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# Identifying the environmental hotspots of dietary fibres extraction from chickpea hull

Ricardo Rebolledo-Leiva<sup>a,\*</sup>, Leyre Sillero<sup>b</sup>, Maria Teresa Moreira<sup>a</sup>, Sara González-García<sup>a</sup>

<sup>a</sup> CRETUS. Department of Chemical Engineering, School of Engineering. University of Santiago de Compostela, Santiago de Compostela 15782, Spain

<sup>b</sup> Chemical and Environmental Engineering Department, University of the Basque Country, Plaza Europa, 1, 20018 Donostia-San Sebastian, Spain

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## ABSTRACT

Pursuing new sources for food production in a context of demographic growth requires achieving a sustainable production model to face the current climate crisis. The biorefinery concept emerges as a technological scheme for the integral processing of renewable resources such as food waste obtained from the processing industry. This research aims to evaluate the potential environmental impacts of the valorisation route of chickpea peel to produce dietary fibre. Coupling process modelling with life cycle assessment approaches allows designing the potential biorefinery platform and identifying factors that may restrict its application in large-scale production. Global warming, particulate matter, eutrophication and ecotoxicity-related, fossil scarcity, among others, were the impact categories analysed with a cradle-to-gate approach. Results showed, for instance, that one kilogram of dietary fibre product emits 7.62 kg CO<sub>2</sub> eq, 14.08 g PM<sub>2.5</sub> and 4.37 g of P eq. Furthermore, alkaline digestion and bleaching were the most impactful stages in the categories analysed, due to the use of potassium hydroxide and sodium chlorite, respectively. This research contributes to rethink chickpea hulls from the food industry as a by-product towards high value-added products with applicability in the same industry.

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## 1. Introduction

The anthropogenic greenhouse gas (GHG) emissions have led to one of the major threats to our planet, and consequently, to human health and safety: the climate change crisis. The Intergovernmental Panel on Climate Change (IPCC) reported that food production systems contribute about 21–37% of total GHG emissions (Masino et al., 2023). In 2019, the EAT-Lancet report suggested healthy and nutritious diets rich in

grains, fruits, vegetables, nuts, and legumes, where meat and dairy have a significantly lower role (Willett et al., 2019). In this regard, moving from an animal to a plant-based diet is considered a sustainable strategy (Sabaté and Soret, 2014; Springmann et al., 2018), which has motivated the population to opt for a vegan diet and, consequently, has encouraged the food market to increase the supply of plant-based products (Kaur and Prasad, 2021).

Legumes are a relevant source of proteins and amino acids both for human and animal consumption, as well as an excellent reservoir of dietary fibre and complex carbohydrates (Kumar and Pandey, 2020). In addition, they lead benefits in soil fertility and nutrient management in agricultural systems due to their nitrogen fixation ability, that

\* Corresponding author.

E-mail address:

[ricardo.rebolledo.leiva@usc.es](mailto:ricardo.rebolledo.leiva@usc.es) (R. Rebolledo-Leiva).

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reduce the environmental load, for example, when introduced in rotation systems with cereals (Almeida-García et al., 2022; Rebolledo-Leiva et al., 2022a, 2022b).

Chickpea is a drought-resistant legume crop that can grow in areas withdrawn of rainfall, which is a rich source of carbohydrates, protein, and dietary fibre along with micro-nutrients (Kaur and Prasad, 2021). It is the second-most grown legume crop world-wide (Johnson et al., 2021), over 15 million tonnes in 2021 (FAO, 2023). In Europe, its area of production reached an eight-fold growth in the 2000–2017 period, and is mainly located in the southern region, with Spain, Bulgaria and Italy as the main producers (Divéky-Ertsey et al., 2022).

The consumption of dietary fibre (DF) provided by legumes has benefits in human health such as the prevention of cardiovascular diseases, the reduction of cholesterol and glycaemic levels, as well as certain forms of cancer (e.g., colon) (Gutöhrlein et al., 2020; Niño-Medina et al., 2017). DF is the portion of plant food that is not completely broken down in the digestive track of the human body, and it can be classified as soluble (digested slowly in the colon) and insoluble (metabolically inert) (Kaur and Prasad, 2021). The first ones decrease cholesterol levels and absorption of intestinal glucose (Rodríguez et al., 2006). The second ones increase the faecal bulk and reduce the gastrointestinal transit time, which are associated with the prevention and treatment of different intestinal disorders (e.g., constipation and haemorrhoids) (Goñi and Martín-Carrón, 1998).

For human consumption, pulses are processed as whole or split seed, or they are milled to flour (Skylas et al., 2022). To improve the nutritional value, chickpea flour is introduced into various food products such as bread, cookies, biscuit, pasta, and dairy products (e.g., yoghurt) (Kaur and Prasad, 2021). As in other food processing industries, chickpea flour production generates by-products, most notably the hulls, which are a potential source of dietary fibre (Niño-Medina et al., 2017).

To promote the use of waste biomass and minimize waste and associated emissions, the biorefinery concept emerges as a strategy to produce high-value products from different biomass feedstocks (Rebolledo-Leiva et al., 2022c). Nevertheless, the valorisation routes of sub-products under a circular thinking should demonstrate their environmental viability at an early stage of design of the process. The life cycle assessment (LCA) is a well-known methodology that allows to estimate the potential environmental impacts of products and services throughout their life cycle. This approach has been applied to determine the sustainability measurement and viability of different technologies mainly focused on alternative fuels, biofuels, or renewable energy generation to reduce GHG emissions (Ferdous et al., 2023).

Regarding the life-cycle environmental assessment of dietary fibre production from agri-food waste, only two articles were found in the Scopus® database (considering as search keywords: “dietary fibre” and “life cycle assessment”). The first one is the work of Khanpit et al. (2022) that evaluated the burdens of convert insoluble DF into soluble DF from orange peels waste at lab scale. The second one is the research of Khanpit et al. (2023), which assessed the environmental burdens of soluble dietary fibre concentrate (SDFC) production from waste citrus peel at pilot scale. Consequently, this research aims to evaluate the environmental burdens of the extraction of DF from chickpea hulls for promoting a valorisation strategy of this sub-product. To

the best of our knowledge, this manuscript provides the first data on the assessment of environmental impacts attributable to the valorisation of legume residues from a biorefinery perspective. In this way, it may be possible to identify critical factors that may restrict its potential application at early design stage.

