost due to premature mortality or lived with disability resulting from disease or injury. Figure 1 presents the analytical framework, which applies two parallel and complementary assessments to evaluate the nutritional and environmental effects of selected products.

In the final phase of the methodology, the dual impact on human health is comprehensively addressed by integrating data about both the environmental footprint arising from the production and the nutritional quality of the food item. This integrated approach provides a more comprehensive understanding of the overall health implications of a product, supporting informed decision-making in sustainable food production and public health policy. Nutritional effects are specific to consumers of the product, whereas the environmental life cycle assessment produces average per capita results. Interpretation therefore requires comparing impacts between consumers and non-consumers to provide a refined perspective on overall effects.

Finally, total DALYs are normalised by multiplying each value by its respective health damage normalisation coefficient. This ensures harmonised comparisons across the three products and maintains consistency with the coefficients previously established from the health damage indicators.

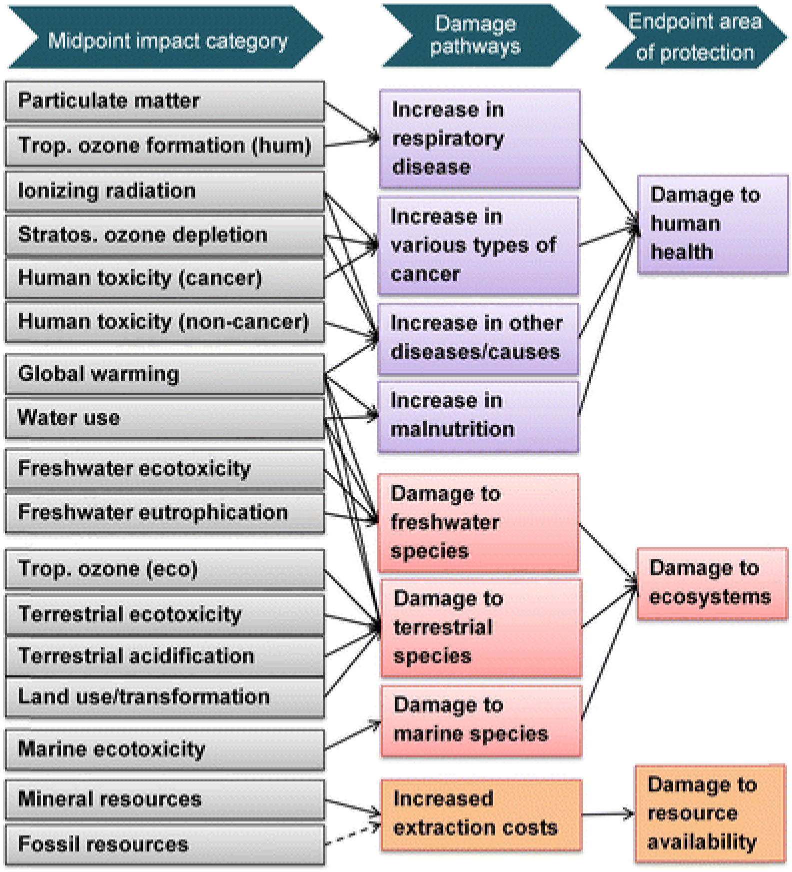


Figure 2. Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection (Huijbregts et al., 2017)

4. Results

4.1. Environmental damage to ecosystems and resource availability

4.1.1. Midpoint impacts

In all categories, C-BA have the highest impact across all categories, and L-BA have the lowest (Appendix 6). This result is not surprising as the L-BA recommended portion is only 14 g, for 25 and 23 g for RPC and C-BA, respectively.

Concerning atmospheric impacts, sunflower oil production (at the plant gate) is the biggest contributor to global warming for all three products, responsible for 78.6% of RPC, 29.1% of L-BA, and 34.4% of C-BA. Sunflower oil production can require clear-cutting secondary forest for arable land (land use change), which is the highest contributor (e.g. 0.00978 kg CO2 eq for RPC), and heat, other than natural gas (e.g. 0.00369 for RPC), that is used at the oil mill. Stratospheric ozone depletion is also driven by sunflower production in all three products, with the biggest contributor to RPC (7.49E-8), while rapeseed flower is the biggest contributor to L-BA (1.99E-8) and chickpea seeds for C-BA (1.39E-7). Examining local air quality and toxicity impacts, ozone formation impact on human health is driven by combine harvester use for a variety of grain crops, as well as transport (sea ship or lorry); this is a top three contributor in all three products. Diesel in water pumping (Lentil Chips), tractors (C-BA), and sunflowers at farm gates (RPC) are the other contributors. Similar large contributions are made to fine particulate formation; C-BA show the biggest impact (7.96E-5) mostly due to transoceanic shipping (1.28E-5), followed by diesel in tractors (1E-5) and carrot production (6.8E-6). L-BA (total 3.95E-5) and RPC (6.47E-5) also include transoceanic shipping (respectively 3.18E-6 and 1.92E-6)). The three products have clear-cut secondary forest to arable land (land tenure), sunflowers at farms, chemical factories, and heat central other than natural gas as contributors.

Figure 3 presents the normalized midpoint impact for each product for a visual comparison of impact importance and product contribution.

Human non-carcinogenic toxicity (HNCT) is largely due to sunflower oil for RPC (55.8%). Chickpea Chip's biggest contributor is tapioca starch (25.5%), sunflower oil (28.5%), and chickpea flour (28.2%). The factors are diverse, but mostly due to chemical application during crop production (e.g. rice, lentils, cassava, potato) .L-BA show the lowest score (0.0326 kg 1,4-DCB) with an interesting negative impact for the lentil consumption mix (-12.7%). This might be underestimated as the model does not include N fixation per tonne of lentils that can be included as an avoided use of N fertilizer for the next crop in the rotation.

Examining resource consumption, L-BA and C-BA show a largely higher **water consumption** than RPC (Respectively 0.00161 and 0.002791), with rice flour as a highly contributing ingredient (respectively 30% and 56,8%). Irrigation is one of the most impactful factors and is 100% allocated to rice flour. L-BA shows coconut oil as the most impactful ingredient (49.6%), while C-BA has Tapioca as the second most impactful ingredient (26.6%). RPC have a smaller water consumption (0.0007) due to potato farming, which has relatively low water inputs.

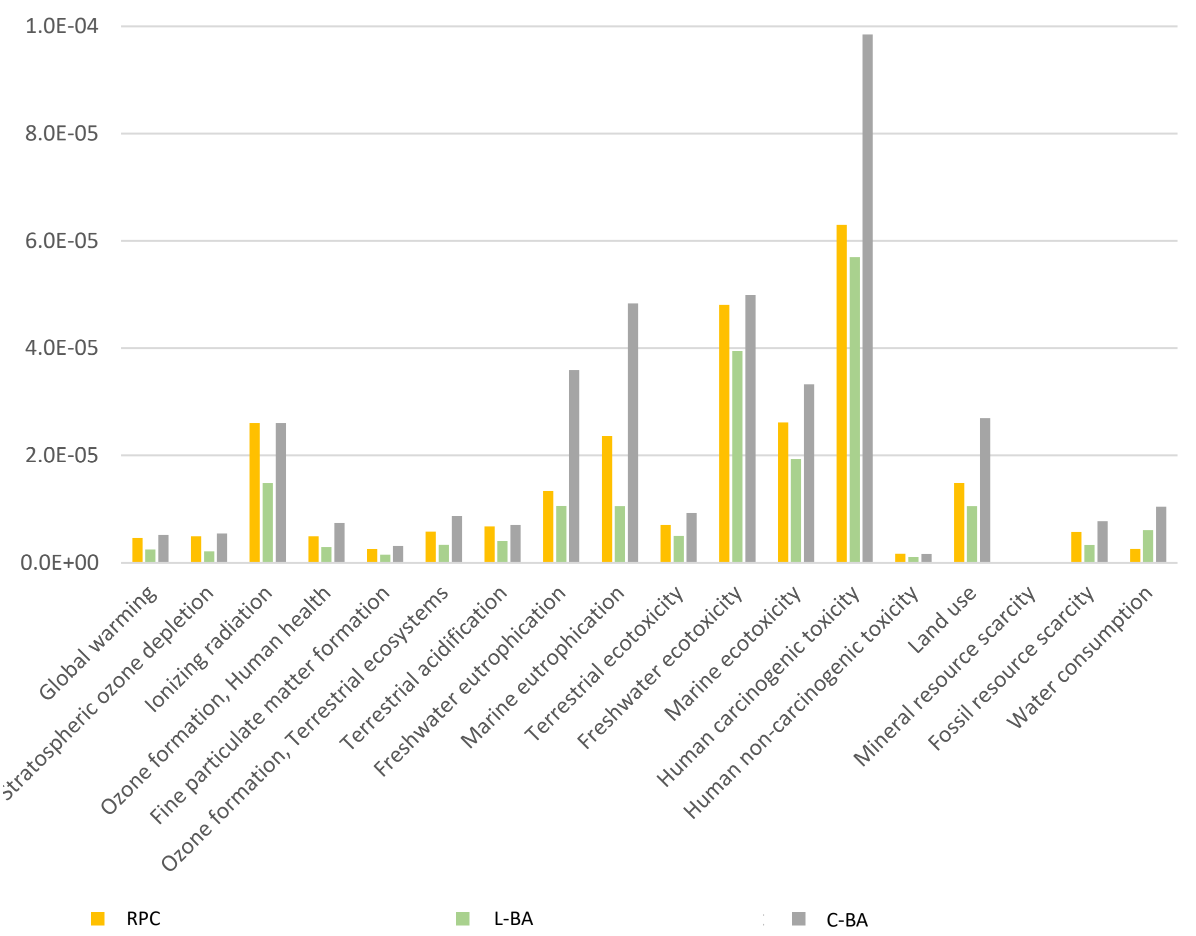


Figure 3. Impacts of product portions (Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H / Normalisation) (Source: Authors own work)

Concerning the other resources, the mineral resources scarcity (depletion) comes from sunflower oil (19.1%) and lentil flour (17.9%) for L-BA 0.00107 kg Cu eq), sunflower oil (44.9%) and potatoes (42.8%) for RPC (0.000227 kg Cu eq), and sunflower oil (31.3%) and chickpea flour (27.5%) for C-BA (0.00016 kg Cu eq). Unsurprisingly, fossil resources scarcity is mostly due to diesel, heat other than natural gas, and transport, lorry, and transoceanic shipping.

Looking at ecological impacts, ecosystem damages are due to factors that damage freshwater, marine, and terrestrial species. Chemical factories contribute to freshwater eutrophication, which also suffers due to pulse production, chickpeas for C-BA, and lentils for L-BA. Sunflower is the primary contributor to RPC. Marine ecotoxicity has various factors across the products, with electricity as a common main factor, and the rest largely attributed to crop production. **Marine eutrophication** contributors are crops at the farm gate, including transformation, storage, and other first-processing activities. In terms of crops, land use change is affected mostly by sunflower, rapeseed, and potato for RPC, chickpea, sunflower, and cassava for C-BA, and lentils, sunflower and coconut for L-BA. Land tenure is contributing across products.

