





## Comparative environmental and nutritional sustainability analysis of Kabuli and Desi Chickpea (*Cicer arietinum* L.) types at the farm and product level

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### ABSTRACT

Life Cycle Assessment (LCA) was conducted to evaluate the environmental impact of cultivating black (Desi type) and white (Kabuli type) chickpeas in Europe under both organic and conventional farming systems. The LCA on a mass basis (1 kg of product) showed that Kabuli chickpea cultivation had a lower global warming potential, water use, and land occupation due to higher yields and more established farming practices for this variety in conventional systems. This study also examined the environmental impact of producing hummus derived from these two raw materials. The LCA on a mass basis (1 kg of product) showed that hummus production generally had a lower environmental impact when using Kabuli chickpeas primarily due to higher yield efficiency and optimised farming practices for the Kabuli type. However, when nutritional LCA is considered, using Nutrient Density as a functional unit (NDU), Desi hummus demonstrates lower environmental impacts in most categories, particularly regarding eutrophication and acidification potential. The study highlights the trade-offs between environmental impacts and nutritional benefits while comparing organic and conventional farming systems, suggesting that incorporating underutilised types such as Desi chickpeas could contribute to a more sustainable and nutritionally diverse food system.

### 1. Introduction

The current food system is at an impasse: it needs to change its ethos urgently to feed the world population while decreasing its environmental impact. The food sector emerges as a significant contributor to the broader environmental effects of human activities (DeClerck et al., 2023). Agricultural intensification has led to substantial biodiversity loss, soil degradation, and greenhouse emissions exacerbating climate change (Poore and Nemecek, 2018). These environmental pressures highlight the urgent need to explore more sustainable approaches, including alternative crop choices and improved farming practices.

This is particularly concerning as the global population is expected to reach 9.7 billion by 2050, necessitating sustainable and resilient food systems to ensure food security while preserving environmental resources. Besides this, dietary patterns worldwide are converging

(Azzam, 2021), with global reliance on a limited number of staple crop. This dependence increases food system vulnerability, as disruptions in the supply of these crops – caused by climate change, political instability, or market fluctuations – can have far-reaching consequences. This pressure fosters a tendency to centralise the production of raw materials, which is suboptimal, as disruptions at various points along the chain can halt the distribution of goods.

Research in this area has emphasised the vulnerabilities of such systems. For instance, the Green Revolution in Asia demonstrated that while high-yielding crops significantly reduced hunger (Singh et al., 2022), this approach also contributed to a reduction in crop diversity and increased environmental strain. Likewise, monoculture farming has been linked to long-term soil degradation, declining genetic diversity, and dependency on synthetic fertilisers and pesticides. The convergence of diets, combined with advancements in food processing technology

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and evolving sedentary lifestyles, has led to the dual burden of malnutrition and an escalation in obesity and non-communicable diseases (Alem et al., 2023; WHO, NMH, and NHD, 2017). These challenges highlight the need for diverse and sustainable food systems that promote biodiversity, dietary variety, and nutritional resilience.

The vulnerability of current global food chains is underscored by the potential ramifications of even minor disruptions, which could cascade into a widespread hunger crisis. Nonetheless, this presents both advantages and disadvantages. On the one side, applying "economies of scale" associated with increased production decreases the environmental impact (Silva et al., 2024) and other costs per unit (Schiffing et al., 2015). On the other hand, a standardised global diet resulting from such a chain contributes to biodiversity loss, soil nutrient depletion, and reduced arable land availability, exacerbated by climate change (DeClerck et al., 2023). To counteract these risks, there is growing interest in the reintroduction of underutilised crops (UCs), which have the potential to enhance agricultural sustainability while improving dietary diversity and recognised as viable solutions to foster sustainability (Pinto et al., 2023). UCs often demonstrate adaptability to adverse environmental conditions, such as drought or nutrient-poor soils (Singh et al., 2022), and their reintroduction into the current food systems can alleviate food insecurity while enhancing ecosystem resilience.

Among UCs, legumes offer several environmental benefits, including nitrogen fixation, being highly recommended for crop rotation as a strategy to reduce fertiliser inputs (Leghari et al., 2016). The symbiotic relationship between legumes and rhizobia bacteria presents a path for transforming atmospheric nitrogen into a plant-useable form, reducing the use of synthetic nitrogen fertilisers (Singh et al., 2022) and associated emissions. Additionally, legumes contribute to lower greenhouse gas emissions compared to other protein sources, making them a valuable component in climate-friendly diets. Consuming UCs also brings multiple health benefits, which include reduced risk of developing cardiovascular diseases (Ayilara et al., 2022).

Amongst the legumes, chickpeas (*Cicer arietinum*) are nutrient-rich foods that provide protein, minerals, and vitamins, making them an excellent choice for a balanced diet (Ferreira et al., 2021; Medeiros et al., 2024). Chickpeas are also good options for novel product development (Sharath Chandra et al., 2020; Singh et al., 2022), supporting the increased rates of plant-based food development (Pointke and Pawelzik, 2022) and the increased demand for vegan and vegetarian products (Bivi et al., 2021). Chickpea genotypes vary substantially in colour, functional properties, and nutritional profiles (Summo et al., 2019), which means they can be used differently in the food industry according to their specifications. Processing of chickpeas creates new products with increased and improved value, and as a reflection, multiple novel products have been developed – from meat analogues to pasta and plant-based beverages – and these are frequently fortified (Saget et al., 2020; Silva and Smetana, 2022). However, processing practices also define consumer perceptions while increasing a product's environmental impact.

When selecting the chickpea type for product development, it is also important to consider its agronomic traits. Several chickpea genotypes have shown high drought tolerance and improved water use (Devasirvatham and Tan, 2018), allowing them to achieve high yields even in regions with limited water resources (Medeiros et al., 2024). Agronomic practices and the farm's location also affect the crop's needs and, consequently, the environmental footprint associated with farming. Organic and conventional farms provide an interesting comparison in terms of LCA because the farming methods in these two systems differ significantly, influencing factors such as energy use, greenhouse gas emissions and resource inputs (Foteinis and Chatzisyneon, 2016; Gomiero et al., 2011). Nutritional quality is also critical in product development, as different processing methods and chickpea types affect the final product's environmental footprint and health profile (Olika et al., 2019). Tools such as the Nutri-Score, a widely recognised nutritional labelling system, can help assess and compare the healthiness of

food products by evaluating their composition (e.g. calories, sugar, saturated fats, sodium, protein, fibre, and vegetable content). In this context, using a framework like Nutri-Score in life cycle assessment provides a holistic view of both environmental and nutritional impacts, which is essential for sustainable product development. However, despite their great agronomical and nutritional potential, limited research has compared the environmental impacts of different chickpea genotypes, such as white (Kabuli) and black (Desi) chickpeas, particularly when processed into popular products like hummus.

Hummus is a chickpea-based product whose popularity has witnessed a notable surge in recent years (Reister et al., 2020; Wallace et al., 2016). Celebrated for its ease of production, versatility, palatability, and health-promoting attributes, it fosters the consumption of plant-based products in alignment with dietary guidelines (Reister et al., 2020). Commercial production of hummus predominantly features white chickpea (Kabuli-type) (CBI, 2023). However, incorporating a more underutilised chickpea type, such as the traditional black chickpea (Desi-type), which has marginal production in occidental countries but has more drought tolerance potential (Medeiros et al., 2024), may benefit the product's nutritional profile and environmental footprint. Despite these potential benefits, there is a notable gap in understanding the implications of integrating underutilised chickpeas into modern food systems, particularly regarding their impact on nutritional quality and environmental outcomes.