## 2. Material and methods

### 2.1. Process description

#### 2.1.1. Chickpea cultivation and flour production

The cultivation of chickpea is performed in the region of Apulia, Italy. The fertilisation procedure consists of supplying 54 kg N·ha<sup>-1</sup> and 138 kg P·ha<sup>-1</sup> as di-ammonium phosphate (DAP) (18–46–0) using a fertiliser spreader. Then, a minimum tillage is carried out with a rotary tiller, followed by the sowing of 60–80 kg·ha<sup>-1</sup> of seeds. The control of weed is performed by 1.25 l·ha<sup>-1</sup> of Corum® (bentazone 480 g·l<sup>-1</sup> and imazamox 2.24% p/v), as well as 1 kg·ha<sup>-1</sup> of Coprantol® 30% is supplied in April to restrict the diffusion of pests. Finally, the harvest is performed through a combined machine with a production yield of about 4 t·ha<sup>-1</sup>. More details regarding the cultivation stage could be found in the work of Lago-Oliveira et al. (2023).

Regarding the industrial processing of chickpea that generates the hulls subproduct, the meal production was considered the sequent stage of the chickpea life cycle. The process was modelled using the dataset available in the Agri-footprint® v6 (2022) database (Blonk Agri-footprint BV, 2015) of flour production from peas as a proxy.

#### 2.1.2. Biorefinery design of hull-based DF production

The biorefinery is designed for an annual processing capacity of 40,000 Mg of chickpea hulls, operating 330 days per year. The biorefinery plant was simulated using the SuperPro Designer® v11 software, where thermodynamic modelling followed the default shortcut physical state (PS) toolbox, which infers the PS of the material using the Normal Boiling Point V/L split criterion for all components. An exception was made for HCl component for which considered a Liquid/Vapour only criterion was considered for the modelling. The process modelling for extracting the DF from chickpea hull is based on the work performed by Kumar et al. (2020). The reactions of the acid-alkali digestion were addressed by stoichiometry. The process begins grinding the hulls (GR-101) into 1–1.5 mm particle size. Then, they are digested by adding of 2 N HCl at 60 °C for 2 h in a stirred reactor with a batch mode (R-101), with a solid to liquid ratio (RSL) of 1:12 (Balicki et al., 2020). The flow is filtered (F-101) to separate acid liquid and solid stream, and the hulls were rinsed with water (W-101). To remove the water, the stream is subjected to a centrifugation process for 10 min (CF-101).

Subsequently, the dewatered hulls are hydrolysed with 2 N KOH, at 60 °C for 2 h (RSL 1:12) also in a stirred (batch) reactor (R-102). Similarly, the liquid and solid streams were separated by filtration (F-102), and the alkaline digested hulls are rinsed with water (W-102). Afterward, the stream is centrifuged (CF-102) for 10 min to remove water. After alkaline hydrolysis, the hulls were autoclaved (A-101) at 121 °C for 10 min. The chickpea hulls require a bleaching process (B-101) to remove pigments and improve their colour level. For this, the fibres were treated with a solution made up of equal parts (v:v) of acetate buffer and aqueous sodium chlorite

(1.7% wt NaClO<sub>2</sub> in water) in a solid to liquid ratio of 1:50 (w:v) for 4 h at 80 °C, and the mixture was filtered (F-103) (Dos Santos et al., 2015). Then, the fibres were dried (D-101) at 70 °C until obtain a moisture close to 9%. The final product reaches a total dietary fibres content of about 78% (Kumar et al., 2020). The liquid flows from the acid and alkaline digestion processes were mixed in a stirred tank (R-103) to obtain a neutralised stream to send it to the wastewater treatment. To achieve the temperature requirement of the processes, the heat transfer agents used in the process modelling were low pressure steam (152 °C) and cooling water (25 °C). The diagram flow of the process is presented in Fig. 1.

2.2. Life cycle assessment

2.2.1. Aim and scope definition

The aim of this LCA research is to estimate the potential environmental burdens of the dietary fibres production from chickpea hull obtained from the flour processing industry under a biorefinery approach. To this end, a cradle-to-biorefinery-gate boundary was followed (see Fig. 2); where activities from feedstock extraction, chickpea cultivation and processing, and DF production in the biorefinery plant were considered. The functional unit (FU) was 1 kg of DF product.

2.2.2. Life Cycle Inventory

The life cycle inventory (LCI) of the cultivation stage of chickpea in Italy is shown in Table 1. This table presents the tractor used in each activity (column A) with the respective tillage equipment (column B) and the total fuel consumption of both equipment (column A+B). From this, tillage is the most energy demanding activity in the chickpea cultivation stage. It encompasses the highest consumption of diesel fuel, which represents almost double the amount consumed in harvesting, as well as the highest energy demand. Fertilization and pest and weed treatment consume little energy, but their environmental implications are more related to the amount of agrochemicals applied and their corresponding emissions. On the other hand, the LCI of the mass and energy balances of the biorefinery platform is presented in Table 2. In addition to the chemical elements, different forms of energy (e.g., steam and electricity) are the most frequently consumed flows throughout the process. A total value of 8.9 Mg per Mg of extracted dietary fibre was consumed, with bleaching being the most demanding process with about 89%. In this regard, the steam supply was assumed to come from a cogeneration system to avoid the consumption of fossil resources. In addition, cooling water was only required in the autoclave process. Electricity consumption is mainly required by the centrifugation processes, which account for about 61% of the total demand.

