Journal of Cleaner Production 477 (2024) 143826

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Nutritional value and environmental footprint of muffins made with green-lentil flour

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ARTICLE INFO

Handling Editor: Giovanni Baiocchi

Keywords:
Gluten-free
Health claims
Legumes
Life cycle assessment
Snack

ABSTRACT

The growing interest in environmentally friendly and protein-rich food choices has prompted the food industry to explore alternative protein sources. Lentils have garnered attention due to their versatile culinary applications and the range of health benefits associated with their nutritional composition. Furthermore, lentils offer an environmentally sustainable solution as they require fewer resources than animal protein sources. In this study, a new muffin recipe was developed, using high-polyphenol green lentil flour as a partial substitute for oatmeal flour. The main goal was to compare the lentil-based muffin's nutritional attributes with a muffin made exclusively from oatmeal flour, and to evaluate their environmental impact, using Life Cycle Assessment (LCA). Research on incorporating lentil flour into muffins, particularly considering its environmental impact is limited, highlighting the importance of this study. Regarding the results, compared with the oatmeal muffin, the lentil-based muffin exhibited improved nutritional properties, including a reduction in fat, an increase in protein, and fibre, and the presence of beneficial omega-3 fatty acids. The LCA revealed that the lentil-based muffin had a lower environmental impact across various categories than the oatmeal muffin. Overall, incorporating lentil flour into muffin recipes not only results in a gluten-free product but also enhances its overall nutritional profile and offers a sustainable alternative for environmentally conscious consumers. The study contributes to the expanding field of sustainable and nutritious food alternatives, providing valuable insights for both consumers and the food industry.

1. Introduction

Global demand for protein is rising due to a growing global population, increased affluence, and changing dietary habits [Henchion et al., 2017]. The food industry is exploring alternative protein formulations [Lima et al., 2022], leading to a shift in the market towards more sustainable, environmentally friendly and health-promoting products [Ziena and Ziena, 2022].

Legumes, belonging to the *Leguminosae* family, are emerging as promising alternative protein sources due to their high protein content and associated health and environmental benefits [Hughes et al., 2022; Kumar et al., 2022; Duarte et al., 2024]. These nutrient-dense foods [Ferreira et al., 2021a; Kumar et al., 2022] contain fibres, fatty acids, complex carbohydrates, B-group vitamins, and minerals [Maphosa and Jideani, 2017; Martín-Cabrejas, 2019a]. They are cholesterol-free, low in fat [Mullins and Arjmandi, 2021], and have a low glycaemic index [Kumar and Pandey, 2020], making them suitable for various dietary preferences and intolerances [Vasconcelos et al., 2020]. Further, they offer environmental advantages [Iannetta et al., 2021], such as reducing greenhouse gas emissions, enhancing soil quality, decreasing reliance on fossil energy in farming [Mus et al., 2016; Stagnari et al., 2017] and improving soil fertility through symbiotic relationships with nitrogen-fixing (N-fixing) bacteria in their roots [Liu et al., 2018; Kebede, 2021].

Recognizing their potential, the food industry is increasingly incorporating legumes into various products [Martín-Cabrejas, 2019b], including baked goods and snacks [Smith and Hardacre, 2011; Costantini et al., 2021; PC et al., 2021; Schmelter et al., 2021]. However,

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https://doi.org/10.1016/j.jclepro.2024.143826
Received 28 September 2023; Received in revised form 27 September 2024; Accepted 28 September 2024
Available online 29 September 2024

this incorporation presents challenges [Binou et al., 2022], including off-flavours and sensory issues, which can be addressed through careful formulation and processing techniques [Jeong and Chung, 2019; Geraldo et al., 2022; Trindler et al., 2022]. Sweet-baked products, like muffins, provide a unique sensory experience but are often high in calories, sugar, and fat, lacking fibre and protein [Heo et al., 2019]. Nonetheless, increasing health awareness has led to a demand for healthier options, including legumes-based ones [Jeong and Chung, 2019].

Lentils, consumed globally [Kaale et al., 2022] are associated with numerous health benefits, including positive effects on cardiovascular disease (CVD) and its risk factors [Bing et al., 2018; Mustafa et al., 2022]. They are a rich source of plant-based protein, containing all essential amino acids [Khazaei et al., 2019; Salaria et al., 2022]. Lentils are also a source of dietary fibre, promoting digestive health, blood glucose regulation, and reduced cholesterol levels [Anderson et al., 2009; Ferreira et al., 2021b]. Additionally, lentils are rich in various vitamins and minerals [Hall et al., 2017] including iron, important for red blood cell production [Gupta et al., 2015; Podder et al., 2017], folate, potassium, magnesium, and zinc, that support heart, bone and immune health [Martín-Cabrejas, 2019b; Benayad and Aboussaleh, 2021]. They also contain secondary metabolites such as phenolic compounds, particularly flavonoids [Ganesan and Xu, 2017; Bing et al., 2018], which may vary between lentil varieties, with the green ones tending to exhibit a higher content [Mirali et al., 2017]. Additionally, lentils are versatile and can be used in various dishes, even ground into flour or pureed for baked goods like bread, and cakes [Khazaei et al., 2019; Carboni et al., 2024]. Although there are a few studies that have included lentils in muffins [IA et al., 2019; Can Karaça and Gülhan, 2023], there is still a gap in research concerning the incorporation of lentil flour into this popular and widely consumed baked item, to explore their nutritional and sensory attributes, and especially their environmental impact, highlighting the importance of further studies. Given the widespread consumption of muffins, fortifying them with lentil flour could be a strategic approach to enhance their nutritional profile.

Oat flour, alongside lentil flour, offers a sustainable alternative to wheat in bakery products [Krochmal-Marczak et al., 2020; Siddiqui et al., 2022], reducing dependence on monoculture and promoting sustainable agriculture practices [Vilvert et al., 2021]. Oats are rich in carbohydrates, dietary fibre (including β-glucan), protein, lipids, phenolic compounds, vitamins and minerals [Paudel et al., 2021]. They thrive in various soil types [Gorash et al., 2017] and demand fewer nutrients (N, phosphorus (P), and potassium) than wheat or maize [Rasane et al., 2015]. Additionally, they are extensively cultivated within crop rotations and as winter cover crops, and therefore can be incorporated into no-tillage systems [Vilvert et al., 2021].