In this context, this study contributes to the existing literature by addressing two key gaps: (1) understanding the environmental benefits of cultivating underutilised black chickpeas compared to more commonly grown white chickpeas, and (2) assessing whether black chickpeas' further processing into hummus offers a more sustainable alternative. To explore these dimensions comprehensively, a combined approach using comparative Life Cycle Assessment (LCA) and Nutritional Scoring analysis are applied, providing an integrated evaluation of environmental and nutritional impacts.

## 2. Material and methods

The Life Cycle Assessment (LCA) was conducted according to ISO standards 14040-14044 (ISO, 2006b, 2006a) and utilising the prospective attributional LCA approach (Hospido et al., 2010). The method applied for this study was ReCiPe 2016 Midpoint (Hierarchist perspective) V1.07. The assessment aimed to compare the environmental and nutritional attributes of Desi and Kabuli chickpea cultivation and hummus production. The approach encompasses two primary assessments, each addressing distinct aspects of the product life cycle.

### 2.1. Environmental life cycle assessment of the grains and further products

The first facet of the methodology concentrates on assessing the environmental impact of chickpea production and hummus manufacturing. Chickpea production evaluation considers the cradle-to-farm gate stages for both Desi and Kabuli chickpeas, with the functional unit (FU) set at 1 kg. The data pertained to the farming stage was collected directly from on-site farmers, providing a comprehensive understanding of the cultivation practices involved. Hummus production assessment extends from cradle to factory gate, encompassing both Desi and Kabuli hummus, with an FU of 1 kg of unpacked product. A modelling approach was adopted for the industrial stage.

#### 2.1.1. Farm characterization

The data refers to farms located in Santarém in Portugal, one of organic production growing the Desi type, and two farms of different sizes of conventional Kabuli production. The characterisation of all farms is described in Table 1.

**Table 1**

Characterisation of the farms (location: south of Portugal) that generate the data used for the current study. Abbreviations: Org – Organic, Conv – Conventional. For further information, please refer to Expanded Table 1 available on the Supplementary Material file.

	Desi chickpea – Organic farm	Kabuli chickpea – Conv. farms	
	Small-sized chickpea farm	Medium-sized chickpea farm	Large-sized chickpea farm
Area	0.3 ha	5 ha	50 ha
Characterisation	Open-air organic production	Open-air conventional production	Open-air conventional production The area can vary yearly depending on field rotation
Fertilisers and pesticides	No fertiliser, pesticides or herbicides	No fertiliser, pesticides or herbicides	Fertiliser and herbicide employed
Machinery	Rarely used – manual labour in most of the process	Machinery employed	Machinery employed
Other transportation	Transportation of farmer to and from the farm	N/A	Transport of compost via truck
Waste	Plant material either for composting or for animal feed	Plant material either for composting, soil covering or for animal feed	Plant material either for composting or for animal feed
Irrigation	No irrigation – rainwater only		
Yield (per ha)	0.53 t	2 t	2 t
Other information:	Growing period: 5 months	Growing period: 4 months	Growing period: 7 months

**2.1.2. System boundaries**

This study has a "cradle-to-industry gate", encompassing both the farming and processing stages. The methodology employs a modular LCA, where the production system or product life cycle is dissected into modules for detailed analysis. The impacts of these modules are then aggregated to calculate the overall impact of the chains. In this case, four distinct modules were identified and divided into two chains (see Fig. 1): farm production for organic (Desi chickpea production) and conventional (Kabuli chickpea production) practices and the industrial processing stage. For a comprehensive understanding of the farming

**Table 2**

Life Cycle Inventory of inputs and outputs for chickpea production in different fields. Abbreviations: Org – Organic, Conv – Conventional. For detailed information, please refer to Expanded Table 2 of the Supplementary Material file.

Stage	Input/output name	Units	Organic farm (Desi)		Conventional farms (Kabuli)			
			Small-sized chickpea farm		Medium-sized chickpea farm		Large-sized chickpea farm	
			Inputs	Outputs	Inputs	Outputs	Inputs	Outputs
Land preparation	Fuel	L	37.1		150		4000	
	Land	m <sup>2</sup>	3000		50000		500000	
	Fertiliser	kg					60000	
	Herbicide	L					150	
Sowing	Seeds	kg	10		400		9000	
	Losses	kg		n.a. (a)		n.a. (a)		n.a. (a)
	Fuel	L			200		750	
Growing	Waste	kg		n.a. (a)		n.a. (a)		n.a. (a)
	Losses	kg		0.4 (b)		40 (b)		400 (b)
	Herbicides	L					150	
Harvesting	Fertilisers	kg					60	
	Fuel	L			190		750	
	Losses	kg		n.a. (a)		n.a. (a)		n.a. (a)
Threshing	Waste	kg		n.a. (a)		n.a. (a)		n.a. (a)
Cleaning	Electricity	Kwh	7.03		n.d.		n.d.	
	Waste	kg		n.a. (a)				n.a. (a)
Chickpea	Yield	kg		160		10000		100000

n.a. – Not accounted: (a) losses not accounted for: seeds and plants eaten by wild animals; waste: material (stalks, roots and pods) used as feed for farm animals; (b) losses calculated via the lowest germination percentage from the literature and assumed to be the same for both species (Gan et al., 2003).

modules, including processing steps and corresponding inputs/outputs, please refer to Fig. 5 of the Supplementary Material file.

**2.1.3. Data collection**

The farmers provided data for this study via answers to a co-created questionnaire. For this, a flowchart was co-developed to resemble the actual production as much as possible (see Figs. 5 and 6 of the Supplementary material). From these, a set of questions was developed to collect accurate data regarding the inputs and outputs of the systems. In this case, all farmers stated that their chickpeas are rainfed and not irrigated, and therefore irrigation was not accounted for in this study.

For the hummus data collection, the recipe was developed in-house at Universidade Católica Portuguesa (UCP), and the background data for each of the ingredients was sourced from the Agribalyse database (v3.1), as detailed in Table 3.

**2.2. Nutritional life cycle assessment (nLCA) of hummus**

In addition to environmental considerations, the methodology integrates a nutritional LCA (nLCA) to inspect the nutritional quality of the final products. This dual-layered approach considers macronutrients, micronutrients, and overall dietary quality. The nLCA employs the Nutrient Density Unit (NDU) as a metric to quantitatively assess the nutritional composition of both Desi and Kabuli chickpeas and hummus. The Goal and Scope, System boundaries and Data of this part of the study overlap with the one described in sections 2.1.1., 2.1.2 and 2.1.3. The only difference is the FU, which changes from a mass unit to an NDU unit.

**2.2.1. Nutrient Density Unit (NDU)**

The Nutrient Density Unit (NDU) FU was applied following Saget et al. (2021) formula:

$$\text{Formula 1 : } NDU = \frac{\left(\frac{EFA}{DV_{EFA}}\right) + \left(\frac{Protein}{DV_{Protein}}\right) + \left(\frac{Fibre}{DV_{Fibre}}\right)}{3 * \left(\frac{S_i}{2000 \text{ kcal}}\right)}$$

Where:

*EFA* is the amount of essential fatty acids in 100 g of product (in grams).

*Protein* is the amount of protein in 100 g of product (in grams).