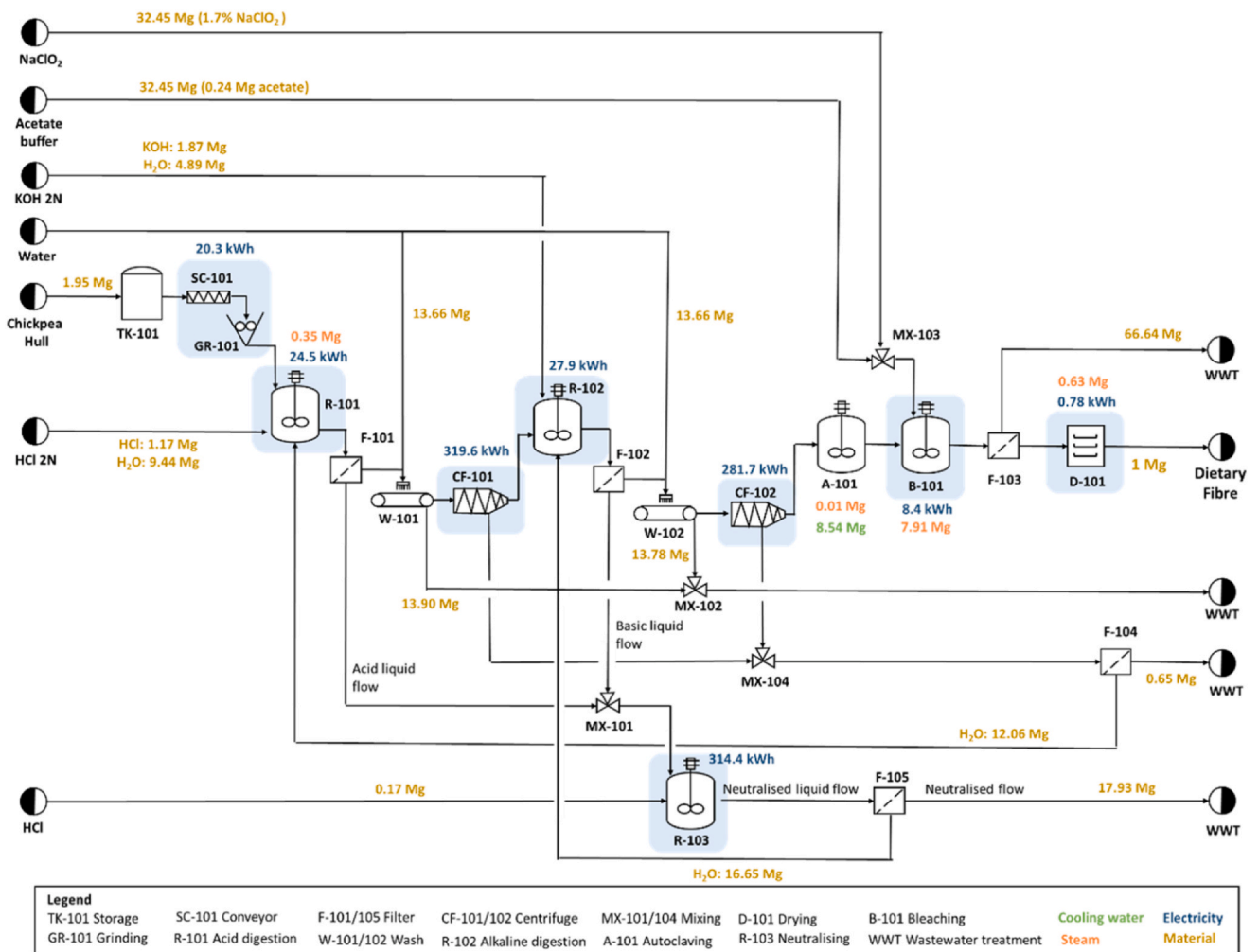
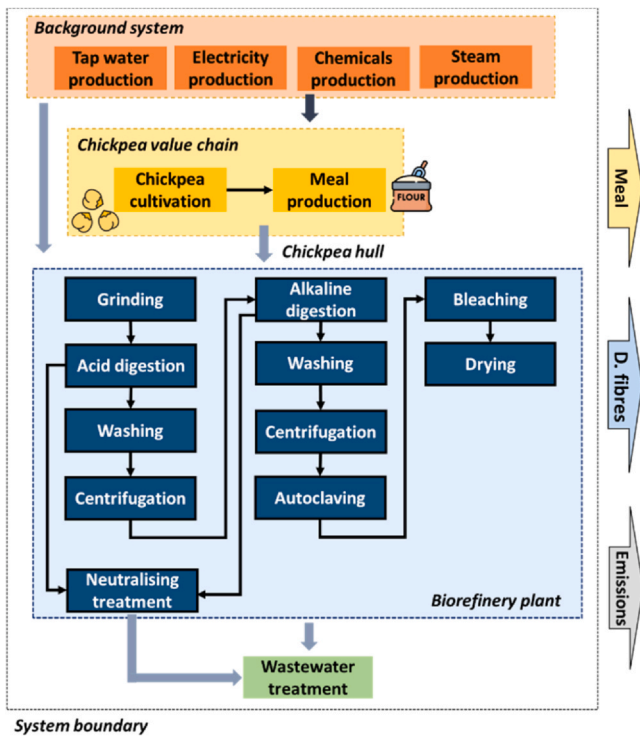


Fig. 1 – Flow diagram of the DF extraction from chickpea hull.



**Fig. 2 – System boundary of the dietary fibre production from chickpea hull.**

The background processes were taken from the Ecoinvent® v3.8 (Wernet et al., 2016) and the Agri-footprint® v6 (2022) (Blonk Agri-footprint BV, 2015) databases. An economic allocation of the burdens between meal and hull products was considered. In addition, it was considered that the biorefinery plant would be located next to the food processing plant, so transportation of the peel feedstock was not considered. In addition, inventory data were obtained to model the sodium acetate used (Jungbluth and Nguyen, 2008). In addition, as the sodium chlorite production dataset was not available in Ecoinvent® v3.8, sodium chlorate was used instead, since NaClO<sub>2</sub> is a derivative of sodium chlorate (Qian et al., 2007). It is important to note that this change was only used in the inventory modelling and not in the process simulation.