Considering these environmental issues, the Life Cycle Assessment (LCA) is an excellent tool for evaluating the environmental impacts (or "footprints") of products through their entire value chain, from raw materials to disposal [Detzel et al., 2022]. LCA's significance in the food industry has increased [Cucurachi et al., 2019; Saget et al., 2020] as consumers become more aware of their food choices' environmental effects. The life cycle of legume-based baked goods varies in environmental impact based on specific practices and technologies. LCA studies can identify opportunities to reduce environmental footprints but are currently lacking for lentil-based products.

The present study aimed to assess the impact of replacing oatmeal flour with lentil flour in a sweet baked product, particularly a muffin. The comparison focuses on a lentil-based muffin against one made solely from oat flour, rather than wheat flour. Oat flour is a nutritious and innovative alternative, as it enriches the nutritional value of baked goods while diversifying food options [Siddiqui et al., 2022]. The study involves a comparative analysis of nutritional characteristics and environmental impact, offering insights into sustainable baking choices.

2. Material and methods

2.1. Muffins preparation

Both lentil (LM) and oatmeal (OM) muffins (Fig. 1) were prepared using ingredients store-bought, except the green lentil Kermit, provided by University of Saskatchewan, Canada. Before finalizing the formulation, various percentages of lentil flour, namely 25 %, 50 %, and 100 %, mixed with oat flour were tested to determine the optimal composition. After internal evaluations, the formulation with 50 % lentil flour was selected, as it provided a better-balanced texture and flavour. The lentil-based formulation (Table 1) comprised, per 100 g of dry mix, 37.9 g oatmeal flour (Seara, Produtos Naturais, Lda, Portugal), 37.9 g lentil flour, 19.0 g xylitol (Iswari, Alma & Valor, Lda, Portugal), 2.9 g baking powder (composed of disodium diphosphate ($Na_2H_2P_2O_7$.), sodium hydrogen carbonate ($NaHCO_3$) and corn starch) (Royal Baking Powder®, Mondelēz International, Unipessoal, Lda, Portugal), 1.5 g baking soda or $NaHCO_3$ (Cimmarom®, Frutogal - Indústria e Comércio de Produtos Alimentares, Lda, Portugal) and 0.8 g powdered vanilla essence (Condi, Condi Alimentar S.A., Portugal). To each 100 g of mix, 5.7 mL of olive oil (Oliveira da Serra, SOVENA-Consumer Goods, S.A., Portugal) and 94.3 mL of water were added and mixed at 280 rpm for 5 min at room temperature (RT) (SAMMIC, BM-5E, Spain). For the OM (Table 1), per 100 g of dry mix, 69.3 g oatmeal flour, 22.4 g xylitol, 6.3 g baking powder, and 1.9 g powdered vanilla essence. This preparation was mixed, under the same conditions as LM, with 7.9 mL of olive oil and 92.1 mL of water. Both muffin batters were placed in silicon moulds and baked in a convection electric oven (Zanussi, FCZ061EBA2, Pordenone, Italia) at 180 °C for 15 min and 25 min, respectively. The composition of both lentil and oatmeal flours used in the muffin formulations is available in Table 4.

2.2. Water holding capacity (WHC) of lentil and oatmeal flour

The WHC of lentils, oatmeal, and a combination of lentils and oatmeal was assessed following [Aziah et al., 2012]. Briefly, 1 g of each sample was mixed with 10 mL of distilled water for 2 min and subsequently allowed to stand at RT for 30 min. The mixture was then centrifuged at 5000 g for 20 min. The resulting residues were weighed. Data, expressed as a percentage, are available in Supplementary Material (Table S1). Analysis was performed in triplicate for each sample.

2.3. Batters and muffin properties

The moisture content of LM and OM batters was analysed by drying using an MS-70 Moisture Analyzer (A&D Weighing LTD, Oxford, UK) until reaching a constant mass at 100 °C. Analyses were performed in triplicate.

A rotational rheometer (Bohlin Instruments, UK), coupled with a Peltier unit for temperature control, was utilized to conduct oscillatory

Fig. 1. Visual comparison between lentil (LM, A) and oatmeal (OM, B) muffins.

Table 1
Formulation of both lentil (LM) and oatmeal (OM) muffins, per 100 g of dry mix.

Ingredients	LM	OM
Oatmeal flour (g)	37.9	69.3
Lentil flour (g)	37.9	–
Xylitol (g)	19.0	22.4
Baking powder (g)	2.9	6.3
Baking soda (g)	1.5	–
Vanilla essence (g)	0.8	1.9
Olive oil (mL)	5.7	7.9
Water (mL)	94.3	92.1

tests to assess the viscoelastic properties of the batters. The assays were performed at 25 °C, with a 40 mm diameter and 4° angle cone-and-plate geometry probe, and a 1 mm gap. Frequency sweeps between 0.1 and 10 Hz were performed using a strain of 0.05 %, which was previously determined to be within the linear viscoelastic region (LVER). The samples were characterized and compared through the assessment of the elastic modulus (G'), viscous (G'') modulus, and complex viscosity (η^*). Analyses were performed in triplicate.

Bake loss, height, and specific volume of both LM and OM were assessed according to [Matos et al., 2014]. Bake loss was determined by subtracting the weight of the muffin before baking from its weight after baking and cooling for 1 h. Height measurements were taken from the highest point of the muffin to the bottom after the 1 h cooling period. Volume was determined using rapeseed displacement. The specific volume of each muffin was then calculated by dividing its volume by its weight. All analyses were performed in triplicate for each sample.

Data are available in Supplementary Material (Table S2 and Figure S1).