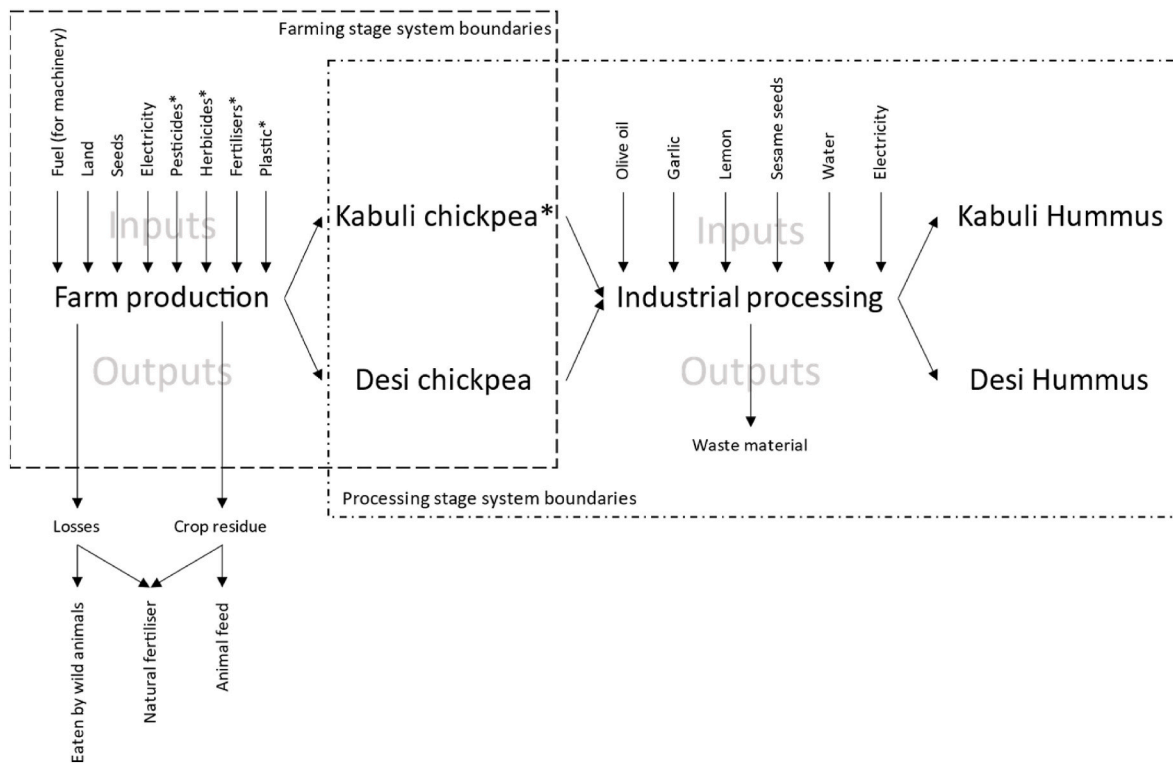


Fig. 1. Chains of Desi and Kabuli hummus production and respective modules and system boundaries (Farming and Processing stages). Inputs and outputs marked with an asterisk (\*) refer exclusively to the Kabuli chickpea product. Source: Authors.

**Table 3**  
Life Cycle Inventory of inputs for producing 1 kg of hummus with the different chickpeas (Desi and Kabuli). For detailed information, please refer to Expanded Table 3 of the Supplementary Material File.

Input/output name	Units	Hummus production	
		Inputs	Outputs
<i>Ingredients/Raw materials</i>			
Chickpeas (Desi or Kabuli)	kg	0.150	
Garlic	kg	0.006	
Lemon juice	kg	0.008	
Olive oil	kg	0.020	
Sesame seed	kg	0.015	
Water	L	0.654	
<i>Flows</i>			
Electricity	kWh	0.0642	
<i>Final product</i>			
Hummus	kg		1

Fibre is the amount of fibre in 100 g of product (in grams).  
 $DV_{EFA}$  is the recommended daily value intake of essential fatty acids (in grams).  
 $DV_{Protein}$  is the recommended daily value intake of protein (in grams).  
 $DV_{fibre}$  is the recommended daily value intake of fibre (in grams).  
 $S_i$  is the amount of kilocalories in 100 g of product (in kilocalories).  
 The calculated NDU values for Kabuli and Desi hummus are 1.958 and 2.404, respectively. To standardise the environmental impact results based on these nutritional values, the following proportional relationship was established:

$$x \cdot NDU_1 = y \cdot NDU_2$$

where  $x = 1$  kg for Kabuli Hummus. From this equation, we find that:

$$y = \frac{NDU_2}{NDU_1} = \frac{1.958}{2.404} = 0.814$$

This indicates that 0.814 kg of Desi hummus is nutritionally equivalent to 1 kg of Kabuli hummus. Consequently, the environmental impacts of each product are adjusted and presented per 1 NDU kg to reflect this nutritional standardisation.

The methodology for acquiring the nutritional data for the legumes and hummus was the same as used by (Saget et al., 2021). In sum, the protein content was analysed using the Kiedahl method, the energy content calculated after EU regulation 1169/2011, the fiber content determined using the enzymatic-Gravimetric Method from the AOAC 991.43 and AOAC 985.29, and the essential fatty acids (EFA) were determined using gas chromatography (FID) from ISO 12966-1:2014; 12966-2:2011; and 12966-3:2016. Details of the nutritional analysis method can be found next (Table 4).

An evaluation of the Nutri-score for chickpea grains and hummus products is incorporated to enhance the analysis further. Subsequently, the equation Santé publique France (2022) developed is applied, and the product is assigned a Nutri-Score that varies from A to E (Table 4).

### 3. Results and discussion

The food sector is a significant contributor to environmental degradation. Food systems account for approximately 30 % of global greenhouse gas emissions, making them a major driver of climate change

**Table 4**  
Summary of nutritional composition and Nutrient Density Units (NDU) of Kabuli and Desi chickpea and hummus. Nutritional values are given per 100 g. Nutriscore calculated as described by Santé publique France (2022).

Content per 100g of product	Units	Kabuli hummus	Desi hummus
Energy	kcal	467	415
Protein	g	4.0	12.3
Dietary fibre	g	17.7	19.1
EFA	g	7.24	6.03
NDU	point	1.958	2.404
NutriScore		D (13 P)	D (12 P)

(Tubiello et al., 2022). Additionally, to feed the growing population, food production needs to increase by 50 % while simultaneously providing living incomes for farmers and creating more jobs in the sector (van Dijk et al., 2021). Importantly, recent improvements in calorie production and food availability have been insufficient in eradication inequalities in food access, while malnutrition coexists with rising rates of obesity and non-communicable diseases, partly due to the increased availability of processed foods and changing lifestyles (Wells et al., 2020). To address these challenges, there is a growing need to develop sustainable and resilient food systems, enable local and regional food networks to reduce transportation-related emissions and support policies and economic incentives that reward sustainable practices and discourage harmful ones. In this context, chickpeas, and chickpea hummus in particular, can help shift diets towards more sustainable, plant-based options in developed communities, by offering a healthier alternative to processed foods, while in underdeveloped communities they can provide a cost-effective, nutritious food source to combat malnutrition, offer economic opportunities for small-scale farmers and

enhance food security in areas vulnerable to climate change (Jha et al., 2024; Chaturvedi et al., 2024).