(1) kBq Co-60 eq; (2) kg 1.4-DCB; (3) kg 1.4-DCB; (4) m3

Figure 4. Results of impact assessment per portion of the product at plant (Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H / Characterisation) (Source: Authors own work)

Sunflower oil is the first contributor to **terrestrial acidification** for RPC, second after Rapeseed oil for L-BA, and after transoceanic ships for C-BA. The top three contributors across all products to **terrestrial ecotoxicity** are transport lorry and chemical factories, with potato production for L-BA.

A 1% (impact contribution) cut-off analysis offers a broad set of impact categories (Appendix 7), with a limited understanding of environmental impacts with oversimplified complexities and missed nuances that could be revealed through a more detailed examination. It is considered as an initial step, a screening tool before an in-depth analysis of selected hotspots. Our study focuses on human health, so we have selected some impact categories for an in-depth analysis, per the methods section (2.2.2). The four selected midpoint impacts are presented in more detail in Figure 4 with characterization of impact assessment, presenting the contribution of the main processes (Appendix 8).

<u>Ionization radiation</u>

At 1% cut-off, electricity medium and low voltage appear first and unique contributors to **ionizing radiation** (>50% total contribution) in all three products. This is mostly to feed the cooking method (W:88.2%, P: 86.8%, B: 87.5%) including oven-baking, deep frying, and boiling, that solicited electricity market (W: 0.0109, P: 0.00613, B: 0.0101) that starts from 1kWh of electricity fed into the medium voltage transmission network and ends with the transport of 1 kWh of medium voltage electricity in the transmission network over aerial lines and cables.

<u>Human carcinogenic toxicity</u>

For RPC, the sunflower oil at the mill represents 69.8% of the total impacts due mostly to chemical factory production (0.000158) that includes land use, buildings, and facilities (including dismantling) of average chemical plants. Combined harvesting processing (4.32E-5) has an impact due to the diesel fuel consumption and the amount of agricultural machinery and the shed attributed to harvesting. It was also taken into consideration the amount of emissions into the air from combustion and the emission to the soil from tire abrasion during the work process. Lorry transport is the third contributor (2.82E-5). L-BA with lentil flour as the biggest contributor to HCT (30.7%), mostly due to lentil production (14.1%) that includes seed, fertilizer, crop protection products, and fuel on the farm. This activity begins with soil preparation about 37 weeks after the harvest of the previous crop and ends with lentil drying to <16% moisture at the farm gate. C-BA have the biggest HCT impact due to Tapioca starch (22.3%) which is impacted by the crop production, transport, and electricity from the process.

<u>Freshwater ecotoxicity</u>

Freshwater ecotoxicity is affected mostly by plant protection products and chemical factories for all products due to farming, with RPC as the biggest contributor for sunflower farming (0.000447), followed by L-BA mostly from coconut farming (0.000441) and C-BA mostly for sunflower farming (0.000220). The plant protection products gather all pesticides, insecticides, and fungicides at the factory gate, and the emission from the plant protection products' applications to soil.

<u>Water consumption</u>

RPC, the smallest contributor, has a water consumption due to potato production (46.2%) that includes the processes of soil cultivation, sowing, weed control, fertilization, pest and pathogen control, harvest; the machines and shed or surface used to park them; all inputs as seed, fertilizers (mineral and organic), active substances, water for irrigation, fuels as well as the transport to the farm; the direct emissions of the fuel combustion, the abrasion of tires and the direct emissions on the field. L-

BA has 40.5% of water consumption allocated to coconut farming, including irrigation, pesticide application, fertilization, and harvest. Rice irrigation represents 23% of the impact. Finally, C-BA are the biggest contributor due to the irrigation of rice farms, and the farming process for rice and cassava.

4.2. Environmental damage to human health - Endpoint

Looking at the results in Table 3 of normalization at endpoints impacts, human health impact (HHI) is the most important before ecosystems and resources. In terms of DALYs, C-BA show the highest impact (1.04E-7) followed by RPC (9.06E-8) and L-BA (5.36E-8).

Label	RPC - At plant	L-BA - At plant	C-BA - At plant
Human health	3.78E-06	2.23E-06	4.35E-06
Ecosystems	6.79E-07	4.65E-07	1.15E-06
Resources	7.87E-08	4.19E-08	9.88E-08

Table 3. Results of impact assessment per portion of the product at plant (Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/A / Normalisation).

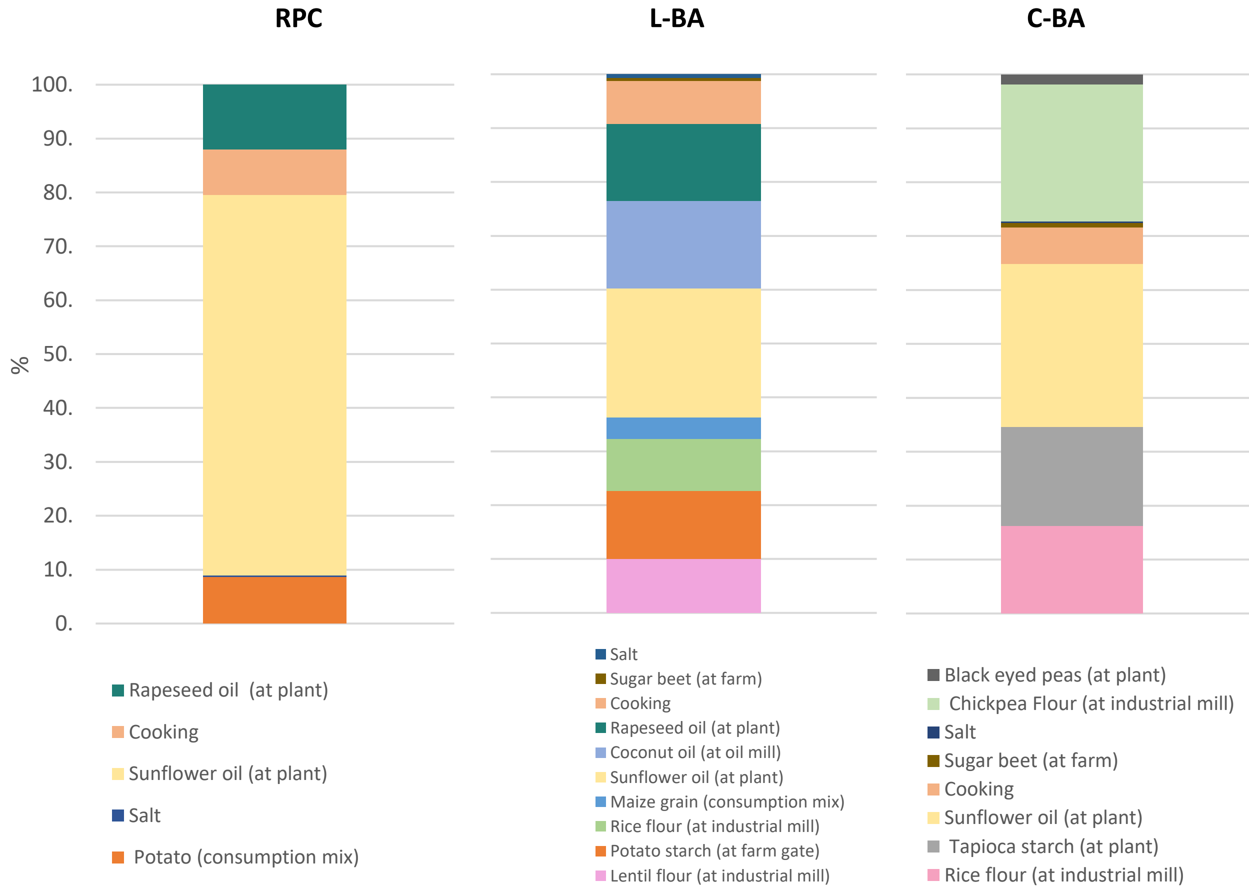


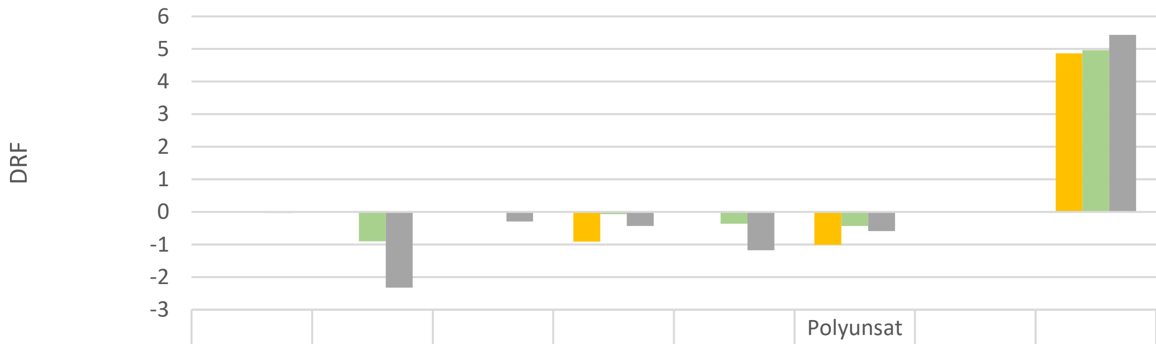
Figure 5. ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/A / Damage assessment to human health (Source: Authors own work)

Looking at the damage assessment to human health with more details in Figure 5, sunflower oil has the biggest impact on all products: C-BA (3.15E-8), RPC (6.4E-8) and L-BA (1.28E-8). RPC have a small allocation to other factors, including rapeseed oil, the cooking process, and potato production. C-BA and L-BA have a different distribution with several allocations with a large variety of impact factors due to the number of ingredients required at production. C-BA cumulate the impact of the Dry milling process of chickpea flour (2.65E-8), tapioca starch production (1.91E-8), Rice flour milling process

(1.69E-8), and cooking process (7.03e-9). L-BA cumulate milling lentil flour (2.7E-9), coconut oil (2.87E-9), rapeseed oil (1.62E-9), potato starch (1.61E-9), and cooking process (1.67E-9).

4.3. Nutritional impact on human health

The three snacks show detrimental effects on human health on average with 2.923 µDALYs for RPC, 3.186 µDALYs for L-BA, and 0.585 for C-BA. Figure 6 presents how the ingredients and nutrients of each product contribute to their DRF. For clarity, we withdrew all the factors that were equal to zero for all three products, namely omega 3 (seafood), nuts and seeds, fruits, vegetables, milk, sugar-sweetened beverages, processed meat, and red meat. Sodium is the greatest health burden contributor, followed by trans fatty acids that are found only in L-BA and make a negligible risk factor. Other ingredients (legumes, whole grains) and nutrients (Fibre, calcium, PUFA) contribute to lowering this risk factor, with a notable contribution from C-BA.