2.4. Muffin nutritional characterization

The nutritional composition of both muffins was defined in terms of macronutrients and some micronutrients. Energy and total carbohydrates were assessed following EU Regulation [R.E.N, 2011]. Crude fat was determined by acid digestion in 25 % hydrochloric acid, followed by a Soxhlet extraction with petroleum ether according to AACC 30–10.01 [AACC, 2000a]. Total sugar was measured by Munson and Walker technique (AOAC 945.66 [AOAC, 2020c]). Kjeldahl method (ISO, 2009) with an N-to-protein conversion factor of 6.25, was used to calculate total protein. AOAC 991.43 and AOAC 985.29 [AOAC, 2020e; d] enzymatic-gravimetric method was applied to determine the total dietary fibre [Lee et al., 2020; Prosky et al., 2020]. Essential fatty acids content was analysed using gas chromatography according to ISO 12, 966–1:2014; ISO, I: 12966-2:2017; ISO, I: 12966-3:2016. Sodium was assessed through Flame Atomic Absorption Spectrometry and moisture by drying the sample in an oven at 105 °C under atmospheric pressure according to AACC 40-71-01 [AACC, 2000b] and AOAC 925.09 [AOAC, 2020a], respectively. Ash content was analysed by heating the sample in a muffle at 550 °C (AOAC 935.39 [AOAC, 2020b]). Random replicates, accounting for 7 % of the analysis, were performed by a certified laboratory, which follows verified and certified protocols and frequently collaborates with the industry.

2.5. Microbiological analyses

Muffins were analysed for total aerobic mesophilic microorganisms, total coliform, *Bacillus cereus*, *Staphylococcus aureus*, *Listeria monocytogenes*, *Escherichia coli*, and Sulphate-reducing bacteria according to EU method ISO, I: 4833-1:2013, ISO, I: 21871:2006, 2006b, ISO, I: 4833:2006, 2006, ISO, I: 6888-2:2021, ISO, I: 11290-1:2017, 2017a, ISO, I: 16649-3:2015 and ISO, I: 15213-1:2023, respectively. Both muffins were individually vacuum-packaged in plastic vacuum bags with 105 μm thickness (Lacor Menaje Professional S.L., Spain) and stored at RT. Analyses were conducted on days 0, 3, and 5 of storage.

2.6. Environmental impact assessment

2.6.1. Goal, scope, and boundary definition

LCA screening compared the overall environmental impact of developing LM and OM. All the ingredients and preparation of products were recorded as inputs. The open-source software OpenLCA v1.10.2 (GreenDelta, 2020) was used for environmental footprint calculations, using Agrifootprint v3.0 [Durlinger et al., 2017] and Ecoinvent v3.7.1 [Wernet et al., 2016] international databases. End-of-life stages were excluded as assumed similar for both products. After observation of the importance of electricity sources for baking, the sensitivity of environmental footprints to different energy markets, from France and Portugal, was assessed.

2.6.2. Functional units

Two functional units (FUs) were used: 100 g of muffin and the Nutrient Density Unit (NDU), according to the formula below [Dooren, 2016].

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

where:

EFA is essential fatty acids amount in 100 g of product, expressed in g.

Protein is protein amount in 100 g of product, expressed in g.

Fibre is fibre amount in 100 g of product, expressed in g.

DV_{EFA} is the essential fatty acids recommended daily value intake, expressed in g = 12,4 g †

$DV_{protein}$ is the protein recommended daily value intake, expressed in g = 50 g*

DV_{fibre} is the fibre recommended daily value intake, expressed in g = 25 g*

S_i is the number of kcal in 100 g of product, expressed in kcal.

† Based on the Institute of Medicine's DRI of EFA.

*Based on the US Food and Drug Administration's recommendations.

2.6.3. Inventories

The main difference between LM and OM was the presence/absence of lentil flour. The ingredients and energy market inputs were extracted from Ecoinvent v3.7.1 and Agrifootprint v3.0 databases (Tables 2 and 3). Some ingredients were not available, so proxies were used: sugar instead of xylitol; chickpea flour instead of lentil flour.

2.6.4. Impact assessment

The environmental footprints were assessed across 13 environmental impact categories. For results interpretation, these were normalized by

Table 2
Inventory for 100 g of Oatmeal muffin (OM). [a] Xylitol was not available, so sugar was used in its place. [b] Portuguese electricity market was used in the sensitivity analysis.

Input/ process	Flow (from LCA database)	Unit	Amount
Oat flour	Oat flour, at industrial mill/FR U	g	69.3
Xylitol [a]	Sugar, white, processed in FR | Ambient | Paper | No preparation | at consumer/FR	g	22.4
Baking Powder	Baking powder, processed in FR | Ambient | Paper | No preparation | at consumer/FR	g	6.33
Vanilla essence	Vanilla	g	1.91
Olive oil	Olive oil, extra virgin, processed in FR | Ambient | PET | No preparation | at consumer/FR	mL	7.90
Water	Tap water	mL	92.1
Oven baking	Oven baking, industrial, 1 kg of oven-baked product, for cooking/FR U [b]	Kg	0.10

Table 3
Inventory for 100 g of Lentil muffin (LM). [a] Xylitol was not available, so sugar was used in its place. [b] Lentil flour was not available, so chickpea flour was used in its place. [c] Portuguese electricity market was used in the sensitivity analysis.

Input/process	Flow (from LCA database)	Unit	Amount
Oat flour	Oat flour, at industrial mill/FR U	g	37.9
Lentil flour [b]	Chickpea flour, processed in FR | Ambient | Paper | No preparation | at consumer/FR	g	37.9
Xylitol [a]	Sugar, white, processed in FR | Ambient | Paper | No preparation | at consumer/FR	g	19.0
Baking soda	Sodium bicarbonate, processed in FR | Ambient | Cardboard | No preparation | at consumer/FR	g	1.50
Baking Powder	Baking powder, processed in FR | Ambient | Paper | No preparation | at consumer/FR	g	2.90
Vanilla essence	Vanilla	g	0.80
Olive oil	Olive oil, extra virgin, processed in FR | Ambient | PET | No preparation | at consumer/FR	mL	5.70
Water	Tap water	mL	94.3
Oven baking	Oven baking, industrial, 1 kg of oven-baked product, for cooking/FR U [c]	Kg	0.10

Table 4
Nutritional composition of 100 g of lentil (LM) and oatmeal (OM) muffins, and oat and green lentil flours. DL-detection limit; NDU- Nutrient Density Unit. Each value of nutritional composition of muffins represents mean ± SD. Comparisons between LM and OM were done by t-student test, with 95 % confidence interval. Significant differences are indicated at * $p < 0.05$.

