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Techno-economic and environmental assessment of dietary fibre extraction from soybean hulls

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ABSTRACT

This research evaluates the economic and environmental feasibility of extracting dietary fibre (DF) from a by-product such as soybean hulls. Techno-economic (TEA) and life cycle assessment (LCA) were carried out to identify the critical factors that may limit the implementation of a potential biorefinery plant. The modelling of the process was carried out on the basis of mass and energy balances, as well as the characteristics of the required equipment. TEA indicators such as minimum selling price (MSP), fixed capital investment, manufacturing costs were evaluated. A cradle-to-gate LCA approach and a functional unit (FU) of 1 kg of product (85% DF content) were considered. Impact categories such as global warming (GW), eutrophication, eco-toxicity, among others, were analysed. The results indicate that the production capacity achieves the plateau at about 56 kt y^{-1}, with an MSP value of 2.6 $\$\cdot kg^{-1}$. Furthermore, the GW profile was 8.76 kg CO_2eq per FU, and the main hotspot is the alkaline digestion stage due to the use of potassium hydroxide (KOH). Nevertheless, the management of the hulls from multi-product food plants and switching KOH production to renewable sources may reduce the profile in almost all categories analysed.

1. Introduction

Globally, agriculture is one of the main drivers of the climate change crisis. The sector accounts for more than 70% of freshwater use, about 25% of greenhouse gas (GHG) emissions and 80% of deforestation, and is the largest contributor to biodiversity loss (Ludwig-Borycz et al., 2023). In the food sector, almost half of its GHG emissions come from livestock production (Takacs et al., 2022). In this regard, it is estimated that animal-based food production accounts for about 57% of global GHG emissions from food production (Xu et al., 2021). Thus, current dietary patterns centred on animal-based foods high in calories, fat, and sugar pose a threat to human health and the environment (Giosuè et al., 2022).

There is broad consensus that diets rich in plant-based foods promote health and environmental sustainability (Kaartinen et al., 2023). Among these, legumes are a source of protein and amino acids for both human and animal consumption, as well as an exceptional source of dietary fibre (Kumar and Pandey, 2020). Dietary fibre (DF) has health and nutritional benefits related to metabolic and physiological effects in the gastrointestinal tract, in reducing the risk of gallstone disease (Tehrani et al., 2023), in lowering blood lipid and glucose levels, and in controlling body weight, among others (Huang et al., 2018). For all these reasons, DF has received a great deal of attention from researchers, the food industry and consumers (Wang et al., 2015).

Different studies have evaluated the extraction of DF from fruit or vegetable waste, Khanpit et al. (2022) converted insoluble DF into soluble DF from orange peels waste at lab scale, and then, Khanpit et al. (2023) evaluated the soluble DF concentrate production from citrus peel waste on a pilot scale. Tariq et al. (2023) reviewed different techniques extraction of DF and polyphenols from mango peel. Kaur et al. (2023) performed an ultrasound-assisted extraction and ultrasound-assisted-enzymatic extraction to maximize DF yield from kinnow peel waste. Almoumen et al. (2024) carried out the extraction of high fibre date ingredient from date fruit pomace and its integration into bread wheat flour. Jiang et al. (2024) performed the extraction of papaya-based DFs by alkaline, water and combination of water/wet ball milling.

Among legumes, soybean, which is grown for oil and protein, is one of the most relevant crops worldwide (FAO, 2024). The top three producing countries worldwide are Brazil, the United States and Argentina with about 154, 113, and 50 million tonnes, respectively, during the 2023-24 season (USDA, 2024). This crop has become the main protein

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plant and one of the most predominant crops in Europe (Divéky-Ertsey et al., 2022); where its production in 2020 was concentrated in countries such as Italy, France, Romania, Croatia, and Austria, accounting for more than 80% (Kuepper and Stravens, 2022). Moreover, Brazil is the world's second largest producer of soybean oil, and a key country in the production of biodiesel where soybean represents about 70% of the feedstock (Zortea et al., 2018). Although, compared to other grain legumes, soybean is higher yielding and improves it faster, its cultivation has a large carbon footprint motivated by deforestation and negative impacts on biodiversity (Rotundo et al., 2024).