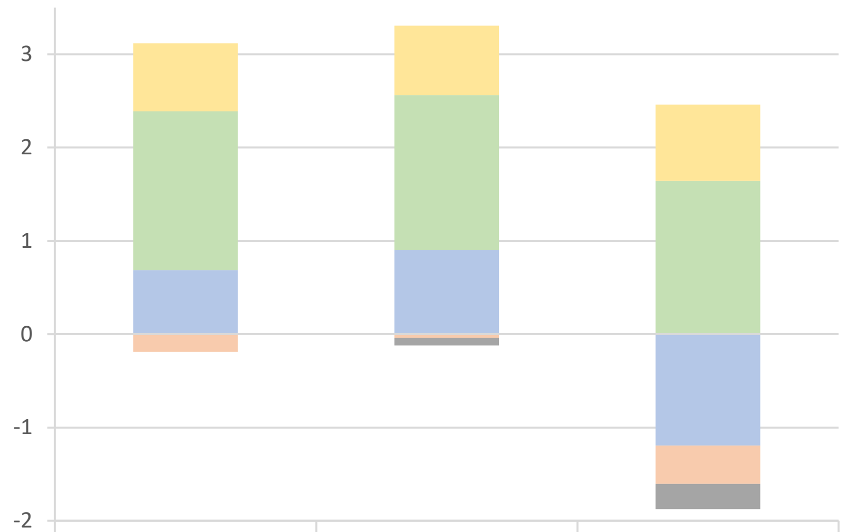


	Calcium	Legumes	Fiberf,v,l,w	Other fibers	Whole grains	Polyunsaturated fatty acids (PUFA)	Trans fatty acids (TFA)	Sodium
RPC	-0.00608226	0	0	-0.91575	0	-1.0136415	0	4.865
L-BA	-0.01465257	-0.9016	-0.01151483	-0.06474169	-0.357	-0.42876288	0.0017248	4.9623
C-BA	-0.03043935	-2.3276	-0.29228404	-0.43526629	-1.173	-0.5915577	0	5.4349

Figure 6. Nutrients and food groups contribution to Direct Risk Factors (Source: Authors own work)

Among these, sodium content in the ingredients bears the greatest responsibility for health burden, with µDALYs of respectively 4.87, 4.96, and 5.43 per FU. Fibre, "other" and PUFA, as well as components like legumes and whole grains in L-BA, partially reduce the health burden, but are still insufficient to counterbalance the burden imposed by sodium. Only C-BA's health burden shows a negative DALY value (Figure 7), attributed to its higher levels of fibre other and legumes. The negative DALYs value suggests that it may have some beneficial impact on health, as shown including ischemic heart disease, colorectal cancer, and diabetes, as shown in Figure 7, which presents how the DRF contributes to the Damage to human health.

However, due to various dietary risks associated with different diseases (Gakidou et al., 2017; Stylianou et al., 2021), the disease burden from different components cannot be completely offset against each other, shown as the column (right y-axis) in Figure 7. Sodium, PUFA, and legumes are primarily associated with the incidence and mortality of ischemic heart disease, and sodium is also linked to the other cardiovascular diseases group and the other diseases group, whereas calcium, fibre, and whole grains can help prevent premature death caused by colorectal cancer. Therefore, although the total health burden values for RPC and L-BA are positive and similar in magnitude, they can still reduce the risk of colorectal cancer to some extent, although this impact is relatively small when compared to that of diseases like ischemic heart disease. Similarly, C-BA, despite their negative total health burden value for the diseases group listed above, can reduce DALYs by increasing the incidence and mortality of other cardiovascular diseases and other diseases, which are respectively equal to 1.64 and 0.82 µDALYs, separately.



	RPC	L-BA	C-BA
Other neoplasms	0	0	0
Other diseases	0.72975	0.744345	0.815235
Other cardiovascular diseases	1.70275	1.658265	1.644155
Diabetes	0	-0.08211	-0.26979
Colorectal cancer	-0.18923226	-0.03911573	-0.409776653
Ischemic heart disease	0.6862585	0.904368571	-1.195070734

Figure 7. Direct Risk Factor's contribution to disease types (Source: Authors own work)

4.4. Overall comparison

Table 4 summarizes the overall environmental and nutritional impact on human health of each product.

	RPC	L-BA	C-BA
ELCA	0.0906	0.0536	0.104
Nutrition	2.9295	3.1857	0.5847
Total	**3.0201**	**3.2393**	**0.6887**

Table 4. µDALYs per recommended portion of each product (Source: Authors own work)

C-BA exhibit the highest environmental impact (1.04E-7 DALYs), followed by RPC (9.06E-8 DALYs) and L-BA (5.36E-8 DALYs). It is noteworthy that, despite C-BA contributing the most to DALYs due to negative environmental impact on human health (0.104 µDALYs), they remain the most favorable option among the three products (0.6887 µDALYs), almost twice the impact of L-BA (0.0536 µDALYs) and slightly higher than RPC (0.0906 µDALYs).

Figure 8 illustrates the normalized results, incorporating both nutritional and environmental DALYs, which have been adjusted using the coefficients employed for normalizing LCA DALYs. The total human negative health impact is measured at 1.26E-04, 1.35E-04, and 2.88E-05 for the respective products. Concurrently, the environmental impacts remain consistent in terms of ecosystems and resources.

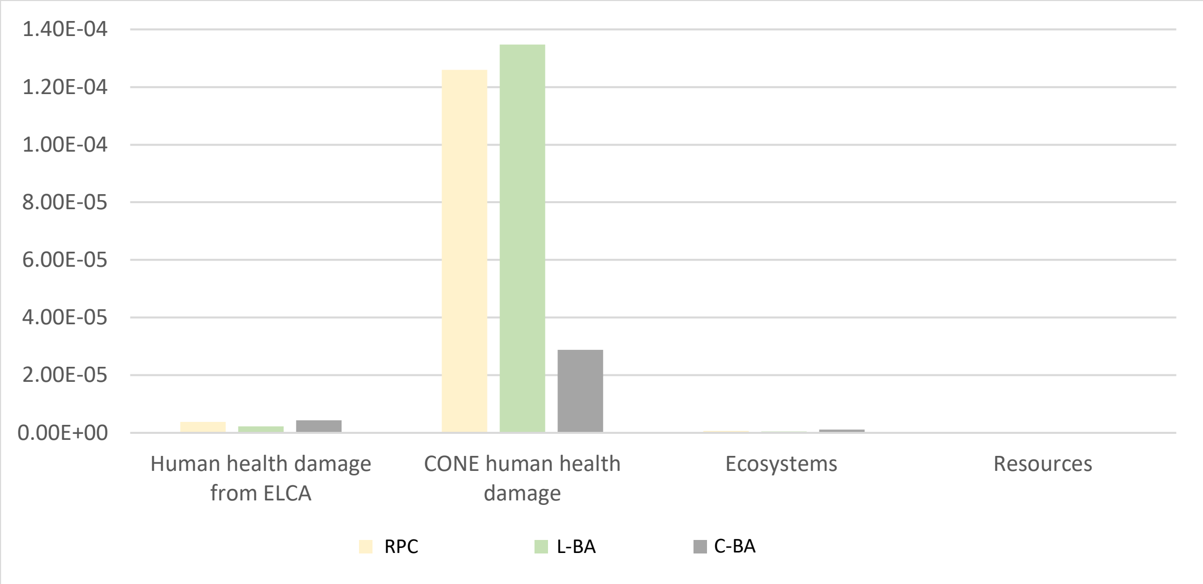


Figure 8. Endpoint normalised results including the total of nutritional and environmental DALYs (Source: Authors own work)

These findings provide a comprehensive insight into the relative effects of the three snack products on human health. RPC and L-BA exhibit notably higher impacts compared to C-BA, transitioning from being the most impactful to the least impactful in terms of damage to human health.

As a reminder, the functional unit in this study is the portion size recommended for individual consumption (grammes per individual pack). To illustrate the importance of the functional unit in food product assessments, Figure 9 presents the µDALYs of each product standardised to 100 g. When expressed per 100 g, RPC shows the highest combined DALYs, followed by L-BA and C-BA. This result is largely driven by nutritional DALYs, which amount to 73.24, 55.02, and 23.92 respectively. Interestingly, C-BA exhibits the highest DALYs from the ELCA perspective (23.92), compared with 13.40 for RPC and 12.68 for L-BA.

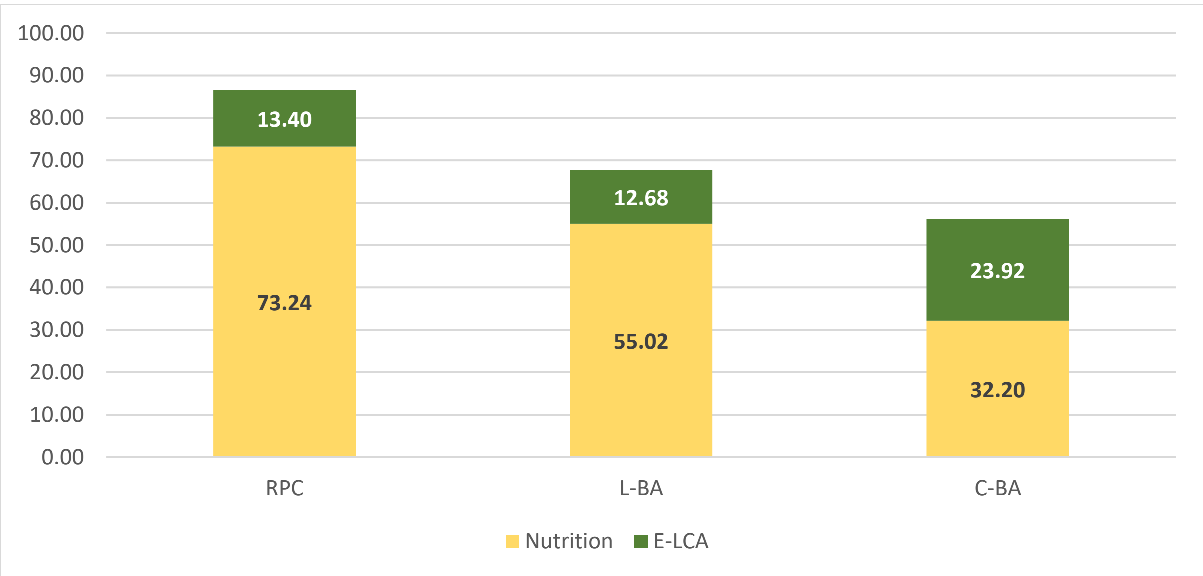


Figure 9. Endpoint normalised results of nutritional and environmental µDALYs per 100 grammes (Source: Authors own work)

5. Discussion

The above section outlined the findings of this research. This section is dedicated to discussing: (i) the significance of employing CONE-LCA, (ii) the selection of the functional unit, and (iii) the relevance of the framework for stakeholders within the food system.