Nutritional composition	LM	OM		Oat flour	Green Lentil flour
Energy (kcal)	231 ± 10	275 ± 9	*	388	341
Total Fat (g)	5.10 ± 0.30	6.40 ± 0.30	*	7.60	1.06
Saturated Fatty Acids (g)	0.90 ± 0.10	1.10 ± 0.10	ns	1.30	0.15
Omega-3 (mg)	4.00 ± 0.20	<DL			
Omega-6 (mg)	1099 ± 55	1506 ± 75	ns		
Total Carbohydrates (g)	41.2 ± 0.9	51.4 ± 0.80	*	56.0	53.0
Digestible carbohydrates (g)	35.5 ± 2.2	46.4 ± 1.9	*		
Total Sugar (g)	1.10 ± 0.06	1.20 ± 0.06	ns	1.10	2.03
Protein (g)	8.10 ± 0.40	5.50 ± 0.30	*	14.0	24.6
Dietary fibre (g)	5.80 ± 1.90	5.00 ± 1.70	ns	10.0	10.7
Sodium (g)	0.51 ± 0.04	0.63 ± 0.04	ns		
Sodium chloride (NaCl) (g)	1.28 ± 0.06	1.58 ± 0.08	ns	0.01	0.02
Humidity (g)	43.6 ± 0.80	34.1 ± 0.60	*		
Ashes (g)	2.10 ± 0.10	2.60 ± 0.60	ns		
NDU	1.39 ± 0.31	1.05 ± 0.23	ns		

global person equivalents with the product environmental footprint (PEF) recommended factors to generate comparable normalized scores across impact categories (European Commission, 2018).

2.7. Statistical analysis

Data were analysed on GraphPad Prism (v.9.0.0, for Windows, GraphPad Software, San Diego, California, USA). Nutritional composition, specific volume, height, bake loss, and batter moisture data underwent t-student test analysis. The WHC data were subjected to a one-way analysis of variance (ANOVA). *P*-values of <0.05 were considered to be statistically significant.

3. Results

3.1. Nutritional and microbial analysis

Table 4 presents the nutritional composition of OM and LM. Note that, LM was made by partially replacing 50 % oat flour with lentil flour. LM contains a significantly lower energy intake, with a 19 % reduction (231 kcal/100 g) than OM (275 kcal/100 g) and has a significantly lower fat content (5.1 g/100 g). Additionally, LM had a higher content of omega-3 fatty acid (4.0 mg/100 g), while OM had a higher omega-6 content (1506 mg/100 g). In terms of total carbohydrates, LM had significantly fewer content than OM, though the total sugar content was similar with 1.1 g/100 g versus 1.2 g/100 g, respectively. Regarding protein content, LM contained a significantly higher protein (14 % of the product's total energy) than OM. Furthermore, LM had higher dietary fibre (5.8 g/100 g), although not statistically significant, compared to OM (5.0 g/100 g) and its sodium and sodium chloride (NaCl) contents were 19 % lower.

Microbial analysis showed no microorganisms in either muffin over a 5-day period.

3.2. Environmental impact

Table 5 presents environmental impact outcomes for both products across 13 categories using two functional units: 100 g of product and one NDU. The LM demonstrated a lower environmental burden in 9 out of 13 categories compared to OM when considering 100 g of product. Specifically, the LM showed a 34 % reduction in marine eutrophication, 22 % lower terrestrial eutrophication, 21 % lower freshwater eutrophication, 18 % lower climate change, and 15 % lower acidification (Table 5). While in ecotoxicity-freshwater, ionizing radiation, ozone depletion, and water use, the LM exhibited 19 %, 7 %, 8 %, and 15 % higher burdens (Table 5). The difference in nutritional composition between muffins resulted in different NDU values, with the LM having a higher NDU (Table 5) and thus a lower environmental burden across all the categories compared to the OM when NDU was considered (Table 5). For instance, LM had a 37 %–50 % lower environmental burden than OM in marine, terrestrial and freshwater eutrophication, climate change, and acidification categories (Table 5).

Fig. 2 displays environmental burdens per 100 g of product or NDU

Table 5
Summary of impact categories for the oatmeal (OM) and lentil (LM) muffins expressed per 100 g of product and NDU.

Impact categories	Unit	Impact per 100g		Impact per NDU	
		OM	LM	OM	LM
Acidification	(mol H^+ eq)	1.75e-003	1.48e-003	1.67e-003	1.06e-003
Climate change	g CO_2 eq	146	120	139	86.4
Ecotoxicity freshwater	CTUe	4.09	4.88	3.89	3.51
Freshwater eutrophication	g P eq	8.21e-002	6.50e-002	7.82e-002	4.68e-002
Marine eutrophication	g N eq	5.23	3.44	4.98	2.47
Terrestrial Eutrophication	mol N eq	7.09e-003	5.52e-003	6.75e-003	3.97e-003
Ionizing radiation	kBq U-235 eq	9.27e-002	9.91e-002	8.83e-002	7.13e-002
Land use	Pt	21.0	20.0	20.0	14.4
Particulate matter	disease inc	1.29e-008	1.05e-008	1.23e-008	7.58e-009
Ozone depletion	kg CFC11 eq	2.04e-008	2.20e-008	1.95e-008	1.58e-008
Resource use. fossils	MJ	3.07	2.79	2.93	2.00
Resource use. minerals and metals	g Sb eq	3.07e-004	2.96e-004	2.92e-004	2.13e-004
Water use	m^3 depriv	0.131	0.150	0.124	0.108

normalized per person equivalents across 13 categories. Normalized scores exhibited a similar pattern as Table 5. In terms of 100 g of product, the LM displayed a lower environmental score than the OM for most categories. When normalized per NDU, the LM had lower environmental scores in all categories (Fig. 2). Both muffins made a relatively higher contribution to marine and freshwater eutrophication, and ecotoxicity freshwater, while their contribution to ozone depletion was relatively lower (Fig. 2).