### 3.1. Environmental impacts of the cultivation of Desi and Kabuli chickpeas

The results of this study show the complexity of balancing environmental sustainability and agricultural productivity. The comparison between Kabuli and Desi chickpeas available in the following Fig. 2, highlights the trade-offs across impact categories, influenced by differences in yield, agronomic practices and farming systems (for full comparison data please refer to Fig. 6 of the Supplementary Material file). Kabuli chickpeas (represented by blue and grey bars) consistently show a lower environmental impact across all 18 categories, though there are some differences between both Kabuli productions where in some categories the larger farm has higher environmental impact than the medium-sized farm (data not shown, please refer to Fig. 6 of the Supplementary Material file). These findings expand on earlier reports of

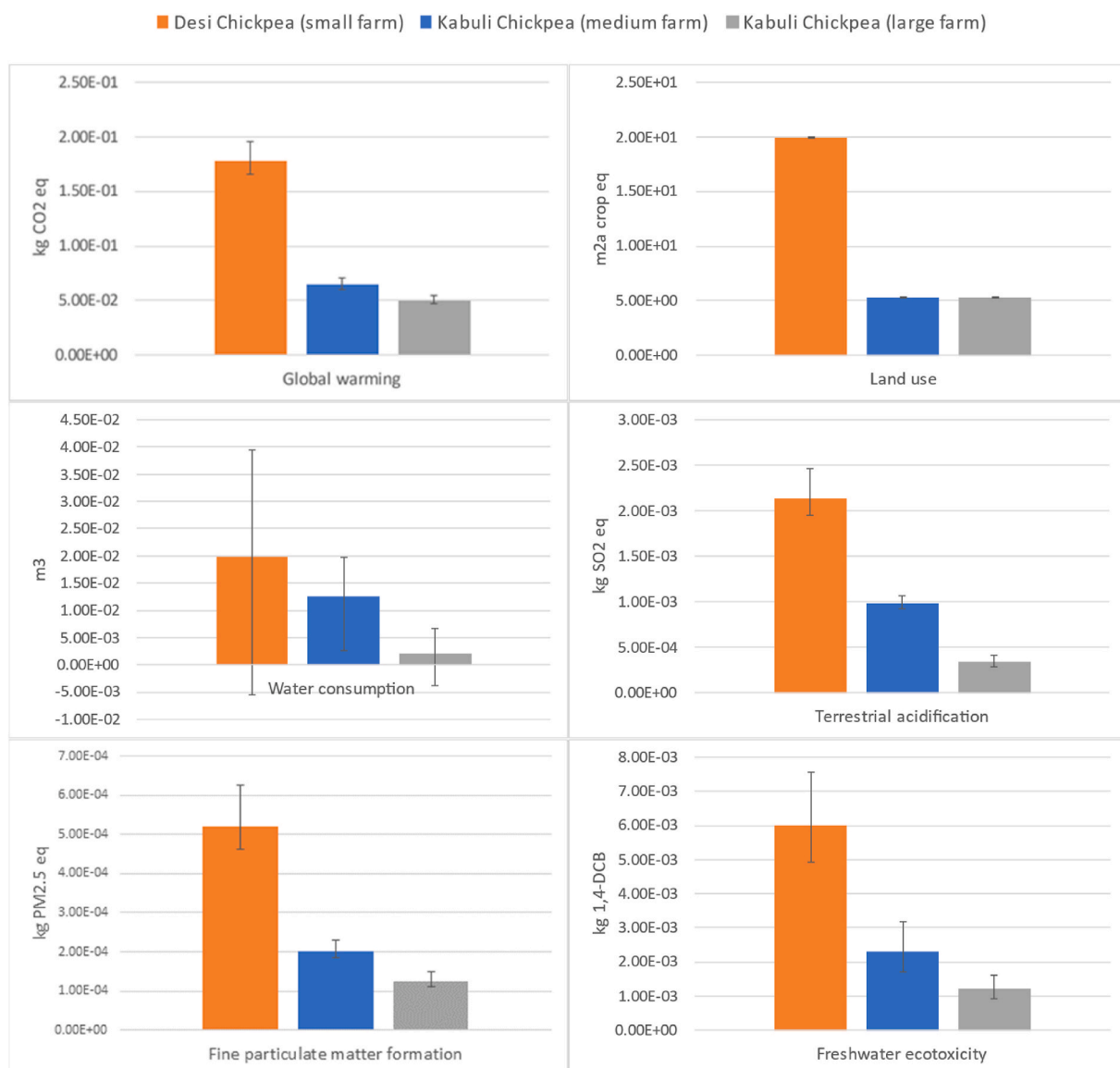


Fig. 2. Results of environmental impact assessment (8 impact categories, for 18 categories, please refer to Fig. 6 of the Supplementary Material file) and uncertainty analysis (10000 Monte Carlo runs) of 1 kg of chickpea at the farm gate. The first bar of each graph (orange) relates to Desi Chickpea production (small farm), the second (blue) to Kabuli Chickpea production (medium farm) and the third (grey) to Kabuli Chickpea production (large farm). Method: ReCiPe 2016 Midpoint (H) V1.07/World (2010) H, confidence interval: 95 %. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

chickpeas having a higher environmental cost compared to lentils (Nategh et al., 2021), demonstrating that Kabuli chickpeas, despite their variability based on farm size, generally offer a more sustainable alternative to Desi chickpeas.

Kabuli chickpeas (represented by blue and grey bars in Fig. 2) show lower Global Warming values than Desi chickpeas (represented by the orange bars), primarily due to their higher yields (which involve different agronomic practices and cultivation techniques), that reduce the emissions per kilogram of product. This aligns with findings from the literature that show that optimised farming systems and crop varieties (which is the case of Kabuli (Eker et al., 2022)) contribute to reduced emissions (Foteinis and Chatzisyneon, 2016). Conversely, Desi chickpeas, despite their resilience to low-water conditions (Nisa et al., 2020; Purushothaman et al., 2014), show higher values in this category due to low productivity.

Land use impacts are a critical concern for Desi chickpeas, where they have 4 times higher impact than the Kabuli. This might be a consequence of organic farming systems, where lower yields need larger cultivation areas. This finding supports previous studies indicating that organic agriculture, while beneficial in reducing synthetic inputs, often demands greater land resources (Foteinis and Chatzisyneon, 2016). Kabuli chickpeas, benefiting from improved agronomic practices, use land more efficiently. However, the environmental trade-offs of relying on high-yield varieties should be considered, as these can contribute to monocropping and biodiversity loss (Eker et al., 2022). Additionally, while Kabuli farming practices may currently appear more resource-efficient, the long-term impacts on soil quality and ecosystem services in intensive systems require further study.

Despite Desi chickpeas' reputation for drought tolerance (Nisa et al., 2020; Purushothaman et al., 2014), their water consumption impact is higher than that of Kabuli chickpeas. As both systems were not watered, being only rain-fed, this difference and high uncertainty values come from background data used to generate the models used in this study. Variations in genotype, local climate conditions, soil properties, and crop management practices could also contribute to this unexpected result (Farooq et al., 2018; Nisa et al., 2020).

Terrestrial acidification impacts are higher for Desi chickpeas, which could reflect the inefficient use of fertilisers use in lower-yield systems. Previous studies have shown that the application of nitrogen fertilizer at the beginning of the growth cycle reduced nitrogen fixation in Kabuli chickpeas, whereas nitrogen fixation in Desi chickpeas appeared to be less sensitive to inorganic nitrogen application (Walley et al., 2005), potentially reducing their need for fertilisers and terrestrial acidification impacts. However, since the Desi system did not use any fertiliser in the current study, the higher values observed are likely a result of the background data and assumptions used in the model. For Kabuli chickpeas, while they use fertilisers and herbicides (compost, algae and biostimulants) – which in theory should increase the impacts – the higher productivity mitigates these impacts by distributing the burden of emissions over larger yields. This result highlights the importance of optimizing fertiliser management practices to reduce acidification impacts across systems.