5.1. The implications of using a combined methodology

This study underscores the significance of integrating multiple methods into ELCA to gain a more nuanced understanding of specific impacts at the product level. While ELCA is a valuable tool, its adaptability to address particular questions is essential. In the context of nutrition, assessing DALYs should extend beyond the environmental impact of the life cycle, particularly when aiming to make informed choices for human health. Comprehensive decisions within food systems, policies, and marketing necessitate a holistic perspective at the product level, providing a more impactful assessment.

Considering the level at which the food impacts are considered (e.g. diet level, meal level), a combination of methods complementary to ELCA is required to address specific questions more accurately. This approach addresses concerns for public authorities (e.g., social marketing campaigns, additional labeling regulations) and companies (e.g., reducing ELCA impact while improving nutritional content by adapting ingredients).

At the same time, the integration of nutritional and environmental assessments also presents challenges that must be acknowledged. Differences in data quality and availability, and uncertainty in converting nutrient profiles into DALYs highlight areas where further methodological refinement is needed. Recognising these challenges strengthens the credibility of the approach and sets an agenda for future research.

As evident in the results, C-BA emerge as the optimal choice for human health when both nutritional and environmental impacts on damage to human health are considered. A modification of its sodium content could be considered to even offer a better nutritional option to consumers if the taste is not too much affected by the change of recipe. Improving the production system could further reduce the burden on ecosystems and natural resources, offering a more sustainable alternative and a better food item option to consumers. Notably, without integrating nutritional assessment into ELCA, C-BA might have been overlooked. This study emphasizes the necessity of regarding ELCA as a component, not the entirety, of the assessment.

Beyond this case study, the combined methodology can shape future research by enabling more holistic comparisons across food categories and by encouraging the integration of other dimensions, such as social impacts or behavioural factors. This broader application has the potential to move food systems research closer to capturing the full spectrum of sustainability trade-offs.

CONE-LCA serves both consumers and policymakers as the primary beneficiaries of its insights. For consumers, it offers evidence and transparency to guide healthier and more sustainable food choices, while for policymakers it provides a robust framework to inform regulations and reformulation targets that improve ingredients and production processes. By bridging nutritional and environmental perspectives, CONE-LCA contributes to shaping better diets and more sustainable food systems

CONE-LCA analysis must be considered in alignment with the consumers' perspective, as it places the burden on consumers who are directly impacted by both the food system and product consumption, rather than treating it as a universally homogeneous burden, as ELCA burden is usually interpreted.

5.2. Recommended portion as a functional unit

The utilization of recommended portions serves as a practical FU for accurately assessing the environmental impacts associated with the actual consumption of products. This approach provides an equivalent measure aligned with the nutritional assessment of food products based on typical consumption patterns, as opposed to fixed quantities like 100 grams or 100 kcal, which have been identified as less relevant for product-scale LCA (Masset et al., 2014, 2015). The FU is an important and complex decision in an ELCA, especially for food products, as the function of food is multifactorial (e.g. satiety, social, nutritional, etc.) (Svanes et al., 2022). Some researchers focus solely on the nutrients in food as its primary function (de Jong et al., 2024), while disregarding the significance of other factors and the reality of consumption behaviour. By considering recommended portions, it reveals the impact of consuming a pack or bag of snacks on the environment, offering a valuable tool for promoting sustainable consumption directly through packaging.

Importantly, portion-based FU also reflects how industry communicates serving sizes and how consumers interpret pack size as a signal for what is considered a “recommended” amount to eat. This strengthens the link between methodological choices in LCA and the realities of both marketing practices and eating behaviour. At the same time, this approach introduces variability, since real consumption may differ from labelled portions, which highlights the need for careful interpretation and further empirical validation.

The choice of the food unit is derived from industrial and consumption perspectives. However, the legitimacy of the recommended portion's accuracy remains a pertinent question. In the comparison of alternative crisps in this study, there arises a consideration of whether a 14-gram portion of L-BA is appropriate or if it might lead to the consumption of multiple portions at once. This issue prompts the need for further studies to comprehend the impact of actual food consumption, adapting to real average portion sizes rather than relying solely on recommended portions.

Additional measurement tools become crucial in defining an appropriate FU and addressing specific research questions. For instance, at the meal scale, understanding the satiety effect of snacks becomes pivotal in determining the potential consumed portion (Fillon et al., 2021). On a diet level, transitioning from one portion of a product to another can impact nutrient intake over the long term, influencing dietary habits and contributing to unhealthy diets. Such diets are associated with various noncommunicable diseases, including overweight, obesity, and direct risk factors such as diabetes, cardiovascular disease, and stroke. The selection of the FU should align with the specific research question, ensuring optimal interpretation and providing solutions for decision-makers.

Beyond these methodological considerations, the use of portion-based FU can also influence future research by improving comparability across different studies and product categories. For practice and policy, it provides a concrete tool for guiding reformulation targets, labelling regulations, and public health messaging that links environmental sustainability with recommended serving sizes. Although our study focused on crisps, the same rationale applies to other packaged foods such as biscuits, cereal bars, or beverages, making this approach widely relevant for food system assessments.

Our results highlight that considering recommended portion size as the functional unit provides a behaviourally relevant measure of impacts per consumption event. This perspective helps to contextualise the health impacts of snack consumption and complements the literature by clarifying how health outcomes may vary depending on what is defined as a portion (Cooke et al., 2024). By integrating portion-based functional units, our analysis adds to frequency-based approaches and better reflects real consumption behaviour.

5.3. Food systems implications

Studies of this nature hold the potential to yield significant industrial and political implications, potentially serving as catalysts for change.

From the producers' perspective, the AGRIBALYSE inventory provides a valuable basis for comparing the production impacts of different crops. The inventory accounts for nitrogen-related emissions (e.g. N_2O, NH_3, NO_3^-), and the reduced need for mineral fertilisers in legumes is reflected through lower input requirements (ADEME, 2022). However, the broader agronomic benefits of biological nitrogen fixation, such as improved soil fertility and reduced fertiliser demand in subsequent crop rotations, are not captured. The exclusion of these indirect benefits may therefore lead to an overestimation of the environmental impacts of legume-based products relative to potato crisps.

From an industrial perspective, the pursuit of healthier products necessitates a careful selection of ingredients that are not only environmentally sustainable but also nutritionally beneficial for consumption. For instance, findings from this study suggest that the inclusion of sunflower oil and oil combinations in various products warrants revaluation to optimize choices. Exploring alternatives such as high oleic acid varieties of sunflower oil, which are rich in monounsaturated fats (Williams et al., 1999), presents a promising avenue for further inquiry. Similarly, the widespread use of starch as a base ingredient poses both nutritional and environmental concerns. High-starch products are associated with limited nutritional benefits and can exacerbate health risks such as those related to diabetes, while starch production also contributes significantly to agricultural impacts. Emerging research highlights the potential of substituting starch with mushroom-derived ingredients, which could provide a healthier and more sustainable alternative (Balan et al., 2021).

Such reformulation opportunities also connect to broader food system transformations, as they encourage the development of products that simultaneously reduce health risks and environmental burdens. In this way, product-level innovation can contribute to wider dietary transitions, supporting both industry competitiveness and public health agendas.

Concerning transports, although transoceanic shipping was included in the system boundaries, its contribution remained secondary compared with agricultural production and processing, though in some cases it ranked as the third or fourth contributor to total impacts. This partly reflects the long distances involved in sourcing some ingredients. While transport is often reported as a minor contributor in global meta-analyses (Poore & Nemecek, 2018), our results suggest that for imported snack ingredients, shipping can represent a non-negligible share and therefore deserves consideration in product-level assessments.

On the policy front, at the national level, there may be opportunities to address environmental and public health concerns by imposing restrictions on the use of certain oils. Additionally, regulating and limiting the levels of fat or salt in products could have significant nutritional impacts, promoting public health and well-being. The use of micro-DALYs at the product level highlights the importance of repetitive choices over the long term for consumers, emphasizing the role of public policies and social marketing in improving the availability and accessibility of food products to enable consumers to make healthier choices over time, and therefore act at a public health level.

Beyond industry and policy, the societal implications are equally important. Consumers stand to benefit from healthier product reformulation and clearer guidance on portion sizes and dietary recommendations, while policymakers gain robust evidence to support structural changes in the food system. Extending CONE-LCA to other food categories could further strengthen its contribution, making it a practical tool for aligning consumer behaviour, industry practices, and public policy toward healthier and more sustainable food systems.

6. Conclusion

A key initial question concerned the healthiness of potato crisp alternatives, as many new products are entering the UK market with claims of health benefits such as high protein or low fat. Our study set out to assess whether these alternatives truly deliver measurable benefits in terms of reduced damage to human health when both nutritional and environmental impacts are considered.

This study applied the CONE-LCA methodology to evaluate the nutritional and environmental impacts of three processed food items, including regular potato crisps and two purported alternatives, one lentil-based and another chickpea-based. Our ELCA primarily focused on assessing damage to human health at the endpoint level. By comparing the products' impacts on human health using DALYs in both ELCA and through the conversion of ingredients into DRF for nutritional assessment, we gained a comprehensive understanding of each food item's overall impact. The incorporation of micro DALYs provided nuanced insights, emphasizing the significance of considering multiple dimensions in sustainability assessments. To ensure consistency with consumption reality and dietary recommendations, the analysis was conducted using the recommended portion as the functional unit.

Our findings indicate that alternatives are not necessarily healthier, whether in terms of ELCA DALYs or nutritional DALYs. Secondary ingredients and processing methods were found to be the main drivers of both environmental and health impacts, which suggests that the potential gains of substituting one snack for another are limited unless reformulation strategies are pursued. In terms of healthiness, sodium and oil content emerged as major contributors to negative outcomes and should therefore be central in any future product reformulation.

Processing and cooking methods also play a decisive role. If oil cannot be replaced in frying, an alternative cooking method might be required. However, this could alter texture and risk reducing consumer acceptance. Switching to another oil or adopting a different cooking process with a more favourable nutritional or environmental profile could materially change the results and may represent a viable reformulation strategy.

Our contributions of using recommended portions as an FU offer guidance for future research to adapt their FU according to specific goals and scopes. This approach also reflects the portion size that industry itself promotes through packaging, thereby aligning the assessment with what consumers are effectively encouraged to eat. Nonetheless, our approach does not capture frequency of consumption, which remains an important dimension for further study.