Fig. 3 illustrates ingredients and process contributions across the 13 environmental impact categories. In both muffins, the main contributors were oat and lentil flour. In LM, lentil flour accounted for 28 %, 24 %, 29 %, 16 %, 24 %, 42 %, and 35 % of the total burdens for climate change, acidification, freshwater, marine, and terrestrial eutrophication, land use, and water use, respectively, while oat flour contributed 38 %, 46 %, 53 %, 78 %, 51 %, 45 % and 21 %. For OM, oat flour contributed 58 %, 71 %, 81 %, 93 %, 73 %, 79 %, and 43 % in the respective categories. In both products, the primary cause of climate change was the emission to air of nitrous oxide (N_2O) and carbon dioxide during oat cultivation. Acidification and terrestrial eutrophication were mainly attributed to ammonia (NH_3) and nitrogen oxide (NO_x) emissions during oat production, while marine eutrophication was linked to nitrate (NO_3^-) water losses. P and phosphate release into water during oat production were the main drivers of freshwater eutrophication. Oven operation had a higher burden on ionizing radiation, ozone depletion, and fossil resource use due to electricity generation (Fig. 3).

Table 6 summarizes the environmental impact of OM and LM across 13 categories, considering an energy change source from France to Portugal. Both muffins had higher environmental burdens in 10 categories with Portuguese energy, while only three categories (ionizing radiation, ozone depletion, and fossil resource use) showed a lower burden (Table 6). Terrestrial eutrophication exhibited the largest relative increase, while ionizing radiation showed the largest decrease (Table 6).

4. Discussion

4.1. Nutritional analysis

Conventional muffins typically contain ingredients like refined wheat flour, sugar, vegetable oil, eggs, and flavourings, that significantly contribute to their structure, appearance, and sensory experience [Ureta et al., 2014]. However, they are often associated with poor nutritional value and high fat and sugar content. Studies attempting to partially replace wheat flour with alternative ingredients reported fat percentages ranging from 14 to 22 %, carbohydrates between 54 and 57 % and fibre between 1 and 7 % [Mrabet et al., 2016; Heo et al., 2019]. Upon observing the nutritional profile of both developed muffins, it is evident that they offer advantages over conventional ones, particularly in fat percentage (Table 4). Both muffins were prepared with two underutilized crops, oats and lentils, instead of wheat, enhancing nutritional value due to richness in fibre, vitamins, minerals, *etc*. Understanding the proximate composition of the muffins is crucial for evaluating their overall health impact and assessing their suitability as an alternative food option. Furthermore, it is widely recognized that food systems are often highly dependent on a limited number of staple crops, like wheat, rice, and corn [Ali and Bhattacharjee, 2023], presenting risks to food security and sustainability. To address this issue, there is a growing recognition of the importance of diversifying food production systems and promoting the cultivation and consumption of a wider range of crops and food products [Ali and Bhattacharjee, 2023].

Comparing both muffins, LM had 25 % lower total fat content than OM (Table 4). It's noteworthy that the OM formulation required a

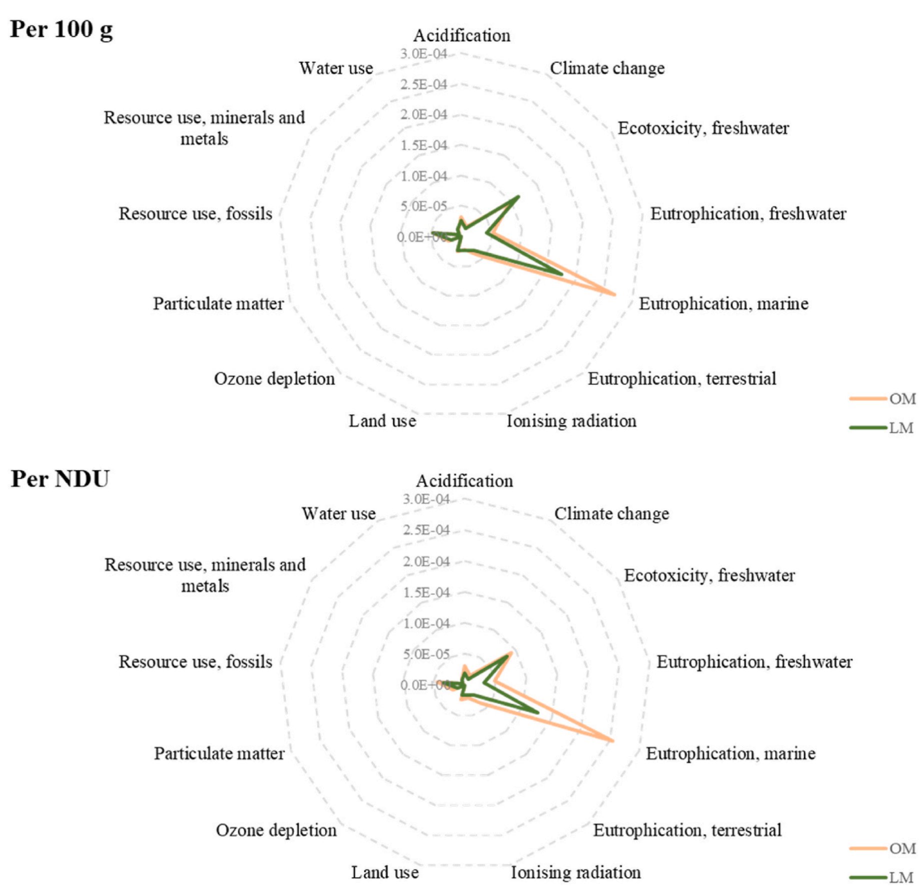

Fig. 2. Normalized environmental scores across 13 impact categories for the oatmeal (OM) and lentil (LM) muffins expressed per 100 g of product and NDU.