**2.2.3. Life Cycle Impact Assessment (LCIA) and interpretation**

To determine the potential environmental impacts of the product system, the ReCiPe 2016 (H) V1.07 / World (2010) (H) method (Huijbregts et al., 2017) was considered. The selected environmental indicators were Global Warming – GW

(CO<sub>2</sub>eq); Particulate Matter – PM (kg PM<sub>2.5</sub> eq); Terrestrial acidification – TA (kg SO<sub>2</sub> eq); Freshwater Eutrophication – FE (kg P eq); Marine Eutrophication – ME (kg N eq); Terrestrial ecotoxicity – TET (kg 1,4-DCB); Freshwater Ecotoxicity – FET (kg 1,4-DCB); Human carcinogenic Toxicity – HT (kg 1,4-DCB); Land Use – LU (m<sup>2</sup>a crop eq); and Fossil Resource Scarcity–FRS (kg oil eq). Furthermore, cumulative energy demand (CED) (Low Heating Values) v1 (Hischier et al., 2010) was applied, as it represents one of the most appropriate LCIA methods for energy requirements (Entrena-Barbero et al., 2023).

In addition, once the environmental impacts have been obtained, a sensitivity analysis is carried out focusing on the reduction of the most impactful stages identified in the product system based on the contribution analysis. Then, in these critical processes, the inventory flows that generate the most environmental burdens (critical points) are identified. Thus, the sensitivity analysis addresses possible changes in these flows. The most contributing steps are identified in the results Section (3.1), and the sensitivity analysis with the changes made in the environmental modelling is addressed in Section 3.2.

**3. Results and discussion**

**3.1. Environmental analysis**

The environmental profile of the dietary fiber (DF) production based on chickpea hull is displayed in Table 3. To identify the main life-cycle stages that contribute to the environmental profile of DF, the analysis of hotspots was carried out (Fig. 3). Accordingly, the alkaline digestion, bleaching and the cultivation of chickpea were the stages more critical in the hull-based DF production. The alkaline digestion was the main contributor in six (GW, PM, TA, FE, TET, and FRS) out of 11 impact categories evaluated, followed by the bleaching stage which was prominent in four of them (FET, HT, LU, and WC), and the chickpea hull production in the FE category.

**3.1.1. Global warming**

The impacts of this category were caused by the alkaline digestion stage, which accounts for 58.0% of CO<sub>2</sub> eq emissions. Although energy production is always a factor to consider in this impact category, the use of potassium hydroxide in alkaline digestion is the main reason for this impact (see Fig. 4a). However, the production of fossil-based electricity required for the production of potassium hydroxide is a determining factor in its contribution. By far, the second highest impact stage was bleaching (22.9%), due to the use of sodium chlorite to improve fibre colour (see

**Table 1 – Inventory data of chickpea cultivation stage.**

Stage	Tractor (A) Power (kW)	Equipment (B) Tillage item	Fuel consumption (L·ha <sup>-1</sup> ) (A+B)	Input rate
Shredding	40	Shredder	8.05	–
Mineral Fertilisation	40	Fertiliser spreader	0.45	Diammonium phosphate (DAP) 18–46–0: 300 kg·ha <sup>-1</sup>
Minimum Tillage	153	Rotatory tiller	42	–
Seeding	24	Seeder	19.8	Seeds: 60–80 kg·ha <sup>-1</sup>
Herbicide Treatment	40	Trailed sprayer	0.45	Corum® (Bentazone 480 g·L <sup>-1</sup> and Imazamox 2.24% p/v.): 1.25 L·ha <sup>-1</sup>
Herbicide Treatment	40	Trailed sprayer	0.45	Coprantol® 30%: 1 kg·ha <sup>-1</sup>
Harvesting	38	Harvester	23.65	–

**Table 2 – Inventory data of 1 Mg (or tonne) of dietary fibre product from chickpea hull.**

Stage	Input	Value	Unit	Output	Value	Unit
Cultivation	Chickpea	1.95	Mg			
Grinding	Electricity	20.25	kWh			
Acid digestion	HCl	1.17	Mg			
	Water	9.44	Mg			
	Steam	0.35	Mg			
	Electricity	24.52	kWh			
Washing	Water	13.66	Mg	Wastewater	13.90	Mg
Centrifugation	Electricity	319.62	kWh			
Alkaline digestion	KOH	1.87	Mg			
	Water	4.89	Mg			
	Electricity	27.87	kWh			
Washing	Water	13.66	Mg	Wastewater	13.78	Mg
Centrifugation	Electricity	281.68	kWh			
Autoclaving	Cooling water	8.54	Mg			
	Steam	0.01	Mg			
	Sodium chlorite	0.55	Mg	Wastewater	66.64	Mg
	Buffer	0.24	Mg			
Bleaching	Water	66.13	Mg			
	Steam	7.91	Mg			
	Electricity	8.4	kWh			
	Steam	0.63	Mg			
Drying	Electricity	0.78	kWh			
	Electricity	0.17	Mg	Wastewater	18.58	Mg
Neutralising treatment	HCl	0.17	Mg			
	Electricity	314.39	kWh			

Fig. 4b). GHG emissions are mainly attributed to fossil CO<sub>2</sub>, which accounts for about 85.6% of the total. Next, fossil methane (CH<sub>4</sub>) emissions appear as the second most relevant substance, but far behind, representing only 8.1% of total emissions. Alkaline digestion was the stage that caused the highest amount of CH<sub>4</sub> emissions (63.5%), due to the production of KOH. In addition, dinitrogen monoxide (N<sub>2</sub>O) ranks third in the relevance of GHG emissions (2.4%), which was produced mainly at the cultivation stage of chickpea.

### 3.1.2. Particulate matter formation and terrestrial acidification

As the global warming category, a similar distribution of the burdens in the hulls-based DF production was observed in the PM and TA categories. In the first one, the alkaline digestion (57.9%) and bleaching (21.1%) stages were the greatest contributors. Sulphur dioxide led the emission of substances related to the particulate matter category with about 44.6% of the total, while particulate matter < 2.5 µm and nitrogen oxides ranked second (36.9%) and third (15.1%), all generated mainly by the alkaline digestion stage.