The fine particulate matter formation impacts, more than double for Desi chickpeas, in comparison with Kabuli, may be attributed to greater reliance on fuel-intensive mechanisation per unit of yield and dust emissions during soil preparation (more private transport, data not shown) (Nategh et al., 2021). Kabuli chickpeas, benefiting from higher efficiency in machinery usage, show reduced impacts in this category. This highlights the potential benefits of integrating cleaner energy sources, such as electric or biofuel-driven machinery, into agricultural operations to further mitigate particulate matter emissions (Noorani et al., 2023). This approach would be especially beneficial for underutilised crops, which often lack the technological advancements seen in major crops like cereals. Importantly, while the environmental impact of infrastructure, primarily machinery (Romero-Gómez et al., 2009) and human labour (Bossek et al., 2021; Rugani et al., 2012) plays a crucial

role in the overall sustainability of agricultural practices, it is important to note that these factors are not explicitly accounted for in the specific analysis presented in this study. The machinery utilised in chickpea cultivation, including its construction-related impacts, is shared across various fields, applications and years, making it challenging to attribute its environmental footprint exclusively to this chickpea production.

Similarly, while human labour is a significant component in specific farming scenarios (in this case, organic small-sized chickpea farms), its impact is not separately quantified in this analysis. While acknowledging the potential influence of these factors on the overall environmental profile, the current study recognises that these aspects are beyond the current scope and, therefore, focuses on key aspects directly related to chickpea cultivation and processing. Bossek et al. (2021) and Rugani et al. (2012) looked into the environmental impact of human labour over a lifetime and the associated challenges and considerations. The current study, however, prioritises the specific aspects of chickpea production and processing.

Similar to previous parameters, the production of Kabuli chickpeas demonstrates lower freshwater ecotoxicity (Fig. 2). This pattern further underscores the significant role of final yield in determining the overall environmental impact. Despite the use of fertilizers and biostimulants throughout the growth cycle, the high yield achieved helps mitigate the potential environmental damage associated with these inputs. In contrast, Desi chickpeas exhibit higher ecotoxicity impacts, likely due to a reliance on less refined farming practices and a greater dependence on traditional methods. Interestingly, these results challenge the findings of studies that link agrochemical runoff to freshwater contamination (Nordahl et al., 2020). In this case, the organic system—free from chemical inputs—demonstrates the highest environmental impact, suggesting that other factors, such as farming practices or crop characteristics, may play a more significant role in freshwater ecotoxicity than the use of agrochemicals alone.

In fact, land use impacts are a significant concern for Desi chickpeas, which exhibit a land use impact four times higher than Kabuli chickpeas (Fig. 2). This is likely due to the lower yields associated with Desi varieties, which require larger cultivation areas to produce the same amount of output. This finding aligns with previous studies suggesting that organic farming systems, while beneficial for reducing synthetic inputs, often necessitate more land to achieve comparable yields (Foteinis and Chatzisyneon, 2016). In contrast, Kabuli chickpeas benefit from improved agronomic practices, enabling more efficient land use. However, the environmental trade-offs of relying on high-yielding varieties should be considered, as these can encourage monocropping and lead to biodiversity loss (Eker et al., 2022). Additionally, while Kabuli farming practices may currently appear more resource-efficient, the long-term effects on soil health and ecosystem services in intensive farming systems warrant further investigation. Interestingly, despite Desi chickpeas' reputation for drought tolerance (Nisa et al., 2020; Medeiros et al., 2024), their water consumption impact is higher than that of Kabuli chickpeas (Fig. 2). Both systems were rain-fed and not irrigated, so this discrepancy, along with the high uncertainty values, is likely due to the assumptions and background data used to model water consumption in this study. Variations in genotype, local climate conditions, soil properties, and crop management practices could also contribute to this unexpected result (Farooq et al., 2018; Nisa et al., 2020). In addition, terrestrial acidification impacts were higher for Desi chickpeas (Fig. 2), which could reflect the inefficient use of fertilizers in low-yield systems. Previous studies have shown that the application of nitrogen fertilizer at the beginning of the growth cycle reduced nitrogen fixation in Kabuli chickpeas, whereas nitrogen fixation in Desi chickpeas appeared to be less sensitive to inorganic nitrogen application (Walley et al., 2005), potentially reducing their need for fertilizers and terrestrial acidification impacts. However, since the Desi system did not use any fertilizers in the current evaluation, the higher acidification impacts values observed for Desi are likely a result of the background data and assumptions used in the model. In addition, the higher productivity of

Kabuli chickpeas also contributes to mitigate the acidification impacts by distributing the emission burden across larger yields. This finding underscores the importance of optimizing fertilizer management practices to reduce acidification impacts across different systems.

The fine particulate matter (PM) formation impacts are more than double for Desi chickpeas compared to Kabuli, which could be due to greater reliance on fuel-intensive mechanization per unit of yield and dust emissions during soil preparation (Nategh et al., 2021). Kabuli chickpeas, benefiting from more efficient farming practices and machinery designed for higher productivity, result in reduced particulate matter emissions. The higher yield per hectare in Kabuli systems allows emissions from mechanized operations to be distributed across a larger quantity of produce, mitigating the per-unit environmental impact. This suggests that incorporating cleaner energy sources, such as electric or biofuel-powered machinery, into agricultural operations could further reduce particulate matter emissions (Noorani et al., 2023). This approach would be especially beneficial for underutilised crops, which often lack the technological advancements seen in major crops like cereals. Importantly, while the environmental impact of infrastructure, primarily machinery (Romero-Gómez et al., 2009) and human labour (Bossek et al., 2021; Rugani et al., 2012), are significant for the overall sustainability of agricultural practices, these factors are not explicitly

accounted for in this study.

Similar to previous parameters, the production of Kabuli chickpeas demonstrates lower freshwater ecotoxicity (Fig. 2). This pattern further underscores the significant role of final yield in determining the overall environmental impact. Despite the use of fertilizers and biostimulants throughout the growth cycle, the high yield achieved helps mitigate the potential environmental damage associated with these inputs. In contrast, Desi chickpeas exhibit higher ecotoxicity impacts, likely due to a reliance on less refined farming practices and a greater dependence on traditional methods. Interestingly, these results challenge the findings of studies that link agrochemical runoff to freshwater contamination (Nordahl et al., 2020). In this case, the organic system—free from chemical inputs—demonstrates the highest environmental impact, suggesting that other factors, such as farming practices or crop characteristics, may play a more significant role in freshwater ecotoxicity than the use of agrochemicals alone.