Furthermore, this study highlights the advantages of combining nutritional and environmental impact assessments to present a more informative and realistic view of potential improvements. Midpoint analysis proved crucial for understanding the drivers of ELCA health damage and for exploring scenarios where environmental burdens may be reduced without compromising human health.

The insights derived from both food consumption and production are highly relevant for industry and consumers alike. For industry, reformulation efforts targeting oil and sodium may be more effective than focusing on alternative base ingredients. For consumers, in the absence of reformulation, strategies such as reducing portion size or moderating intake may be the most effective means of achieving health and sustainability gains. Public authorities can also leverage these findings to design informed policies addressing food-related diseases and environmental threats.

Looking ahead, future research should continue to refine FU and delve deeper into understanding the complex interactions between nutritional and environmental impacts. By doing so, we can further advance our understanding of sustainable food production and consumption, ultimately promoting human and environmental well-being.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Chatgpt to proofread the English writing, as the main author is a non-native speaker. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

References

Action on Salt. (2021). *Salt Content in Pulse-based SnacksSnacks*. https://www.actiononsalt.org.uk/media/action-on-salt/Salt-Content-in-Pulse-based-Snacks.pdf

ADEME. (2022). *AGRIBALYSE v3.1: The French agricultural and food LCI database. Methodology and data report.* French Environment and Energy Management Agency. https://agribalyse.ademe.fr/app

Afshin, A., Sur, P. J., Fay, K. A., Cornaby, L., Ferrara, G., Salama, J. S., Mullany, E. C., Abate, K. H., Abbafati, C., Abebe, Z., Afarideh, M., Aggarwal, A., Agrawal, S., Akinyemiju, T., Alahdab, F., Bacha, U., Bachman, V. F., Badali, H., Badawi, A., … Murray, C. J. L. (2019). Health effects of dietary risks in 195 countries, 1990–2017: A systematic analysis for the Global Burden of Disease Study 2017. *The Lancet*, *393*(10184), 1958–1972. https://doi.org/10.1016/S0140-6736(19)30041-8

Andersson, S., & Listén, M. (2014). *Life Cycle Impact Assessment: A comparison of three contemporary methodologies*. https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-148059

Balan, V., Novak, D., Knudson, W., Jones, A. D., Iñiguez-Franco, F. M., Auras, R., Cho, S., Rodgers, A., & Ubanwa, B. (2021). Nutritious mushroom protein crisp – healthy alternative to starchy snack. *Food Production, Processing and Nutrition*, *3*(1), 33. https://doi.org/10.1186/s43014-021-00077-7

Beharrell, B., & Denison, T. (1991). Food Choice in a Retail Environment. *British Food Journal*, *93*(7), 24–30. https://doi.org/10.1108/EUM0000000002353

Bevan, A. (1974). The U.K. Potato Crisp Industry, 1960-72: A Study of New Entry Competition. *The Journal of Industrial Economics*, *22*(4), 281–297. https://doi.org/10.2307/2097976

Blood Pressure UK. (2021). *The healthy-looking snacks that are sabotaging our health*. https://www.bloodpressureuk.org/news/news/the-healthy-looking-snacks-that-are-sabotaging-our-health.html

Calorie-Charts.info. (2023, May). https://www.calorie-charts.info/

Chaudhary, A., Marinangeli, C. P. F., Tremorin, D., & Mathys, A. (2018). Nutritional Combined Greenhouse Gas Life Cycle Analysis for Incorporating Canadian Yellow Pea into Cereal-Based Food Products. *Nutrients*, *10*(4), 490. https://doi.org/10.3390/nu10040490

Cooke, C. B., Greatwood, H. C., McCullough, D., Kirwan, R., Duckworth, L. C., Sutton, L., & Gately, P. J. (2024). The effect of discretionary snack consumption on overall energy intake, weight status, and diet quality: A systematic review. *Obesity Reviews*, *25*(4), e13693. https://doi.org/10.1111/obr.13693

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, *2*(3), 198–209. https://doi.org/10.1038/s43016-021-00225-9

Crippa, M., Solazzo, E., Guizzardi, D., Tubiello, F. N., & Leip, A. (2022). Climate goals require food systems emission inventories. *Nature Food*, *3*(1), 1–1. https://doi.org/10.1038/s43016-021-00450-2

Dady, J. (2021, April 26). *Healthy crisps: The best and worst crisps for your diet revealed*. Good To Know. https://www.goodto.com/wellbeing/crisps-the-best-and-worst-revealed-29343

de Jong, P., Woudstra, F., & van Wijk, A. N. (2024). Sustainability Evaluation of Plant-Based Beverages and Semi-Skimmed Milk Incorporating Nutrients, Market Prices, and Environmental Costs. *Sustainability*, *16*(5), Article 5. https://doi.org/10.3390/su16051919

Department for Environment, Food & Rural Affairs. (2023). *Family food datasets* (Statistical Data Set No. EID-household nutrient intakes). https://www.gov.uk/government/statistical-data-sets/family-food-datasets

Department for Environment Food & Rural Affairs. (2024). *Family food datasets* [Statistical data set]. https://www.gov.uk/government/statistical-data-sets/family-food-datasets

Dogbe, W., & Revoredo-Giha, C. (2021). Nutritional Implications of Trade-Offs Between Fresh and Processed Potato Products in the United Kingdom (UK). *Frontiers in Nutrition*, *7*. https://doi.org/10.3389/fnut.2020.614176

Drewnowski, A., & Specter, S. (2004). Poverty and obesity: The role of energy density and energy costs. *The American Journal of Clinical Nutrition*, *79*(1), 6–16. https://doi.org/10.1093/ajcn/79.1.6

Ebert, A. W. (2014). Potential of Underutilized Traditional Vegetables and Legume Crops to Contribute to Food and Nutritional Security, Income and More Sustainable Production Systems. *Sustainability*, *6*(1), Article 1. https://doi.org/10.3390/su6010319

Escobedo, A., & Mojica, L. (2021). Pulse-based snacks as functional foods: Processing challenges and biological potential. *Comprehensive Reviews in Food Science and Food Safety*, *20*(5), 4678–4702. https://doi.org/10.1111/1541-4337.12809

Fanzo, J., Bellows, A. L., Spiker, M. L., Thorne-Lyman, A. L., & Bloem, M. W. (2021). The importance of food systems and the environment for nutrition. *The American Journal of Clinical Nutrition*, *113*(1), 7–16. https://doi.org/10.1093/ajcn/nqaa313

Fernández-Ríos, A., Laso, J., Amo-Setién, F. J., Abajas-Bustillo, R., Ortego-Mate, C., Fullana-i-Palmer, P., Bala, A., Batlle-Bayer, L., Balcells, M., Puig, R., Aldaco, R., & Margallo, M. (2022). Water–Energy–Food Nexus and Life Cycle Thinking: A New Approach to Environmental and Nutritional Assessment of Potato Chips. *Foods*, *11*(7), Article 7. https://doi.org/10.3390/foods11071018

Fillon, A., Beaulieu, K., Mathieu, M. E., Tremblay, A., Boirie, Y., Drapeau, V., & Thivel, D. (2021). A systematic review of the use of the Satiety Quotient. *The British Journal of Nutrition*, *125*(2), 212–239. https://doi.org/10.1017/S0007114520002457

Frankowska, A., Jeswani, H. K., & Azapagic, A. (2019). Environmental impacts of vegetables consumption in the UK. *Science of The Total Environment*, *682*, 80–105. https://doi.org/10.1016/j.scitotenv.2019.04.424

Furberg, A., Arvidsson, R., & Molander, S. (2018). Live and Let Die? Life Cycle Human Health Impacts from the Use of Tire Studs. *International Journal of Environmental Research and Public Health*, *15*(8), 1774. https://doi.org/10.3390/ijerph15081774

Gakidou, E., Afshin, A., Abajobir, A. A., Abate, K. H., Abbafati, C., Abbas, K. M., Abd-Allah, F., Abdulle, A. M., Abera, S. F., Aboyans, V., Abu-Raddad, L. J., Abu-Rmeileh, N. M. E., Abyu, G. Y., Adedeji, I. A., Adetokunboh, O., Afarideh, M., Agrawal, A., Agrawal, S., Ahmadieh, H., … Murray, C. J. L. (2017). Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2016: A systematic analysis for the Global Burden of Disease Study 2016. *The Lancet*, *390*(10100), 1345–1422. https://doi.org/10.1016/S0140-6736(17)32366-8

Garnett, T. (2013). Food sustainability: Problems, perspectives and solutions. *Proceedings of the Nutrition Society*, *72*(1), 29–39. https://doi.org/10.1017/S0029665112002947

Goffart, J.-P., Haverkort, A., Storey, M., Haase, N., Martin, M., Lebrun, P., Ryckmans, D., Florins, D., & Demeulemeester, K. (2022). Potato Production in Northwestern Europe (Germany, France, the Netherlands, United Kingdom, Belgium): Characteristics, Issues, Challenges and Opportunities. *Potato Research*, *65*(3), 503–547. https://doi.org/10.1007/s11540-021-09535-8

Hawkes, C., & Ruel, M. T. (2006). *Understanding the links between agriculture and health*. https://doi.org/10.2499/2020focus13

Hawthorne, E. (2018, April 20). Eight innovative new crisp alternatives. *The Grocer*. https://www.thegrocer.co.uk/analysis-and-features/eight-innovative-new-crisp-alternatives-/566007.article

Henley, J. (2010, September 1). Crisps: A national obsession. *The Guardian*. https://www.theguardian.com/lifeandstyle/wordofmouth/2010/sep/01/crisps

Hess, J. M., Jonnalagadda, S. S., & Slavin, J. L. (2016). What Is a Snack, Why Do We Snack, and How Can We Choose Better Snacks? A Review of the Definitions of Snacking, Motivations to Snack, Contributions to Dietary Intake, and Recommendations for Improvement. *Advances in Nutrition*, *7*(3), 466–475. https://doi.org/10.3945/an.115.009571

Hospes, O., & Brons, A. (2016). Food system governance: A systematic literature review. In *Food systems governance* (1st edn, pp. 13–42). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315674957-2/food-system-governance-otto-hospes-anke-brons

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, *22*(2), 138–147. https://doi.org/10.1007/s11367-016-1246-y

IBISWorld. (2024). *Potato Crisps & Snacks Production in the UK - Market Size, Industry Analysis, Trends and Forecasts (2024-2029)| IBISWorld* (UK-SIC 2007 10.31) [Industrial Report]. https://www.ibisworld.com/united-kingdom/market-research-reports/potato-crisps-snacks-production-industry/

Kerr, M. A., Rennie, K. L., McCaffrey, T. A., Wallace, J. M. W., Hannon-Fletcher, M. P., & Livingstone, M. B. E. (2008). Snacking patterns among adolescents: A comparison of type, frequency and portion size between Britain in 1997 and Northern Ireland in 2005. *British Journal of Nutrition*, *101*(1), 122–131. https://doi.org/10.1017/S0007114508994769