Regarding the TA category, the alkaline digestion stage represented almost the half of the impacts, followed by bleaching (23.2%). Sulphur dioxide and nitrogen oxides stood out as the first and second substances emitted, respectively, both generated by the alkaline stage. On the other hand, ammonia emissions accounted for only about 9.9% of total loads, which were caused by the fertilisation of the chickpea crop.

### 3.1.3. Eutrophication related categories

For the freshwater eutrophication category, a similar share was observed for the alkaline digestion (38.5%) and bleaching (37.6%) stages. Phosphate was the main substance emitted (87.3%) along the life cycle of hull-based DF, generated by the above-mentioned processes, which accounting for about 74.9% of its total emissions. With a percentage of less than 10% each, the chemical oxygen demand (COD) and biological

**Table 3 – Environmental profile of the DF production from chickpea hull (based on FU: 1 kg of product).**

Impact category	Unit	Total
Global warming	kg CO <sub>2</sub> eq	7.62
Fine particulate matter formation	g PM <sub>2.5</sub> eq	14.08
Terrestrial acidification	g SO <sub>2</sub> eq	32.10
Freshwater eutrophication	g P eq	4.37
Marine eutrophication	g N eq	2.81
Terrestrial ecotoxicity	kg 1,4-DCB	14.87
Freshwater ecotoxicity	kg 1,4-DCB	0.14
Human carcinogenic toxicity	kg 1,4-DCB	0.36
Land use	m <sup>2</sup> a crop eq	0.92
Fossil resource scarcity	kg oil eq	2.12
Water consumption	m <sup>3</sup>	0.18

oxygen demand (BOD<sub>5</sub>) emissions were the second and third most relevant substances emitted to water courses. Regarding the marine eutrophication category, the cultivation of chickpea crop was the greatest hotspot with 65.3% of the global impacts (see Fig. 3). This stage represented the greatest contributor to the nitrate emissions (74.0%) due to the fertilisation of this legume crop.

### 3.1.4. Ecotoxicity related and human toxicity categories

In the TET category, the loads have a similar distribution to the GW and PM categories, where alkaline digestion reaches approximately 60% of the burdens, and bleaching was the second hotspot. The emissions of this category were mainly related to copper (52.4%), followed far by zinc (17.0%), and antimony (11.9%) substances. Copper and antimony have the highest sharing in the alkaline stage (above 67.5%) caused by the production of KOH, meanwhile, most of the zinc emissions were observed in the bleaching process (40.2%) because of the steam generation. On the other hand, in the categories of freshwater ecotoxicity and human toxicity, the bleaching process is of greater relevance (see Fig. 3). Concerning the FET category, this stage was the main hotspot representing

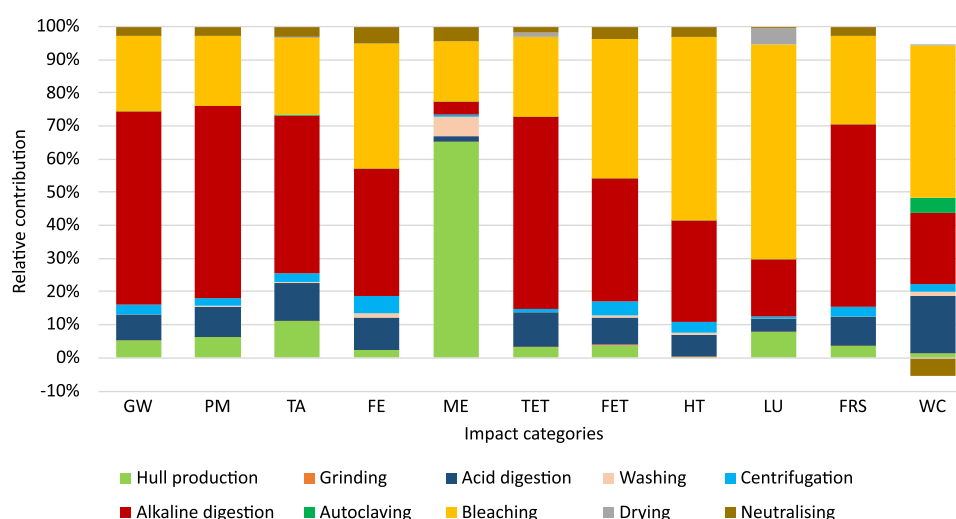


Fig. 3 – Relative contribution of the life cycle stages to the DF environmental profile.

41.7% of the total impacts. The most relevant emissions in this category were identified as zinc (61.1%) and copper (13.3%). The first one was produced by quite similar sharing of burdens between the bleaching and alkaline digestion processes (about 39–41% each), whereas the second one was generated mostly by bleaching (62.5%). Moreover, in the HT category, bleaching accounted for more than half of the total impacts, where the emissions of chromium VI from upstream stages of the life cycle, in particular from the production of the sodium component, were the most significant, expressing about 94.4% of the burdens of this category.

### 3.1.5. Land use, fossil resource scarcity and water consumption

In the land use category, the burdens were mainly produced by the bleaching stage, which represented 64.9% of the total share. The impacts related to this category were generally caused by the occupation (extensive) of forest. Furthermore, the extensive and intensive transformation of land were other sources of the burdens. The reason behind these results was the assumption of steam production based on cogeneration systems using woodchips as energy source. Concerning the FRS category, alkaline digestion was the critical hotspot with more than half of the total impacts. The burdens were generated by the demand of natural gas (37.0%), hard coal (32.0%) and oil crude (18.3%). Regarding the WC category, the bleaching process was the main water consumer process representing about 48.9% of the total. In addition, the negative contribution in this category (e.g., Fig. 3) corresponds to the water returned to the Technosphere through the wastewater treatment.