Overall, Kabuli chickpeas exhibit lower environmental impacts across most categories, highlighting the significance of optimizing cultivation systems, even for underutilised crops. For instance, while Desi chickpeas are currently less efficient, they may offer valuable contributions to enhancing resilience in agricultural systems in water-scarce regions (Medeiros et al., 2024). These findings emphasize the

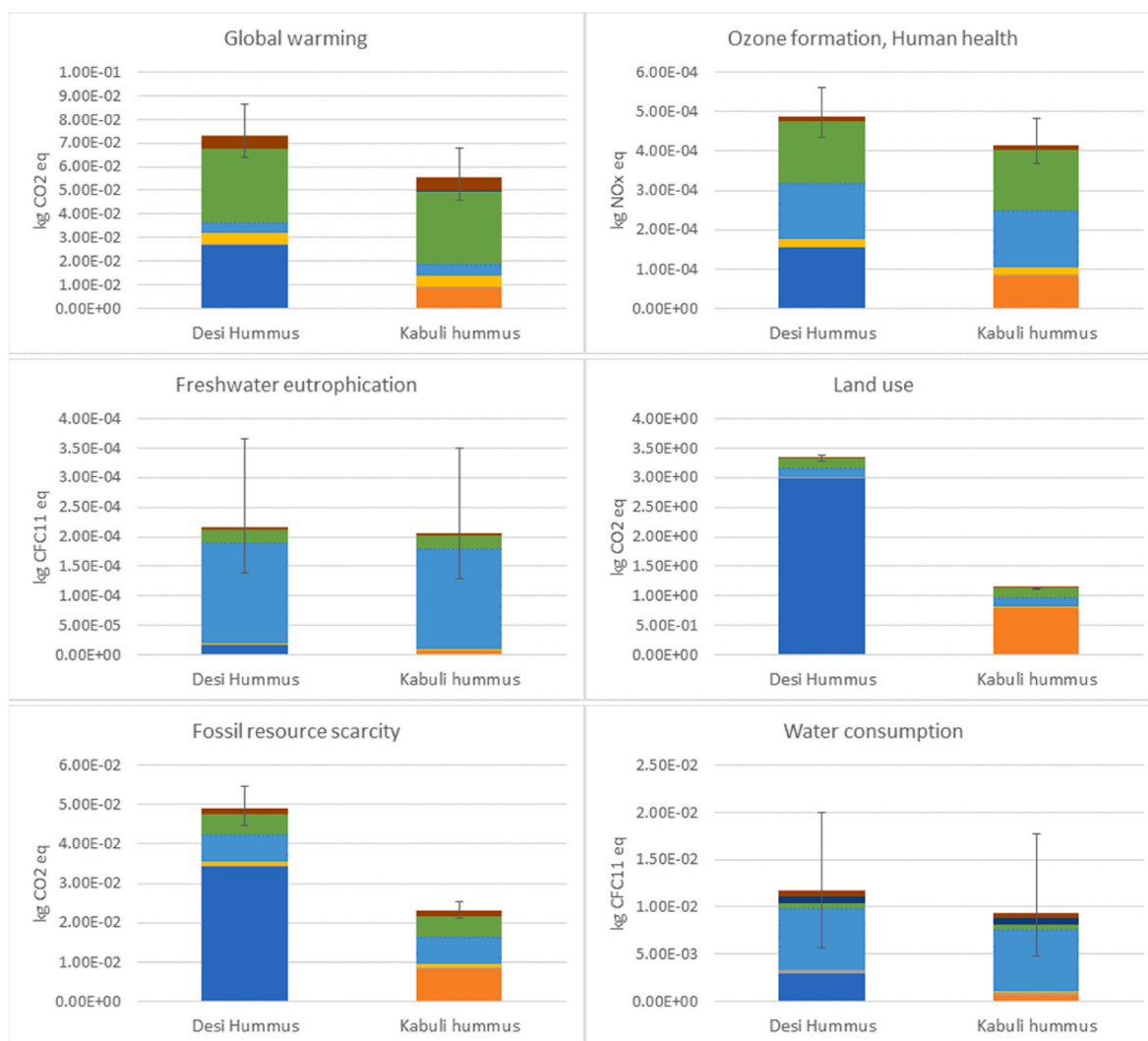


Fig. 3. Results of environmental impact assessment (6 impact categories, for 18 categories, please refer to Fig. 7 of the Supplementary Material file) and uncertainty analysis (10000 Monte Carlo runs) of 1 kg of unpacked hummus at the factory gate. The first bar of each graph relates to Desi hummus production and the second to Kabuli hummus production (Kabuli chickpea from the large farm). Background data from Agribalyse database. Method: ReCiPe 2016 Midpoint (H) V1.07/World (2010) H, confidence interval: 95 %.

need to carefully consider system-level trade-offs when assessing agricultural practices. Organic farming, although it reduces synthetic inputs and fosters soil health, can result in higher environmental impacts per unit of yield. Conversely, conventional farming systems, while offering higher productivity, may increase reliance on agrochemicals and more intensive farming practices, potentially exacerbating environmental concerns (Knapp and van der Heijden, 2018; Montgomery and Biklé, 2021). Thus, balancing productivity with environmental sustainability is key to developing more resilient and resource-efficient agricultural systems.

### 3.2. Environmental impacts of Desi and Kabuli Hummus

For the model of hummus production, data from the chickpea production model was used (for Desi chickpea data from the small organic farm and Kabuli chickpea data from the large conventional farm). The environmental impacts of the two production chains can be found in Fig. 3 (for complete data with 18 impact categories, please refer to Fig. 7 of the Supplementary Material file). When analysing the environmental impact of 1 kg of unpacked hummus at the factory gate (which is the functional unit in this case), it is possible to see that the environmental impact of Desi hummus (represented by the bar on the left in every graph) has a higher average impact in all impact categories – the difference between these two categories varies between 0.80 % (in the category of Ionising radiation) and 98.47 % (in the Land Use category). Once again, the uncertainty results are presented in the same figure; however, this time, the categories with the highest uncertainty are *Stratospheric ozone depletion*, *Freshwater eutrophication*, *Marine eutrophication*, and *Water consumption* (some data is not shown, so please refer to Fig. 7 of the Supplementary Material file). In this scenario, both products' uncertainty results are similar (except for *Human non-carcinogenic toxicity* and *Fossil fuel scarcity*).

These findings resonate with existing literature on plant-based food systems. Poore and Nemecek (2018), in their large-scale analysis of food systems, identified that plant-based products, such as legumes, generally have lower environmental impacts than animal-based foods. However, they also highlighted that within plant-based products, the choice of ingredients and cultivation methods greatly affects the overall environmental impact. This point is supported by the results of the previous section, which shows that optimised cultivation systems have a lower environmental impact. This supports the significant variations in environmental footprints between both products found in the current study, which can be due to differences in the cultivation methods or the production volume. Additional studies have corroborated these insights, demonstrating how different plant-based foods can vary in their impact on land use, greenhouse gas emissions, and resource consumption (Clark et al., 2019).

When looking at where the impacts originate from, most of the impact categories for Desi hummus come from olive oil. Its impact varies between 33 and 79 % of the following impact categories: *Stratospheric ozone depletion*, *Freshwater eutrophication*, *Terrestrial ecotoxicity*, *Freshwater ecotoxicity*, *Marine ecotoxicity*, *Human carcinogenic toxicity*, *Mineral resource scarcity*, and *Water consumption* (please refer to Fig. 7 of the Supplementary Material file). The same trend is seen for Kabuli hummus, where olive oil (represented in light blue in Fig. 3) is the main contributor to most impact categories (*Stratospheric ozone depletion*, *Freshwater eutrophication*, *Terrestrial ecotoxicity*, *Freshwater ecotoxicity*, *Marine ecotoxicity*, *Human carcinogenic toxicity*, *Human non-carcinogenic toxicity*, *Mineral resource scarcity* and *Water consumption*) (visible in Fig. 3 in the graphs of *Ozone Formation*, *Human health* and *Water consumption*), with the amount varying between 35 and 83 %. This observation aligns with Poore and Nemecek (2018) who demonstrate that olive oil has higher greenhouse gas emissions per kilogram than staple crops such as cereals, fruits, and vegetables. In terms of land use, olive groves require significant areas, and the yield per hectare is lower compared to other crops, resulting in greater land use impacts (Patsios

et al., 2021). However, in this case, Desi and Kabuli chickpea production lead by contributing 52 and 71 %, respectively, for the land use category (Fig. 3).