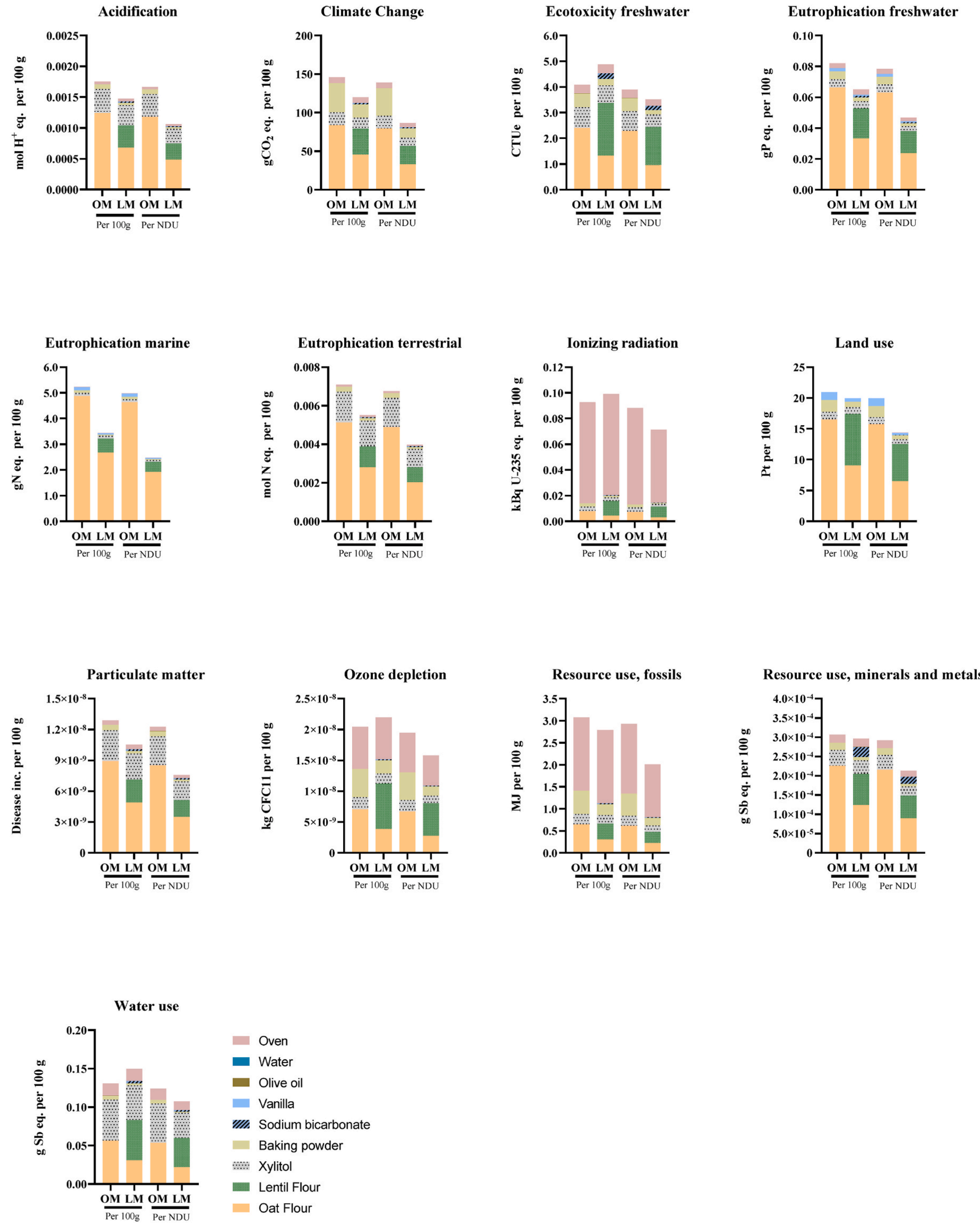

Fig. 3. Process and ingredients contributions across 13 impact categories for oatmeal (OM) and lentil (LM) muffins, expressed per 100 g of product or NDU.

slightly higher amount of olive oil, offering a potential justification for this observed change in fat content. Besides, oat flour inherently contains a higher percentage of fat compared to lentil flour (Table 4). According to European regulations (1924/2006), low-fat foods must have less than 3 g of fat per 100 g, while high-fat contain 13 g or more per 100 g of product [Samuel et al., 2014]. In this context, and although neither formulations qualifies as low-fat, they both contain a moderate fat amount.

The addition of lentil flour increased protein content by 47 %, fibre by 16 %, and omega-3 (below DL in OM) compared to OM. This rise in protein content could be attributed to the higher protein content present in lentil flour compared to oat flour (Table 4). According to European standards (1924/2006), LM, unlike the OM, qualifies as a protein source, providing 14 % of the product's total energy value, surpassing the established value of 12 %. Legumes are an affordable source of protein that can contribute to eradicating hunger and malnutrition [Ferreira et al., 2021a]. They are commonly used to supplement product formulations to enhance their protein and fibre content [Binou et al., 2022; Gallo et al., 2022]. However, it is important to note that lentil flour supplementation affects not only protein content but also protein

Table 6
Sensitivity analysis of the change in the energy market from France to Portugal by impact category in oatmeal (OM) and lentil (LM) muffins per 100 g and NDU.