### 3.1.6. Cumulative energy demand results

Table 4 indicates the results related to the CED indicator. From this, the most outstanding contribution encompassed fossil and biomass sources in the non-renewable and renewable categories, correspondingly. The first one represented about 76.2% of the total non-renewable sources, while the second one accounted for 72.1% of the total renewable energy. On the other hand, the contribution analysis of these categories is displayed in Fig. 5. Similar to the results obtained in the impact categories of the LCA approach, the alkaline digestion and the bleaching

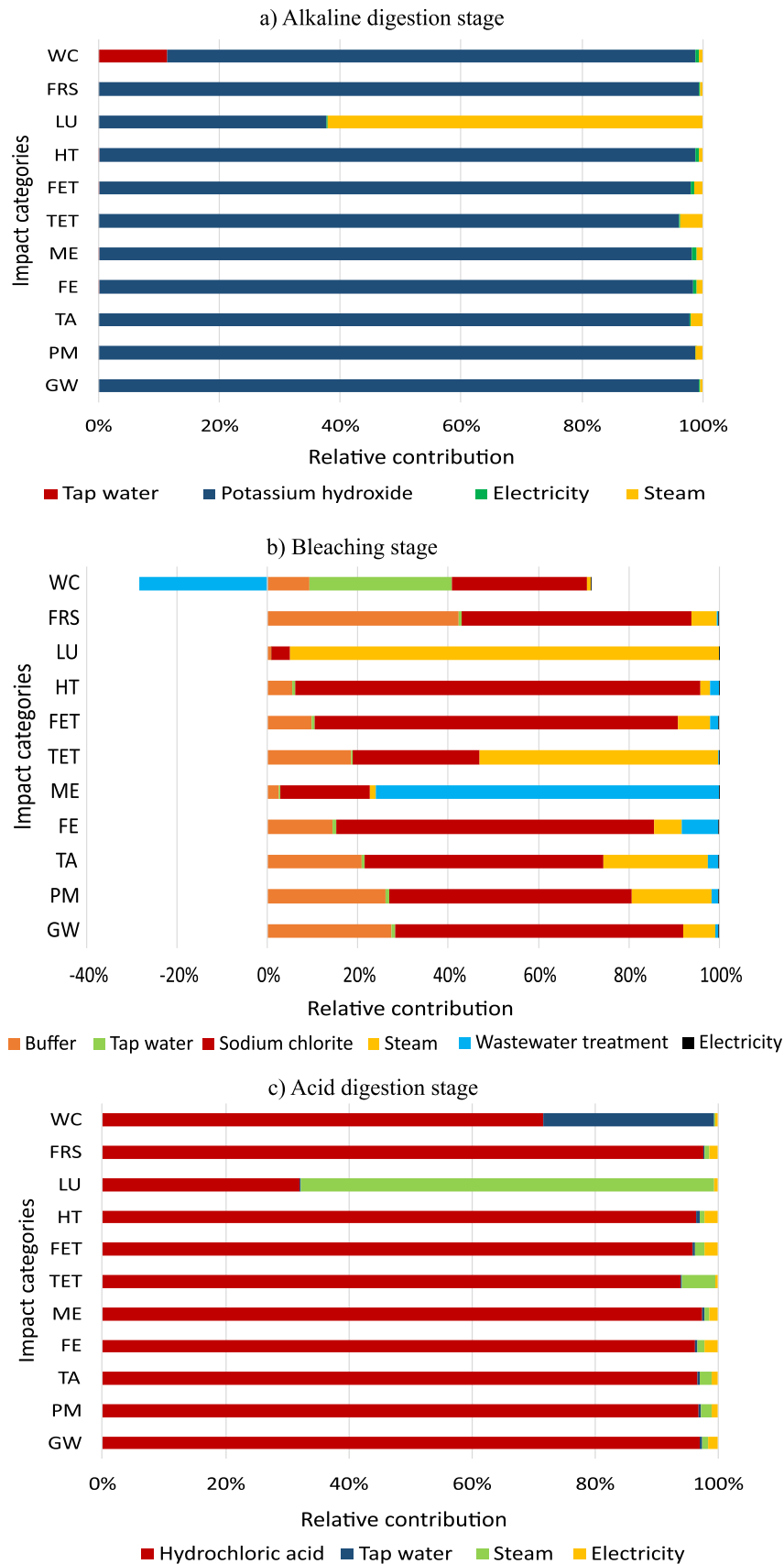
processes were the main contributors in the cumulative energy demand indicator. In the non-renewable sources, alkaline digestion contributes the most both in fossil (55.1%) and biomass (75.1%), because of the potassium hydroxide production and the steam supplied by the cogeneration system. The bleaching process highlighted in the nuclear one (43.4%) due to the European electricity generation mix to produce sodium chlorite. Regarding renewable energy, bleaching was the critical factor in biomass (72.2%) as well as in the wind, solar, and geothermal category (43.1%), whereas the alkaline digestion was the critical one in water source (39.5%) due to the KOH production.

## 3.2. Sensitivity analysis

From the previous results, it was possible to identify that the environmental performance of the production of dietary fibre from chickpea hull can be restricted by the alkaline digestion and bleaching stages, because of the use of chemicals such as potassium hydroxide (KOH) and sodium chlorite ( $\text{NaClO}_2$ ), respectively. Thus, a sensitivity analysis to identify potential improvement in the environmental performance was carried out.

Firstly, for the modelling of the inventory in the baseline scenario, the KOH was considered with the market dataset at global region, which is available in the ecoinvent® database v3.8. In this inventory dataset, the production of KOH is mainly based on the rest of the world (RoW) (82.6%), meanwhile the remaining fraction corresponds to Europe (17.4%). In this regard, the upstream life-cycle stages of KOH were modelling considering only the production in a European context with the transport characteristics (e.g., truck size) and distance available in the mentioned database for the European market. Thus, the DF-E scenario is proposed with the objective of avoiding the demand for products from long-distance markets.