Another product that has a high environmental impact in varying categories is the sesame seeds (which represent the ingredient tahini), leading the impact of Desi Hummus in the categories of *Global warming* (42 %), *Ozone formation*, *Human health* (32 %), *Fine particulate matter formation* (36 %), *Terrestrial acidification* (40 %) and *Marine eutrophication* (57 %). In the case of Kabuli hummus, the categories are the same with 56 %, 37 %, 46 %, 49 % and 61 %, respectively, but there is an extra category, *Ozone formation, Terrestrial ecosystems*, where the impact is 34 %. This aligns with previous research on the environmental impact of sesame cultivation and tahini production, particularly in traditional systems (Noorani et al., 2023; Fereidani and Görkem Üçtuğ, 2024).

On the other hand, the lowest contribution comes from the water (<1 %) in all categories except *Human carcinogenic toxicity* and *Water consumption* (the lowest impacts for these categories are 1 % and 3 %, respectively, and both come from garlic production). For Kabuli hummus production, there is a similar tendency where the lowest impact comes from water for most of the categories, except for *Human carcinogenic toxicity* (the lowest impact is 1 % and comes from garlic) and *Water consumption* (the lowest impact is 4 % and comes from Kabuli chickpea). These low impacts are likely due to the minimal environmental footprint of garlic production, which typically requires fewer resources, such as water and energy, compared to other ingredients (Martínez-López et al., 2022). Because it is used in low quantities in hummus production, its contribution to the environmental impact of both Desi and Kabuli hummus remains relatively low.

### 3.3. Environmental impact of Desi and Kabuli hummus integrating a nutritional life cycle assessment (nLCA)

During an LCA study, the chosen FU must reflect the question that needs answering as best as possible. By changing the FU from 1 kg of unpacked product to an NDU, the results of the environmental impact also change, as seen in Fig. 4 (for complete data with 18 impact categories, please refer to Fig. 8 of the Supplementary Material file). This shows that, when considering a nutritional-related functional unit, the environmental impact of products generated with the underutilised crop (Desi chickpea) is, on average, lower (0.49–19.72 %) in the majority of the categories (except in the categories of *Global Warming*, *Fine Particle formation*, *Human Non-carcinogenic Toxicity*, *Land Use*, *Fossil Resource Scarcity* and *Water consumption* where there is an increase in the average impacts of 7.45 %, 3.11 %, 48.80 %, 82.11 %, 53.38 %, and 1.10 % respectively). The uncertainty results are presented in the same figure and the categories of *Stratospheric ozone depletion*, *Freshwater eutrophication*, *Marine eutrophication* and *Water consumption* have the highest values. The contribution of the inputs in this analysis follows the same description presented previously in chapter 3.2. Environmental Impacts of Desi and Kabuli Hummus, though the values for Desi hummus, in this case, have a lower environmental footprint due to the change of the functional unit (in 12 out of 18 categories to be precise, data not shown, please refer to Fig. 8 of the Supplementary Material file). This can be seen in some of the graphs presented in Fig. 4, though in others, it is clear that the environmental impact is still higher than the Kabuli hummus.

In the case of this study, both a mass and nutritional unit were beneficial. A nutritional unit emphasises the nutritional function of the food item (McLaren et al., 2021). This type of unit is important because the mass unit may not accurately represent what the consumer will consume later – the product will most likely go through transformations and processing before it can be eaten. In the case of chickpea, it cannot be consumed as is: it needs to be soaked and cooked if the intent is to consume the legume or further process it to obtain other products such as hummus or other alternatives (for example, protein balls (Saget et al., 2021) or pasta (Saget et al., 2020)). Besides this processing, other ingredients are added, which contain healthy oils, essential nutrients and



**Fig. 4.** Results of environmental impact assessment (6 impact categories, for 18 categories, please refer to Fig. 8 of the Supplementary Material file) and uncertainty analysis (10000 Monte Carlo runs) of 1 NDU kg of hummus at the factory gate. The first bar of each graph (orange) relates to Desi hummus production, and the second (blue) to Kabuli hummus production (Kabuli chickpea from the large farm). Background data from Agribalyse database. Method: ReCiPe 2016 Midpoint (H) V1.07/World (2010) H, confidence interval: 95 %. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

bioactive microconstituents (see Table 1 of (Reister et al., 2020)). Furthermore, it facilitates the achievement of recommended dietary fibre intake for sustainable and healthful living (Willett et al., 2019). Reister et al. (2020) and Wallace et al. (2016) show that the consumption of this type of product can lead to a decrease in the risk of type 2 diabetes, cardiovascular diseases and other health problems.

### 3.4. Integration of sustainable chemistry principles in the current study

Incorporating sustainable chemistry principles into the current study ensures a holistic understanding of the sustainability aspects related to chickpea cultivation and hummus production. According to the study of Fegade and Tremblay (2017), they refer to the importance of the separation between the terms “green” and “sustainable”, which tend to be used interchangeably. Green chemistry focuses on reducing toxicity, preventing pollution, and mitigating environmental impacts, with limited tolerance for risks or pollutants. In contrast, sustainable chemistry adopts a broader perspective, balancing environmental impacts with societal benefits, economic considerations, and political realities, tolerating risks when justified by broader societal or political acceptance.

The current study aligns with the principles of “sustainable” rather than “green”, as it allows for a more comprehensive framework which is

critical when talking about agricultural systems and food production chains, where trade-offs between environmental impacts, societal needs and economic efficiency are needed and inevitable. For example, the current study focuses on the possibility of implementing an underutilised crop in the current food system and their impacts. For a successful implementation there’s the need for the use of fertilisers and herbicides (as its common practice in the cultivation of the commercial counterpart (Knez et al., 2023)). This leads to the production of toxic products, but at the same time, higher yields - which balances the system. Besides this, the implementation of Desi variety there are health benefits associated with it, as well as environmental impacts (Jameel et al., 2024) - agricultural biodiversity, resilience to drought conditions, and others (Knez et al., 2024).

Besides this, the current study looks also at a product that can be made from chickpea: the hummus. This product is made from plant ingredients which tend to offer a lower environmental footprint than animal-based products or counterparts, as shown in several studies (Ferdouse et al., 2024; Silva and Smetana, 2022; Silva et al., 2023), while addressing dietary and nutritional needs of the society.

## 4. Conclusions

Understanding chickpea cultivation and hummus production of two

different chickpea types through a comprehensive environmental and nutritional lens has provided valuable insights into sustainable value chains. This study aimed to compare the environmental impacts and nutritional quality of an underutilised Desi type, underrepresented in production systems in the Global North, and the commercially dominant Kabuli chickpea type and their respective hummus products.

The results underline the importance of considering both environmental and nutritional dimensions in assessing the sustainability of food production and consumption. Environmental life cycle assessments revealed variations in the environmental footprints of Desi and Kabuli chickpea cultivation and hummus production, influenced by factors such as cultivation practices, farming methods, and processing techniques. Due to an upscaled and optimised process, the commercial variety (Kabuli-type) has a lower environmental impact when both the chickpeas and the resulting hummus products are compared on a weight basis. However, the analysis suggests that improving farming techniques and increasing scale could allow the underutilised Desi crop to achieve comparable environmental efficiency.