Lal, R. (2021). Chapter 31—Climate change and agriculture. In T. M. Letcher (Ed.), *Climate Change (Third Edition)* (pp. 661–686). Elsevier. https://doi.org/10.1016/B978-0-12-821575-3.00031-1

Leek, S., & Afoakwah, D. (2023). Lunch meal deals contribution to overconsumption and use of the intervention ladder models to examine stakeholders' potential actions to reduce calorie content. *Journal of Marketing Management*, *39*(7–8), 648–669. https://doi.org/10.1080/0267257X.2022.2157462

Leng, G., Adan, R. A. H., Belot, M., Brunstrom, J. M., Graaf, K. de, Dickson, S. L., Hare, T., Maier, S., Menzies, J., Preissl, H., Reisch, L. A., Rogers, P. J., & Smeets, P. A. M. (2017). The determinants of food choice. *Proceedings of the Nutrition Society*, *76*(3), 316–327. https://doi.org/10.1017/S002966511600286X

Liu, Y., Lee, H., Achananuparp, P., Lim, E.-P., Cheng, T.-L., & Lin, S.-D. (2019). Characterizing and Predicting Repeat Food Consumption Behavior for Just-in-Time Interventions. *Proceedings of the 9th International Conference on Digital Public Health*, 11–20. https://doi.org/10.1145/3357729.3357736

Masset, G., Soler, L.-G., Vieux, F., & Darmon, N. (2014). Identifying Sustainable Foods: The Relationship between Environmental Impact, Nutritional Quality, and Prices of Foods Representative of the French Diet. *Journal of the Academy of Nutrition and Dietetics*, *114*(6), 862–869. https://doi.org/10.1016/j.jand.2014.02.002

Masset, G., Vieux, F., & Darmon, N. (2015). Which functional unit to identify sustainable foods? *Public Health Nutrition*, *18*(13), 2488–2497. https://doi.org/10.1017/S1368980015000579

McAuliffe, G. A., Takahashi, T., & Lee, M. R. F. (2020). Applications of nutritional functional units in commodity-level life cycle assessment (LCA) of agri-food systems. *The International Journal of Life Cycle Assessment*, *25*(2), 208–221. https://doi.org/10.1007/s11367-019-01679-7

National Institute for public health and environment. (2016). *ReCiPe 2016 v1.1 A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization* (No. RIVM Report 2016-0104a). Ministry of Health, Welfare and Sport. www.rivm.nl/en

Nilsson, K. (2011). *The environmental impact of the consumption of sweets, crisps and soft drinks*. Nordic Council of Ministers.

O'Connor, L., Brage, S., Griffin, S. J., Wareham, N. J., & Forouhi, N. G. (2015). The cross-sectional association between snacking behaviour and measures of adiposity: The Fenland Study, UK. *The British Journal of Nutrition*, *114*(8), 1286–1293. https://doi.org/10.1017/S000711451500269X

Office for Health, Improvement, & & Disparities. (2023). *Healthy eating: Applying All Our Health*. UK government. https://www.gov.uk/government/publications/healthy-eating-applying-all-our-health/healthy-eating-applying-all-our-health

Poore, J., & Nemecek, T. (2018). Reducing food’s environmental impacts through producers and consumers. *Science*, *360*(6392). https://ora.ox.ac.uk/objects/uuid:b0b53649-5e93-4415-bf07-6b0b1227172f

Raghunathan, R., Naylor, R. W., & Hoyer, W. D. (2006). The Unhealthy = Tasty Intuition and Its Effects on Taste Inferences, Enjoyment, and Choice of Food Products. *Journal of Marketing*, *70*(4), 170–184. https://doi.org/10.1509/jmkg.70.4.170

Rayner, M., & Scarborough, P. (2005). The burden of food related ill health in the UK. *Journal of Epidemiology & Community Health*, *59*(12), 1054–1057. https://doi.org/10.1136/jech.2005.036491

Raynor, H. A., & Wing, R. R. (2007). Package Unit Size and Amount of Food: Do Both Influence Intake? *Obesity*, *15*(9), 2311–2319. https://doi.org/10.1038/oby.2007.274

Reap, J., Roman, F., Duncan, S., & Bras, B. (2008). A survey of unresolved problems in life cycle assessment. *The International Journal of Life Cycle Assessment*, *13*(4), 290–300. https://doi.org/10.1007/s11367-008-0008-x

Rippin, H. L., Hutchinson, J., Jewell, J., Breda, J. J., & Cade, J. E. (2018). Portion Size of Energy-Dense Foods among French and UK Adults by BMI Status. *Nutrients*, *11*(1), 12. https://doi.org/10.3390/nu11010012

Ritchie, H., & Roser, M. (2023). Food production is responsible for one-quarter of the world’s greenhouse gas emissions. *Our World in Data*. https://ourworldindata.org/food-ghg-emissions

Saget, S., Costa, M., Barilli, E., Wilton de Vasconcelos, M., Santos, C. S., Styles, D., & Williams, M. (2020). Substituting wheat with chickpea flour in pasta production delivers more nutrition at a lower environmental cost. *Sustainable Production and Consumption*, *24*, 26–38. https://doi.org/10.1016/j.spc.2020.06.012

Sobal, J., & Bisogni, C. A. (2009). Constructing Food Choice Decisions. *Annals of Behavioral Medicine*, *38*(suppl_1), s37–s46. https://doi.org/10.1007/s12160-009-9124-5

Steptoe, A., Pollard, T. M., & Wardle, J. (1995). Development of a Measure of the Motives Underlying the Selection of Food: The Food Choice Questionnaire. *Appetite*, *25*(3), 267–284. https://doi.org/10.1006/appe.1995.0061

Stylianou, K. S., Fantke, P., & Jolliet, O. (2016). Combined nutritional and environmental life cycle assessment of fruits and vegetables: 10th International Conference on Life Cycle Assessment of Food. *10th International Conference on Life Cycle Assessment of Food 2016*.

Stylianou, K. S., Fulgoni, V. L., & Jolliet, O. (2021). Small targeted dietary changes can yield substantial gains for human health and the environment. *Nature Food*, *2*(8), Article 8. https://doi.org/10.1038/s43016-021-00343-4

Stylianou, K. S., Heller, M. C., Fulgoni, V. L., Ernstoff, A. S., Keoleian, G. A., & Jolliet, O. (2016). A life cycle assessment framework combining nutritional and environmental health impacts of diet: A case study on milk. *The International Journal of Life Cycle Assessment*, *21*(5), 734–746. https://doi.org/10.1007/s11367-015-0961-0

Sundin, N., Bartek, L., Persson Osowski, C., Strid, I., & Eriksson, M. (2023). Sustainability assessment of surplus food donation: A transfer system generating environmental, economic, and social values. *Sustainable Production and Consumption*, *38*, 41–54. https://doi.org/10.1016/j.spc.2023.03.022

Svanes, E., Waalen, W., & Uhlen, A. K. (2022). Environmental impacts of field peas and faba beans grown in Norway and derived products, compared to other food protein sources. *Sustainable Production and Consumption*, *33*, 756–766. https://doi.org/10.1016/j.spc.2022.07.020

Tapsell, L. C., Neale, E. P., Satija, A., & Hu, F. B. (2016). Foods, Nutrients, and Dietary Patterns: Interconnections and Implications for Dietary Guidelines12. *Advances in Nutrition*, *7*(3), 445–454. https://doi.org/10.3945/an.115.011718

The Eatwell Guide. (2024, January 2). GOV.UK. https://www.gov.uk/government/publications/the-eatwell-guide

USDA. (2023, May). *US Department of Agriculture* [Official Website of the United States government]. https://www.usda.gov/

Vinyes, E., Gasol, C. M., Asin, L., Alegre, S., & Muñoz, P. (2015). Life Cycle Assessment of multiyear peach production. *Journal of Cleaner Production*, *104*, 68–79. https://doi.org/10.1016/j.jclepro.2015.05.041

Visioli, F., Marangoni, F., Poli, A., Ghiselli, A., & Martini, D. (2022). Nutrition and health or nutrients and health? *International Journal of Food Sciences and Nutrition*, *73*(2), 141–148. https://doi.org/10.1080/09637486.2021.1937958

Walker, C., Gibney, E. R., Mathers, J. C., & Hellweg, S. (2019). Comparing environmental and personal health impacts of individual food choices. *Science of The Total Environment*, *685*, 609–620. https://doi.org/10.1016/j.scitotenv.2019.05.404

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Wijerathna-Yapa, A., & Pathirana, R. (2022). Sustainable Agro-Food Systems for Addressing Climate Change and Food Security. *Agriculture*, *12*(10), Article 10. https://doi.org/10.3390/agriculture12101554

Williams, C. M., Francis-Knapper, J. A., Webb, D., Brookes, C. A., Zampelas, A., Tredger, J. A., Wright, J., Meijer, G., Calder, P. C., Yaqoob, P., Roche, H., & Gibney, M. J. (1999). Cholesterol reduction using manufactured foods high in monounsaturated fatty acids: A randomized crossover study. *British Journal of Nutrition*, *81*(6), 439–446. https://doi.org/10.1017/S0007114599000793

Wilson, L. B., Pryce, R., Moore, E. C., Burke, L., & Breeze, P. (2023). Does cutting down on your food consumption lead to a net improvement in nutritional intake? A panel data approach using data from the UK Biobank. *BMC Public Health*, *23*(1), 2274. https://doi.org/10.1186/s12889-023-17217-y

Appendices

Appendix 1. Changes made in Agribalyse to adapt to the ingredients.

	RPC	C-BA	L-BA
	Based on Potato Crisps - Agribalyse	Based on Potato Crisps – Agribalyse	Based on Puffed salty snack – made from maize/corn - Agribalyse
At Farm gate	X	X	Lentil flour (Based on soy flour processing – at industrial mill)
Consumption Mix	"Ware potato variety mix" changed for "Ware potato conventional, for industrial use, at farm gate"		Tapioca starch is based on Maize starch – Agribalyse – Wastewater from potato because more similar
At plant	Added "Rapeseed oil, at plant FR U" and transferred 0.6kg from "Sunflower oil" to "rapeseed oil"	Black eyed peas replaced with Red Kidney Beans Consumption Mix – itself is based on Fava beans	Potato starch Rice flour – at industrial mill Maize grain – adapted with % of import

Appendix 2. Categories created on Python for further data checking.