On the other hand, when analysing the contribution of the KOH and  $\text{NaClO}_2$  production, it was observed that the electricity mix was the main contributor in most of the categories evaluated for both chemicals. Given that conventional electricity production from fossil fuels has decreased and renewable sources have increased their share instead (Rebolledo-Leiva et al., 2022c), it was assumed a future scenario where the electricity production mix is generated



**Fig. 4 – Contribution analysis in the main stage production of DF.**

only by renewable sources considering a sharing of 40% wind (onshore wind farms), 30% hydro, and 30% solar. In addition to the above assumption, the traditional production method of KOH is based on the electrolysis of potassium chloride (KCl) (Schultz et al., 2000), where the main

impacts are related to heat requirements, supplied by fossil resources (e.g., natural gas), mainly. Consequently, it was considered that the heat demand in the production of KCl was provided by a cogeneration system, which could be integrated into the biorefinery platform. The reason behind

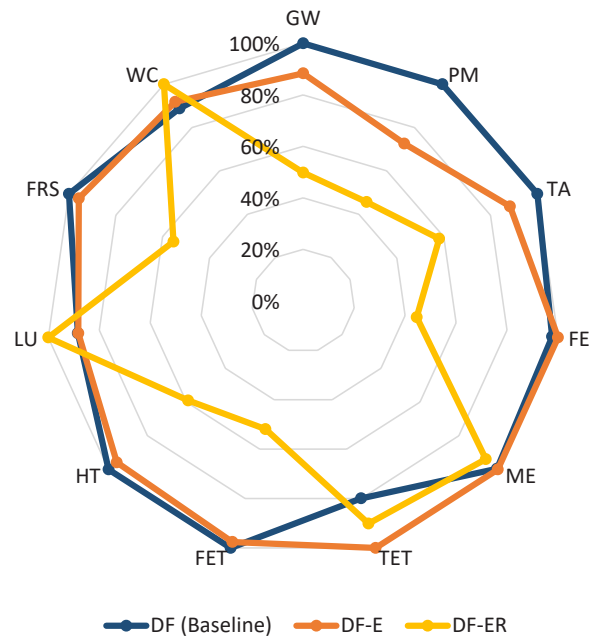
**Table 4 – CED indicator of the DF production based on the FU (i.e., 1 kg DF product).**

Impact category	Total (MJ)
Non renewable, fossil	90.22
Non-renewable, nuclear	28.10
Non-renewable, biomass	0.02
Renewable, biomass	27.60
Renewable, wind, solar, geothe	3. 60
Renewable, water	7.09

this was due to the heat energy was the main hotspot in the production process of this chemical in different categories such as GW, PM, TA, FE, HT, and FRS. This scenario was called DF-ER.

The profiles comparison between the abovementioned alternatives and the baseline scenario is shown in Fig. 6. From this figure, it is observed a trade-off in the impact categories evaluated among these scenarios. Comparing the baseline profile with the scenario DF-E, a decrease in seven out of 11 categories was reached, standing up PM (27.4%), TA (11.7%), and GW (11.7%). Nevertheless, an increase in TET, FE, ME, and WC categories was also identified. The first category reached the greatest growth accounting for 20.1%, while the remaining burdens accomplished a marginal increase in a range from 0.4% to 3.1% with respect to the baseline. In the case of the TET category, the growth in the impacts was related to the higher burdens of the KOH production profile of Europe with respect to the rest of the world (about 45%).

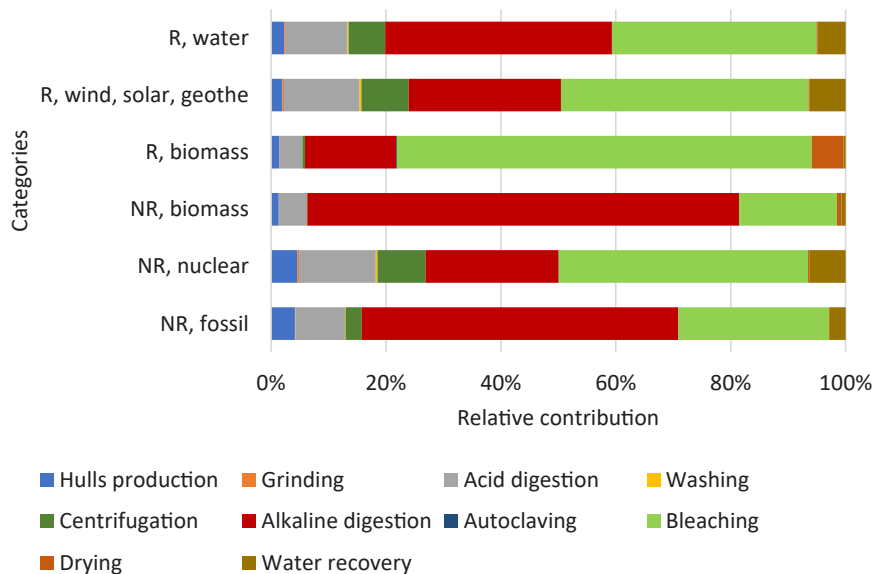
On the other hand, when the baseline scenario was compared with the scenario DF-ER, eight impact categories improved their environmental performance. From them, the highest reductions were obtained in categories such as PM (54.4%), FE (53.1%), GW (50.2%), and FET (48.1%). However, higher burdens (between 10% and 12%) were observed in LU, WC, and TET categories. The increase in the LU category was associated with the alkaline process, where the steam demand to produce KCl was assumed to be supplied by cogeneration systems. In addition, the increase in the WC category was related to the increase in loads associated with



**Fig. 6 – Sensitivity analysis of hull-based dietary fibre: DF (baseline scenario), DF-E (European production of KOH), DF-ER (European production of potassium hydroxide, renewable electricity mix and potassium chloride production with cogeneration system).**

the alkaline digestion and bleaching processes, due to the change in the electrical mix to produce KOH and NaClO<sub>2</sub> required by these stages.