In the horticulture industry, about one third of the production is discarded during the preparation and processing stages (Yang et al., 2014). In particular, the production of oil and meal from soybean processing generates by-products, the main one being the hulls (Niño-Medina et al., 2017). This by-product is generated from the dehulling process, representing about 5–8% of dry mass of the soybean (Barros et al., 2020). Globally, soybean hulls production is estimated at around 18–29 million metric tons during the period 2020–2021 (Bittencourt et al., 2022). Soy hulls are either underutilized or discarded as an agricultural waste, causing waste disposal costs and environmental issues (Kim et al., 2015), or they are sold in pelletized or milled form for ruminants feeding, as a partial replacement for cereal grains (Barros et al., 2020). Nevertheless, soybean hulls contain a large amount of DF, which could have great potential in various food applications due to their functional properties (Yang et al., 2014). Some previous works related to DF extraction from soyhulls are: Kim et al. (2015) whose evaluated chemical extraction methods for pectin and insoluble fibre, and Niño-Medina et al. (2017) whose compared their extraction from chickpea and soybean hulls, showing that the latter achieved the highest levels. On the other hand, for industrial scale designs, process modelling based on simulation tools (e.g., Superpro designer® or Aspen plus®) has been applied, where soy biomass has been converted into value-added products. Some examples are: Riazi et al. (2019) performed the isostearic acid production from soybean oil and tall oil; Woinaroschy (2014) carried out a multiobjective optimisation for biodiesel sustainable production from soybean oil. Okolie et al. (2021) proposed a conceptual design for the catalytic supercritical water gasification of soybean straw, while Ahire et al. (2024) performed a bioadhesive production from isolated soy protein and kraft lignin.

There are different aspects that motivate this research: (i) the large amount of hulls generated by the soybean processing industry, (ii) the diverse environmental impacts of soybean cultivation (e.g., global warming, land use), which demands valorisation strategies to maximize the use of this biomass into multiple value-added products, (iii) the need to diversify sources of fibre for a healthy diet, and (iv) the scarce information about the environmental impacts and economic performance of DF extraction. Thus, this manuscript aims to assess the economic and environmental feasibility of extracting DF from soybean hulls in a potential large-scale operation. For this purpose, the process at industrial scale will be carried out using process modelling through a simulation tool (Superpro designer®). A techno-economic analysis (TEA) will then be carried out to estimate the economic indicators that will demonstrate the potential viability of the design. In addition, a life cycle assessment (LCA) is carried out to obtain the environmental profile to identify the critical factors contributing to the environment throughout the life cycle of the fibre and to perform sensitivity analysis to determine possible improvements in the product system. The results will support the decision-making process related to economic and environmental issues on the possible application of legume waste recovery models.

2. Material and methods

2.1. Process modelling for TEA and LCA approaches

New bio-based strategies that valorise by-products to obtain value-added products are mainly carried out on a laboratory scale. However, in order to determine their environmental and economic feasibility, it is necessary to address process modelling in order to prospect an industrial-scale operation. In this sense, the simulation of a process sequence favours a detailed understanding of the product life cycle, allowing to understand the related environmental impacts, at operation scale, and to assess the contribution of the operating conditions on the environmental loads (Julio et al., 2017). Thus, process modelling, performed using simulation software, allows obtaining mass and energy balances, which are used for the life cycle inventory stage in the LCA methodology. In addition, data obtained from process modelling, such as equipment parameters (e.g., size, capacity), raw material and energy demands, production level, labour requirements, among others, are also useful for estimating different economic indicators of the TEA. In general, the procedure (see Fig. 1) consists of obtaining laboratory-scale data, which are simulated at industrial scale, to obtain the mass and energy flows needed for the inventory analysis in the LCA, and to estimate the cost and revenue flows in the TEA. It is then possible to identify the main limiting factors and evaluate improvement strategies.