Category	Sub-category
Transport	Lorry
	Train
	Sea
	In land water
Farming	Plant protection products
	Fertilizers
	Tools and machinery
	Crops
Processing	At mill
	Oil
	Flour
	Cooking methods
Energy	Electricity
	Natural gas
	Fuel oil
Water	Tap water
	Ocean water
	Irrigation
	Waste water

Appendix 3.Products

Ingredients	RPC	L-BA	C-BA
Potatoes	16.25[2]		
Potato Starch		2.45[2]	
Lentil Flour		3.92[3]	
Chickpea flour			8.28[3]
Rice flour		1.05[2]	3.45[2]
Corn Flour		1.05[2]	
Tapioca Starch			3.45[2]
Sunflower oil	6.5[1]	1.4[2]	3.45[2]
Rapeseed oil	1.25[1]	1.4[2]	
Coconut oil		1.4[2]	
Black Eyed Peas			1.84[3]
Sugar	0.1[1]	0.63[1]	1.70[1]
Salt	0.90[1]	0.92[1]	1.01[1]

[1]Based on the nutritional values of each product (Table 2)

[2]Based on industrial partners and experts.

[3]Based on the label of each product (Table 2)

Appendix 4. Commonly used DRFs (calculated by US data)

Dietary risk	DRF (µDALYs/g)		
	Mean	Lower	Upper
Omega-3 (seafood)	-81	-37	-110
Calcium	-5.1	-4	-6.2
Nuts and seeds	-1.5	-1.1	-1.9
Fiber$_{other}$	-0.99	-0.71	-1.3
Polyunsaturated fatty acids (PUFA)	-0.6	-0.26	-0.94
Whole grains	-0.34	-0.28	-0.4
Legumes	-0.23	-0.1	-0.34
Fiber$_{f,v,l,w}$	-0.19	-0.11	-0.26
Fruits	-0.18	-0.12	-0.22
Vegetables	-0.083	-0.042	-0.11
Milk	-0.0077	-0.0027	-0.012
Sugar-sweetened beverages (SSB)	0.066	0.043	0.089
Red meat	0.099	0.038	0.15
Processed meat	0.86	0.41	1.1
Trans fatty acids (TFA)	4.4	3.3	5.6
Sodium	13.9	11.5	16.1

Fiber$_{other}$= fiber obtained from sources other than fruits, vegetables, legumes, and whole grains

Fiber$_{f,v,l,w}$=fiber obtained from fruit, vegetables, legumes, and whole grains

Omega-3 fatty acids are restricted to those that originate from seafood sources

Appendix 5. Weight of main diseases caused by each Dietary Risk (lack or over intake) and disease group details.

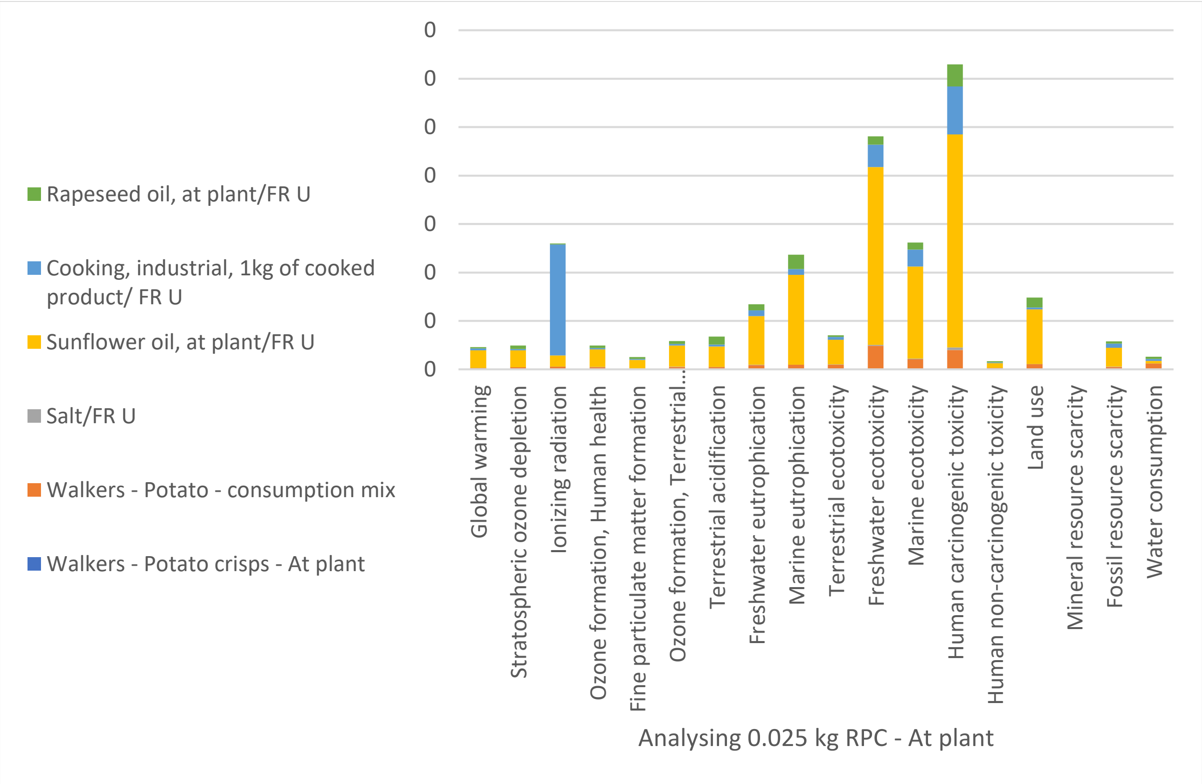
	Ischemic heart disease	Colorectal cancer	Diabetes	Other cardiovascular diseases	Other diseases	Other neoplasms
Omega-3 (seafood)	100.00%					
Calcium		100.00%				
Nuts and seeds	80.00%		20.00%			
Fiberother	80.00%	20.00%				
Polyunsaturated fatty acids (PUFA)	100.00%					
Whole grains	55.00%		23.00%	22.00%		
Legumes	100.00%					
Fiberf,v,l,w		100.00%				
Fruits	37.00%		18.00%	23.00%		22.00%
Vegetables	78.00%			22.00%		
Milk		100.00%				
Sugar-sweetened beverages (SSB)	22.00%	3.00%	25.00%	20.00%		
Red meat		70.00%	30.00%			
Processed meat	62.00%	8.00%	30.00%			
Trans fatty acids (TFA)	100.00%					
Sodium	50.00%			35.00%	15.00%	

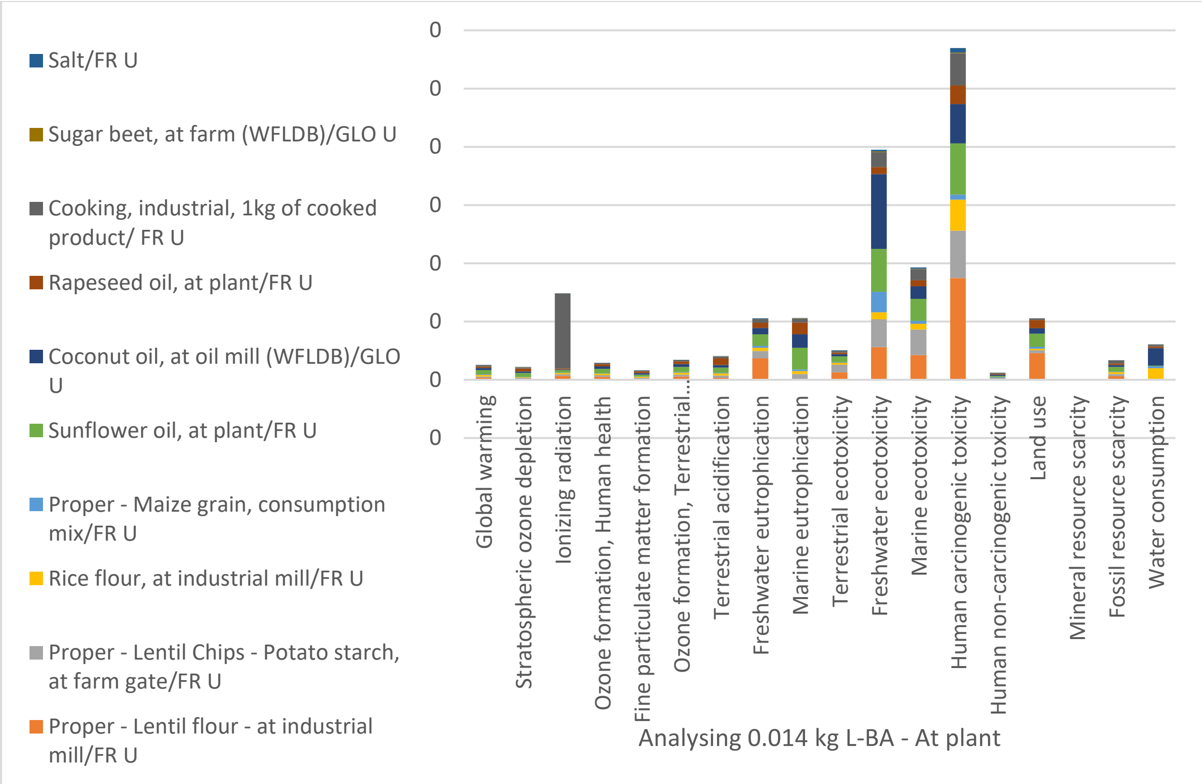
Disease group	Disease
Other cardiovascular diseases	Aortic aneurysm Atrial fibrillation and flutter Endocarditis Haemorrhagic stroke Hypertensive heart disease Ischemic stroke Other cardiomyopathy Other cardiovascular and circulatory diseases Peripheral artery disease Rheumatic heart disease
Other diseases	Alzheimer disease and other dementias Asthma Cataract Chronic kidney disease due to diabetes mellitus Chronic kidney disease due to glomerulonephritis Chronic kidney disease due to hypertension Chronic kidney disease due to other causes Gallbladder and biliary diseases Gout Low back pain Osteoarthritis