Impact categories	Unit	OM			LM		
		%	100 g	NDU	%	100 g	NDU
Acidification	mol H^+ eq	(+24 %)	2.18e-003	2.07e-003	(+29 %)	1.90e-003	1.37e-003
Climate change	g CO2 eq	(+29 %)	188	179	(+35 %)	163	117
Ecotoxicity freshwater	CTUe	(+11 %)	4.55	4.34	(+10 %)	5.34	3.85
Freshwater eutrophication	g P eq	(+23 %)	1.01e-001	9.62e-002	(+29 %)	8.38e-002	6.03e-002
Marine eutrophication	g N eq	(+1 %)	5.29	5.03	(+2 %)	3.49	2.51
Terrestrial Eutrophication	mol N eq	(+88 %)	7.68e-003	7.32e-003	(+11 %)	6.11e-003	4.39e-003
Ionizing radiation	kBq U^{-235} eq	(-79 %)	1.90e-002	1.81e-002	(-74 %)	2.54e-002	1.82e-002
Land use	Pt	(+1 %)	21.2	20.2	(+1 %)	20.2	14.5
Particulate matter	disease inc	(+5 %)	1.36e-008	1.29e-008	(+6 %)	1.12e-008	8.05e-009
Ozone depletion	kg CFC_{11} eq	(-23 %)	1.57e-008	1.5e-008	(-21 %)	1.73e-008	1.24e-008
Resource use. fossils	MJ	(-34 %)	2.03	1.93	(-37 %)	1.74	1.25
Resource use. minerals and metals	g Sb eq	(+3 %)	3.16e-004	3.01e-004	(+3 %)	3.05e-004	2.20e-004
Water use	m^3 depriv	(+11 %)	0.145	0.138	(+9 %)	0.164	0.118

digestibility and structural properties [Gallo et al., 2022]. This finding is significant as the current consumption of animal-source protein in European countries remains twice the global average, highlighting the need for alternative lower-impact protein sources [Ferreira et al., 2021a; Dietz and Pryor, 2022].

LM can also be regarded as a high-fibre food according to EU standards (at least 6 g of fibre per 100 g of product) (1924/2006). Increased fibre intake may contribute to reducing cardiovascular risk factors, including body weight, blood pressure, and total cholesterol [Hemler and Hu, 2019], and prevention of type 2 diabetes [Hemler and Hu, 2019; Dietz and Pryor, 2022]. Another advantage of LM is the presence of the omega-3 fatty acid (alpha-linolenic acid) which plays a role in nervous system function and has anti-atherogenic properties, lowering blood pressure and heart rate, thus improving cardiovascular health [Di Pasquale, 2009].

Both LM and OM can be classified as low in sugar content (1924/2006), containing less than 5 g of sugar per 100 g. Excessive sugar consumption is usually associated with increased CVD risk, possibly through lowering high-density lipoprotein cholesterol and increasing plasma triglycerides and blood pressure [Yu et al., 2018]. To mitigate the risks associated with high sugar intake, both muffins were prepared replacing refined white sugar with sugar alcohol xylitol. This sweetener possesses anti-plaque effects, prevents dental cavities, and reduces gingival inflammation [Gasmi Benahmed et al., 2020]. Additionally, xylitol can reduce the risk of CVD, diabetes, and obesity as it contains fewer calories than refined white sugar and a low glycaemic index, thus not raising blood glucose levels [Gasmi Benahmed et al., 2020; Arruda et al., 2022]. However, excessive xylitol consumption may lead to side effects like irritable bowel syndrome, diarrhoea, *etc* [Gasmi Benahmed et al., 2020]. Concerning sodium content, neither muffin can be considered “low sodium” (requires less than 0.12 g per 100 g). Nevertheless, the use of lentil flour, rich in minerals, has the potential to reduce sodium content without compromising sensory properties. It is worth mentioning that salt is commonly added to many foods, especially baked products, to improve flavour and texture, leading to “hidden-salt” consumption [Ayed et al., 2021]. Given these characteristics, lentil flour makes the muffins appealing to hypertensive consumers and health-conscious individuals. The developed formulations can be classified as functional foods, offering health benefits beyond basic nutrition. Additionally, LM complies with three nutritional claims: source of protein, high in fibre, and low in sugar content.

Both muffins remained free of detected microorganisms over five days, indicating their microbiologically safety for human consumption under anaerobic, RT storage conditions, and that the handling and cooking process were sufficient for controlling microorganism contamination. *Bacillus* spp., typically present in raw ingredients like flour, sugar, and yeast, can cause bacterial spoilage in baked products but showed no growth during the analysis period. They can survive to baking process and germinate under both aerobic and anaerobic conditions [Miñarro et al., 2012]. Although no growth was observed, further research could assess longer-term growth potential.

To provide a more comprehensive understanding of the flours used and muffin properties, WHC of the flours, the specific volume, height, and bake loss, of both muffins and moisture and rheology batter analyses were conducted (Tables S1 and S2; Fig. S1). Assessing the WHC of the flours is relevant as they can affect the sensory experience, particularly texture, and overall quality. Interestingly, while lentil flour exhibited a higher WHC, the combination of oat and lentil (utilized in LM muffin) did not significantly differ from oat flour alone (Table S1). The rheological analysis revealed consistent behaviour between OM and LM batters, indicating similar viscoelastic properties, namely a solid-like behaviour (G’ > G’’). Both batters showed an increase in stiffness or solidity (expressed by the increase of the elastic modulus) with higher frequencies, along with an increase in resistance to flow (expressed by the increase of the elastic modulus). Additionally, both samples exhibited a decrease in complex viscosity. Notably, most parameters showed no significant differences between the muffins, except for bake loss, in which OM was significantly higher, indicating a potentially lower capacity to retain moisture during baking.