Regarding the CED indicator (see Fig. 7), a variation of only 4% was observed between the baseline and the DF-E scenarios, whereas a potential reduction of about 25% could be achieved with the DF-ER scenario. As it can be seen in Fig. 7, the contribution of the fossil and nuclear sources decreases about 45% and 56%, respectively, moving from the baseline to the DF-ER scenario. However, an intensive demand for renewable energy sources can also be observed in the DF-ER scenario, with a rise of about 234% in the wind and solar, and 45% in water sources with respect to the baseline.



**Fig. 5 – Stage contribution of DF production in the CED indicator. (NR: Non-renewable; R: Renewable).**

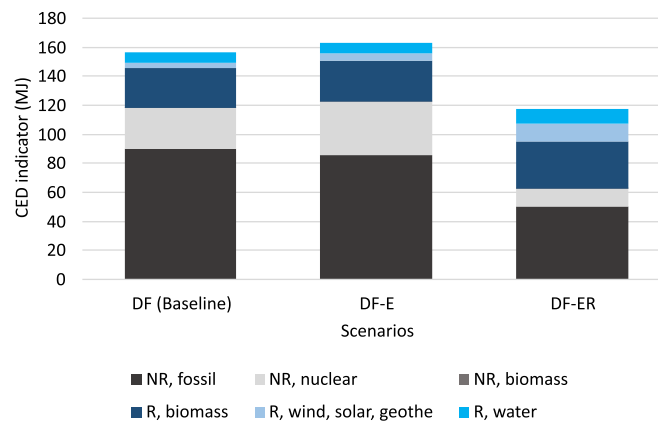


Fig. 7 – Sensitivity analysis in the CED indicator (NR: non-renewable, R: renewable).

### 3.3. Comparison with studies from literature

As mentioned previously in the introduction section, two articles have addressed a close aim of this research: the extraction of dietary fibre from agro-food waste. The work of Khanpit et al. (2022) that determines the environmental impacts of converting insoluble DF into soluble DF from orange peels waste, through extrusion and ultrasonication methods at lab scale. Their study considered a gate-to-gate scope, i.e., it only considers the manufacturing process. Their results showed that ultrasonication encompassed the highest burdens compared to extrusion method in the four impact categories analysed, which were global warming, acidification, eutrophication, and ozone creation. Particularly, the impacts related to the global warming category were 1.5 and 3.97 kg CO<sub>2</sub> eq for the extrusion and ultrasonication strategy, respectively, at a basis of 0.1 kg of input of fresh orange peels.

Subsequently, Khanpit et al. (2023) evaluated the environmental burdens of soluble dietary fibre concentrate (SDFC) production from waste citrus peel at pilot scale and following a gate-to-gate approach. They compared different methods such as micronization (MC), autoclave (AC), and autoclave followed by micronization (AM), extrusion (EX), and ultrasonication (US). The pilot scale analysed consist of 40 kg of SDFC manufacturing per batch and the functional unit was 40 kg of SDFC. Their results showed that US was the worst alternative strategy accounting for 145 kg CO<sub>2</sub> eq, which was 2.96, 1.43, 1.29, and 2.50 folds more with respect to MC, AC, AM, and EX strategies, respectively (Khanpit et al., 2023). In addition, these authors demonstrated that global warming can be reduced by more than 90% by switching to renewable energy sources.

The two previous articles present some differences with this work. First, they focused on soluble DFs, whereas here the total proportion of DFs in the valorisation strategy was addressed. Therefore, a comparison of the environmental performance between them could not be appropriate. Second, the methodological aspects of the LCA approach were also diverse, such as the system boundaries (gate-to-gate versus cradle-to-gate) and, more importantly, the scale of production, as the results at laboratory scale cannot be directly extrapolated to the process at industrial scale. Typically, at laboratory scale there is usually a much higher impact compared to commercially available counterpart materials (Piccinno et al., 2016).

### 3.4. Limitations and future research

In this manuscript, the environmental profile of the production of dietary fibre from chickpea hull was estimated. The main limitation in the environmental modelling was the use of proxy data sets for the inventory processes of flour production based on peas (instead of chickpea) and for the production of sodium chlorate (instead of sodium chlorite), because they were not available in the ecoinvent® v3.8 database. In addition, no other similar studies were found in the literature, which restricts the discussion of the main results of this research.

As prospective lines of research, firstly, other extraction methods that do not require the use of chemicals to obtain dietary fibre could be investigated. As could be demonstrated here, the alkaline digestion step was the main limitation due to the use of KOH, but also the use of sodium chlorite in the bleaching process is a factor to be taken into account. Furthermore, other technologies related to the bleaching process could be analysed to reduce the contribution of this stage. The economic feasibility of this product system could be another research objective, as well as the possible social impacts to ensure a sustainable valorisation alternative of the hull by-product. Based on these results, the environmental consequences of the possible implementation of this circular model could be another line of research, the objective of which would be to identify the effects of the products displaced on the market by the implementation of this valorisation route. In this way, a broad understanding of the environmental dimension of the growing interest in promoting circular models could be achieved.

## 4. Conclusions

This research addresses the environmental assessment of the production, at industrial scale-up, of dietary fibre from the valorisation of chickpea hull. For this purpose, the integration of process simulation and life cycle analysis allowed identifying, at an early design stage, the critical factors that may restrict the possible implementation of this bio-refinery plant. The results showed that the alkaline digestion and bleaching stages were the major contributors to most of the impact categories evaluated, due to the chemical demand for potassium hydroxide and sodium chlorite. In addition, upstream phases of the life cycle, such as chickpea cultivation and steam production from the cogeneration system, were also relevant in the eutrophication and land

use categories. Overall, strategies to switch to renewable sources for electricity and steam generation, as they were the critical factors in both chemicals (i.e., potassium hydroxide and sodium chloride) production, may lead to improvement in the environmental performance of DF extraction. In the design phase of bioeconomy platforms, the life cycle approach makes it possible to identify how these potential corrective actions can lead to trade-off effects between the impact categories analysed, i.e., improve some of them but also worsen the performance of others. Thus, the selection of improvement strategies must pursue the challenging objective of achieving an environmental profile with a balanced impact, while also addressing the consequences of displaced substitute products in the promotion of this type of circularity model.

### 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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