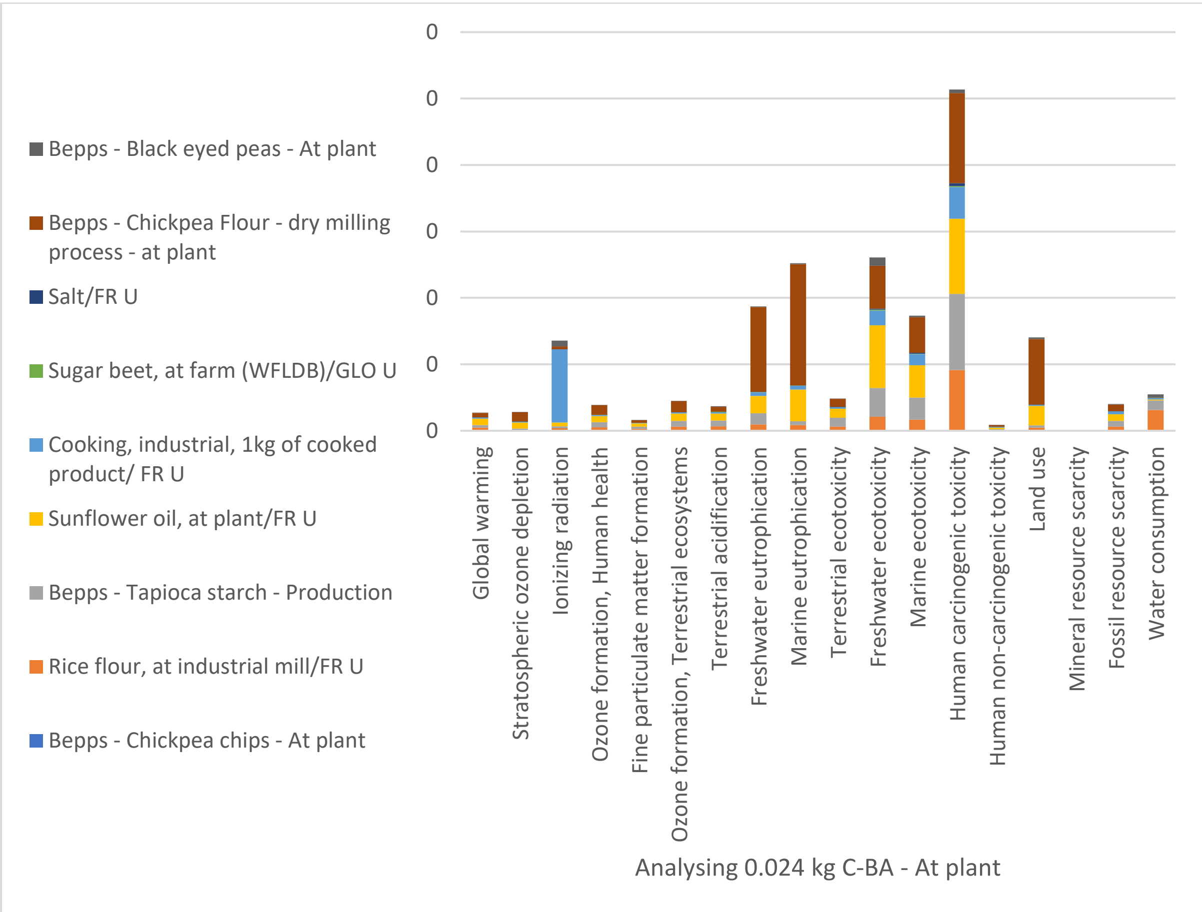
Appendix 6. Summary of characterisation results for environmental burden from selected midpoint impact categories

Impact category	RPC	L-BA	C-BA
Global warming (kg CO2 eq)	0.036927	0.019981	0.041741
Stratospheric ozone depletion (kg CFC11 eq)	2.96E-07	1.28E-07	3.26E-07
Ionizing radiation (kBq Co-60 eq)	0.012504	0.007115	0.012524
Ozone formation, Human health (kg NOx eq)	0.000102	5.91E-05	0.000153
Fine particulate matter formation (kg PM2.5 eq)	6.47E-05	3.95E-05	7.96E-05
Ozone formation, Terrestrial ecosystems (kg NOx eq)	0.000104	5.99E-05	0.000154
Terrestrial acidification (kg SO2 eq)	0.000277	0.000165	0.00029
Freshwater eutrophication (kg P eq)	8.71E-06	6.86E-06	2.33E-05
Marine eutrophication (kg N eq)	0.000109	4.86E-05	0.000223
Terrestrial ecotoxicity (kg 1,4-DCB)	0.106993	0.076566	0.141232
Freshwater ecotoxicity (kg 1,4-DCB)	0.001212	0.000995	0.001258
Marine ecotoxicity (kg 1,4-DCB)	0.001138	0.00084	0.001445
Human carcinogenic toxicity (kg 1,4-DCB)	0.000649	0.000587	0.001014
Human non-carcinogenic toxicity (kg 1,4-DCB)	0.052872	0.032628	0.051027
Land use (m2a crop eq)	0.091668	0.064937	0.166085
Mineral resource scarcity (kg Cu eq)	0.000227	0.000107	0.00016
Fossil resource scarcity (kg oil eq)	0.005652	0.00327	0.007551
Water consumption (m3)	0.0007	0.00161	0.002791

Appendix 7. Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H / Normalisation




Salt/FR U
Sugar beet, at farm (WFLDB)/GLO U
Cooking, industrial, 1kg of cooked product/ FR U
Rapeseed oil, at plant/FR U
Coconut oil, at oil mill (WFLDB)/GLO U
Sunflower oil, at plant/FR U
Proper - Maize grain, consumption mix/FR U
Rice flour, at industrial mill/FR U
Proper - Lentil Chips - Potato starch, at farm gate/FR U
Proper - Lentil flour - at industrial mill/FR U
0
0
0
0
0
0
0
0
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter formation
Ozone formation, Terrestrial...
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption
Analysing 0.014 kg L-BA - At plant


Bepps - Black eyed peas - At plant
Bepps - Chickpea Flour - dry milling process - at plant
Salt/FR U
Sugar beet, at farm (WFLDB)/GLO U
Cooking, industrial, 1kg of cooked product/ FR U
Sunflower oil, at plant/FR U
Bepps - Tapioca starch - Production
Rice flour, at industrial mill/FR U
Bepps - Chickpea chips - At plant
0
0
0
0
0
0
0
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter formation
Ozone formation, Terrestrial ecosystems
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption
Analysing 0.024 kg C-BA - At plant

Appendix 7. At farm contribution

Impact	Product	First contributing crop	First contributor to Crops at Farm	Comment
IR	RPC	Sunflower	Combine harvesting (CH) -Processing	Pesticide, unspecified (RER) Production is the second contributor to Sunflower, similar to the first one.
	L-BA	Rapeseed	Drying of feed grain CH – Processing	Urea: A Low Cost Nitrogen Fertilizer with Special Management Requirements, is the second contributor to rapeseed. Second contributor to Lentil Chips as a crop is sunflower, followed by coconut
	C-BA	Organic chickpea seed	Harvesting with combine harvester	Ploughing is the second contributor to chickpea seed, followed by sowing. Sunflower and organic chickpea at farm gate are the two other important contributor to Chickpea Chips IR.
HCT	RPC	Sunflower	Combine harvesting (CH) Processing	N/A
	L-BA	Rapeseed	Combine harvesting (CH) Processing	Urea: A Low Cost Nitrogen Fertilizer with Special Management Requirements, is the second contributor to rapeseed. Second contributor to Lentil Chips as a crop is sunflower.
	C-BA	Sunflower	Combine harvesting (CH) Processing	N/A
FE	RPC	Ware potatoes	Fungicide (Mancozeb)	Followed by sunflower and potato seeds.
	L-BA	Sunflower	Emissions from pesticides, unspecified.	Second contributor to Lentil Chips as a crop is rapeseed and coconut
	C-BA	French bean	Ammonium nitrate, as N RER production	Chickpea seed and sunflower are the two other crops contributing to FE
WC	RPC	Ware potatoes	Market for pyridine-compound.	Followed by sunflowers and potato seeds.
	L-BA	Coconut	Urea as N, at plant	Irrigating surface diesel powered is the second contributor to coconut at farm.
	C-BA	French bean	Ammonium nitrate, as N RER production	The second contributor to WC is Urea-compound market – estimation of the distance

Appendix 8. Three biggest contributors to most important environmental impacts.

Impact category	Potato Crisps		Lentil Chips		Chickpea Chips	
Terrestrial ecotoxicity (kg 1,4-DCB)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, S - Copied from Ecoinvent	0.025831957	Potato, Swiss integrated production {CH}| potato production, Swiss integrated production, intensive | Cut-off, S - Copied from Ecoinvent	0.01133668	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S - Copied from Ecoinvent	0.028754061
	Chemical factory, organics {RER}| construction | Cut-off, S - Copied from Ecoinvent	0.02410945	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S - Copied from Ecoinvent	0.008521889	Chemical factory, organics {GLO}| market for | Cut-off, S - Copied from ecoinvent	0.021823675
	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S - Copied from Ecoinvent	0.010682484	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S - Copied from Ecoinvent	0.006866002	Chemical factory, organics {RER}| construction | Cut-off, S - Copied from Ecoinvent	0.018464964
Freshwater ecotoxicity (kg 1,4-DCB)	Emissions from pesticides, unspecified (WFLDB 3.1)/GLO S	0.000423	Emission from insecticides, unspecified, family Organophosphorus-compound (WFLDB)/GLO S	0.000191	Emissions from pesticides, unspecified (WFLDB 3.1)/GLO S	0.000208
	Potato Crisps - Ware potato, conventional, for industrial use - at farm gate	6.66E-05	Emissions from pesticides, unspecified (WFLDB 3.1)/GLO S	8.45E-05	Carrot {RoW}| carrot production | Cut-off, S - Copied from Ecoinvent	5.15E-05
	Sunflower, at farm (WFLDB 3.1)/FR U	2.8E-05	Emission from fungicides, unspecified, family Dithiocarbamate-compound (WFLDB)/GLO S	6.94E-05	French bean, conventional, national average, at farm gate/FR U	4.65E-05
	Sunflower, at farm (WFLDB 3.1)/FR U	0.023873	Lentil {CA-AB}| lentil production | Cut-off, S	0.012427	Chickpea seed, organic, at farm gate/FR U	0.103816

Land use (m2a crop eq)	Sunflower, at farm (WFLDB 3.1)/UA U	0.017572	Lentil {RoW}| lentil production | Cut-off, S	0.009369	Chickpea, organic, system n°1, at farm gate/FR U	0.01257
	Sunflower, at farm (WFLDB 3.1)/HU U	0.017232	Rapeseed, at farm (WFLDB 3.1)/CA U	0.007106	Sunflower, at farm (WFLDB 3.1)/FR U	0.011766
Water consumption (m3)	Potato Crisps - Ware potato, conventional, for industrial use - at farm gate	0.00031	Coconut, dehusked, at farm (WFLDB)/PH U	0.000645	Irrigation {CN}| market for | Cut-off, S - Copied from Ecoinvent	0.000371
	Rape seed {FR}| production | Cut-off, S - Copied from Ecoinvent	8.96E-05	Irrigation {CN}| market for | Cut-off, S - Copied from Ecoinvent	0.000371	Rice {IN}| rice production | Cut-off, S - Copied from Ecoinvent	0.000298
	Electricity, medium voltage {FR}| market for | Cut-off, S - Copied from Ecoinvent	6.07E-05	Rice {IN}| rice production | Cut-off, S - Copied from Ecoinvent	0.000298	Carrot {RoW}| carrot production | Cut-off, S - Copied from Ecoinvent	0