4.2. Environmental impact assessment

Considering the LCA analysis, LM had a smaller environmental footprint than OM in most of categories (9 out of 13) per 100 g of product. It is important to note, that lentil flour was not included in the databases used and therefore, chickpea flour was used as an alternative. Chickpeas belong to the same family as lentils and share similarities in their production when compared to other crops, namely in environmental aspects. However, it’s crucial to highlight that, in terms of mechanization, chickpea production involves more automated processes, while lentil production relies more on manual labour [Aghili Nategh et al., 2021]. Although traditionally lentil production is considered more sustainable than chickpea production, the difference between them is not expected to result in a significant discrepancy as observed between legumes and oats. Major differences between legumes are anticipated in the final consumer stage which was not assessed [Bandekar et al., 2022]. The LM had a higher protein and fibre content, resulting in a higher NDU. This functional unit is an effective way to differentiate products based on their nutritional value and unlike more complex units, it only requires energy, essential fatty acids, protein, and fibre content [Saget et al., 2020]. The difference in the NDU led to a reversal in higher burdens for LM (ecotoxicity-freshwater, ionizing radiation, ozone depletion and water use) relative to OM. As a result, the overall environmental impact of LM became lower in all categories. The proximate composition of the muffins played a crucial role in determining the NDU, highlighting the importance of understanding the nutritional content of food products for assessing their environmental impact. Both muffins contributed highly to marine and freshwater eutrophication primarily due to oat production, mainly attributed to fertilizers use. Nitrogen and P inputs from fertilisers can be carried off by rainwater or irrigation into nearby water bodies, leading to eutrophication [Schindler, 2006; Jwaideh et al., 2022]. In this study, the release of NO_3^- to groundwater was identified as a potential driver of environmental impact in marine eutrophication, whilst the main cause for freshwater eutrophication was the loss of P from soils into rivers. The contribution of lentil production to marine and freshwater eutrophication had a relatively lower impact, as legumes can fix N from the air, reducing the need for synthetic fertilizers [Reckling et al., 2016; Kebede, 2021]. Consequently, the risk of nutrient runoff and subsequent marine and freshwater eutrophication is generally lower for lentil production compared to other crops. Oat production was also the key reason for acidification due to emissions of acidifying substances, such as sulphur dioxide (SO_2) and NO_x, from fossil fuels combustions during activities like field preparation, irrigation, and harvesting [Murphy et al., 2014; Motevali et al., 2023], as well as ammonia (NH_3) emissions form application of N fertilizers. In the case of muffin production, it was the release of NH_3 and N during oat production that contributed to acidification. Terrestrial eutrophication can occur from the use of N and P fertilizers [Clark et al., 2017] during oat cultivation, as well as the combustion of fossil fuels. In fact, the main reasons for this impact were found to be the same as for acidification. The higher environmental impact of oat production in terms of acidification and terrestrial eutrophication compared to lentils is due to their greater reliance on N fertilizers [Allwood et al., 2021]. N fertilizers contributed to acidification by converting NH_3 emissions into nitric acid, leading to a decrease in soil and water pH [Kunhikrishnan et al., 2016; Schmidt Rivera et al., 2017]. They also contribute to eutrophication when unused by plants and instead leach into the soil [Khan and Mohammad, 2014]. Furthermore, N fertilizers release N_2O, a potent greenhouse gas that contributes to ozone depletion burden from production [Rahman and Forrestal, 2021]. It is worth noting that both lentils and oats have relatively low environmental impacts compared to many other food products, including animal-based products.

Regarding the shift from French to Portuguese electricity sources, there is a clear increase in environmental burden in most categories, particularly in terrestrial eutrophication. However, Portuguese electricity results in a smaller ionizing radiation as well as fossil fuel usage. Data from Eurostat Statistics Explain [Energy statistics, 2022], showed that France primarily relies on nuclear power generation, while Portugal depends on a mix of oil/petroleum fuels, renewables and biofuels for power generation. These findings highlight the importance of electricity sources in the footprint of baked products.

5. Limitations of the study

Despite the promising insights of the study, some limitations need to be considered. The first concerns the simultaneous alteration of more than one ingredient in the muffin formulations. This approach makes it challenging to attribute specific nutritional effects to individual ingredient changes. A more controlled experimental design, altering one ingredient at a time, could provide clearer insights into the impact of each modification. These formulations were designed to produce more acceptable products overall.

Additionally, sensory analyses and several quality parameters were not assessed in this study, including colour, texture, porosity and density. These attributes provide a more comprehensive evaluation of the overall quality and consumer acceptance of the muffins. Future research should incorporate these factors to offer a more complete assessment of the product.

In the LCA, lentil flour and xylitol were not included in the databases used, so similar ingredients, such as chickpea flour and sugar, were employed. While chickpeas belong to the same family as lentils and share similarities, their production methods may differ (more automated for chickpeas vs. more manual labour for lentils), potentially leading to different environmental impacts. Although this difference is not expected to be significant, it remains a consideration. The alteration of xylitol with sugar was applied to both muffin types, so the difference in LCA results remains the same. However, the specific impacts of xylitol and sugar may vary, and future studies should consider this impact.

6. Conclusion

This work evaluated the nutritional and environmental aspects of LM compared to OM. The LM showed superior nutrition, including higher protein, fibre, and omega-3 content, thus qualifying as a source of protein and high in fibre. These findings offer opportunities to promote alternative protein sources with lower environmental impacts. The environmental impact assessment using LCA demonstrated that the LM exhibited a smaller environmental footprint compared to the OM in most categories. It is noteworthy that oat production significantly contributed to marine and freshwater eutrophication, primarily due to the use of fertilizers. In contrast, lentil production had relatively low contributions to eutrophication, reflecting the legume's reduced need for synthetic fertilizers.

This work highlights the potential of using legume-based ingredients in the development of not only healthier but also eco-friendly products. Further research and consumer education are vital to improve acceptance and awareness of these foods, emphasizing nutrition, sensory appeal, and positive environmental contributions.

CRediT authorship contribution statement

Rafaela Geraldo: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Carla S. Santos:** Writing – review & editing, Methodology. **David Styles:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Sérgio Sousa:** Validation, Supervision, Methodology, Investigation. **Elisabete Pinto:** Supervision, Formal analysis. **Delminda Neves:** Writing – review & editing, Supervision. **Marta W. Vasconcelos:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, 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.

Data availability

Data will be made available on request.

Acknowledgements

This research was supported by the European Union's Horizon 2020 Research and Innovation Programme through projects "Realising Dynamic Value Chains for Underutilized Crops" (RADIANT) - Grant Agreement #10100062, "Intelligent Collections of Food Legumes Genetic Resources for European Agrofood Systems" (INCREASE) - Grant Agreement #862862, and by the Fundação para a Ciência e Tecnologia (FCT, Portugal) through PhD scholarship 10.54499/2021.05683. BD and through 10.54499/2022.01903.CEECIND/CP1745/CT0002. The authors would also like to thank the scientific collaboration under the FCT project UIDB/50016/2020.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.jclepro.2024.143826.

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