Furthermore, when analysing hummus products derived from Desi and Kabuli chickpeas, the integration of nutritional life cycle assessments provided insights into their nutritional profiles. While environmental impacts were a focal point, the nutritional quality assessment highlighted the importance of considering health outcomes in sustainability evaluations. Additionally, when analysing the LCA results with a nutritional functional unit, the Desi hummus has a lower environmental impact (1.67–19.04 % lower) in most categories analysed (10 out of 18). Besides this, these findings have implications for promoting sustainable and resilient food systems.

From a policy perspective, the current study provides valuable guidance into how regulatory frameworks and targeted incentives can support sustainable agriculture and food systems. Encouraging the cultivation of underutilised crops, such as Desi chickpea, offers a viable strategy to enhance biodiversity, improve soil health, and build resilience against climate change. To facilitate this transition, governments could introduce financial incentives such as subsidies, technical assistance and support for diversified cropping systems, investment in breeding programs for drought-resistant legumes, and support for local seed banks to preserve and promote underutilised species. Besides this, government support for market development could facilitate the adoption of these crops in regions with suitable agronomic conditions.

Beyond agricultural production, food labelling policies could be strengthened by integrating environmental (LCA or nLCA) and nutritional metrics (Nutri-Score) into consumer-facing tools. This study highlights the importance of holistically combining LCA and nLCA to evaluate food products. Policymakers could expand existing systems like Nutri-Score or implement eco-labelling schemes that account for carbon footprints, resource efficiency, and nutritional value. By mandating transparent labelling, consumers can make more sustainable dietary choices, incentivising the market to favour environmentally friendly products.

Additionally, research-driven policy interventions could play a critical role in encouraging sustainable farming practices. This study shows that optimised farming systems, such as those used in Kabuli chickpea production, can significantly lower environmental impacts. Governments and agricultural bodies could invest in knowledge-sharing platforms, precision agriculture technologies and fertiliser optimisation strategies to increase productivity while reducing environmental footprints. Furthermore, policies should address trade-offs between organic and conventional farming, supporting research into yield improvement strategies for organic agriculture to bridge the productivity gap.

Finally, integrating UCs into food systems also presents opportunities for enhancing circular economy practices. Policies incentivising value-added processing and the utilisation of agricultural by-products can reduce waste generation while improving the economic viability of sustainable farming. Furthermore, addressing the trade-offs associated with organic farming is vital. This study highlights the higher land use

and other environmental impacts of organic Desi chickpea production, suggesting that policies could support research into improving organic farming yields through crop breeding and optimising soil management practices.

By implementing these multi-level policy interventions, stakeholders across the food value chain can mitigate environmental pressures associated with monoculture farming and promote biodiversity in agricultural landscapes by advocating for crop diversification and utilising underutilised crops like Desi chickpeas. Moreover, informed decision-making by policymakers, producers, and consumers, informed by comprehensive environmental and nutritional factors assessments, is crucial for advancing food production and consumption sustainability.

While these findings are insightful, this study acknowledges variability in some categories due to differences in datasets, farming practices, and limited geographic scope. These limitations discussed in Chapter 5, should be addressed in future studies (Chapter 6. Future work) to provide a more holistic and complete view. Expanding research to the same or other legume- or plant-based products with varying agricultural practices will enrich the existing literature and scientists' understanding of different food systems, which may lead to new strategies for reducing the environmental impact of food production.

Lastly, including Nutri-Score analysis further enriched the assessment, facilitating a holistic evaluation of the sustainability and healthfulness of chickpea-based products. This article's holistic approach facilitates a comprehensive evaluation of the sustainability and health implications of the examined food items, providing valuable information for consumers, producers, and policymakers.

## 5. Limitations of the study

Our study primarily evaluates the environmental footprint associated with chickpea cultivation (two different types) and posterior hummus production, considering a "standard" LCA as well as an nLCA. The latter allowed us to understand if the different nutritional values of the two hummus types could influence their LCA outcomes. While this provides valuable insights into the environmental implications of these processes, it is important to acknowledge the inherent limitations of the LCA methodology. One significant limitation is the challenge of comparing different farming practices and scales. In this study, the Kabuli chickpeas were sourced from large conventional farms, whereas the Desi chickpeas were obtained from small organic farms. Ideally, comparisons should be made between chickpeas cultivated under similar farming conditions, such as Desi and Kabuli chickpeas both grown on either small organic farms or on large conventional farms. The current approach of comparing different farm types introduces variability that could influence the LCA outcomes, potentially leading to inconsistencies when assessing the environmental impacts of the two chickpea types. This limitation highlights the need for future research to consider more controlled comparisons to provide clearer insights.

Other factors, such as data availability, quality, system boundaries, and allocation methods, can influence the accuracy and reliability of the findings. Additionally, while this study includes an uncertainty analysis to evaluate the variability of results due to input data and model assumptions, a sensitivity analysis focusing on specific parameters—such as yield variation, farming practices, or alternative processing methods—could further strengthen the robustness of the conclusions. Incorporating such analyses in future research would provide deeper insights into how individual parameters influence environmental outcomes, enhancing the reliability of the results.

The scope of the study is predominantly environmental, not analysing potential economic or social benefits associated with chickpea cultivation and hummus production. Future research could delve deeper into these aspects to provide a more comprehensive understanding of the implications of adopting different chickpea types. The analysis is based on data collected from chickpea farms in a specific geographic region (Portugal). As agricultural practices, environmental conditions,

and resource availability vary across different regions, the findings of the study may not be directly applicable to other locations. Implementing similar practices in different geographic contexts could yield different outcomes, highlighting the need for region-specific analyses. The data utilised in the study, sourced from databases and on-site observations, may vary in accuracy and reliability. Discrepancies in data quality, methodologies, and specific parameters across different sources could introduce uncertainties and biases in the analysis. Caution should be exercised when interpreting and generalising the results to broader contexts. Lastly, the study focuses on specific stages of the chickpea cultivation and hummus production processes, from cradle to farm gate for chickpea cultivation and from cradle to factory gate for hummus production. Future research should address these boundary considerations to comprehensively assess the entire supply chain and its associated environmental impacts.

## 6. Future work

Future research should focus on refining existing data and developing scenarios that accurately reflect the diversity of chickpea cultivation practices across different geographical regions and agricultural systems. Collecting more primary data from a broader range of sources will contribute to developing more comprehensive and representative scenarios. In addition to environmental considerations, future research should assess the social and economic impacts not only of chickpea cultivation but also of other underutilised crops. Understanding the broader implications of agricultural activities and selecting particular types that are underutilised in local communities and economies is essential for developing holistic and inclusive sustainability strategies.

Consumer behaviour and preferences regarding underutilised types can provide valuable insights into market demand and consumer acceptance. Understanding factors influencing consumer food choices, such as taste preferences, nutritional awareness, and sustainability considerations, can inform product development strategies and marketing initiatives to promote sustainable food choices.

## CRediT authorship contribution statement

**Beatriz Q. Silva:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marta Nunes da Silva:** Writing – review & editing, Funding acquisition, Data curation. **Sergiy Smetana:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition. **Marta W. Vasconcelos:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2025.145706>.

## Data availability

Data available on supplementary material file.

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