2.2. Biorefinery design of the DF extraction

The biorefinery is designed for an annual processing capacity of about 35 kt of soybean hulls, operating for 330 days per year. The process modelling of the DF extraction is based on the work of Yang et al. (2014) and Kumar et al. (2020). At the beginning of the process, soybean hulls contain approximately 57% (as is) of total dietary fibres (Kumar et al., 2020). The process starts by grinding the hulls to a particle size of 1–1.5 mm. They are then digested in an acid-base hydrolysis sequence using 2 N HCl and 2 N KOH, respectively for 2 h at a solid-liquid ratio of 1:12 and 60 °C (Balicki et al., 2020) with intermediate washing with water and centrifugation. After acidic-base hydrolysis, the hulls are autoclaved at 121 °C for 10 min and dried at 60 °C to reach a final moisture content in the order of 9–11%. Finally, the dried soybean hulls are crushed to homogenise the size a powdered DF. The final product contains about 85% total DF, as mentioned by (Kumar et al., 2020). The process flow diagram is presented in Fig. SM1 of the Supplementary materials.

2.3. Techno-economic analysis

2.3.1. Estimation of total capital investment

The mass and energy balances and equipment design were calculated with Superpro designer® v11 software, while the estimation of costs of purchased free-on-board equipment (Ceq.fob) was carried out based on textbooks and reports (Dheskali et al., 2017; Peters et al., 2003; Turton et al., 2018). The fixed capital investment (FCI) was obtained by multiplying the sum of Ceq.fob with a lang factor of 5 (Dheskali et al., 2020). The value of this factor was selected because the design involves the construction of a biorefinery plant with high-risk new technology and the use of expensive construction material in the process equipment (Ioannidou et al., 2022a). The working capital (WC) was equivalent to 5% of the FCI value (Ladakis et al., 2022). Finally, the total capital investment sums the values of FCI and WC.

2.3.2. Estimation of manufacturing costs

The manufacturing cost (COM) was estimated as $COM = 0.18 \times FCI + 2.73 \times C_{OL} + 1.23 \times (C_{UT} + C_{RM} + C_{WT})$, as proposed by Turton et al. (2018). Where C_{OL} represents the operating labour cost, while C_{UT} and C_{RM} correspond to utilities and the raw material expenses, respectively. Based on Turton et al. (2018), these coefficients encompass the contribution of all secondary cost categories such as maintenance, marketing, research, and development.

Labour cost (C_{OL}) was estimated considering the total quantity of workers demanded based on the annual operation (see Table SM1 in the Supplementary Materials), the working time of each worker (2080 $h \cdot y^{-1}$) and the average labour cost (20 $\$ \cdot h^{-1}$) (Ioannidou et al., 2022a,

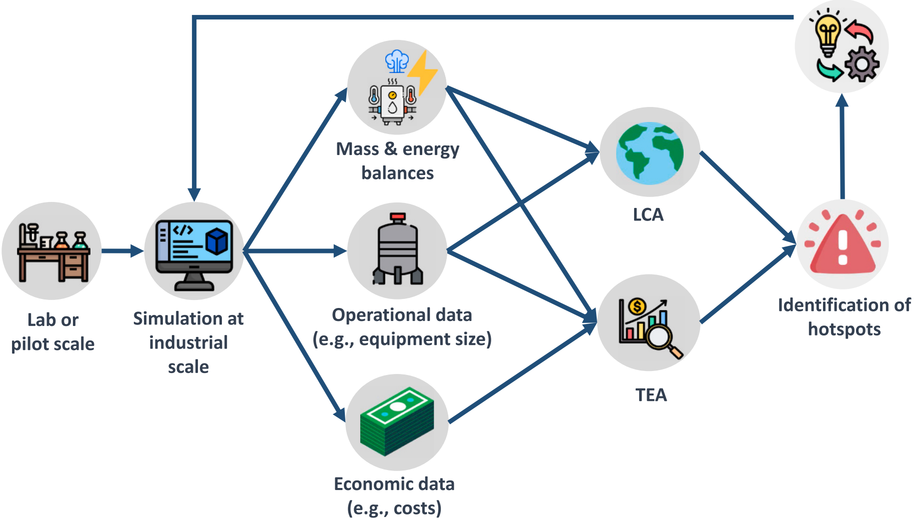


Fig. 1. Process modelling for LCA and TEA approaches.

2022b; Ladakis et al., 2022). Furthermore, the costs related to utilities (C_{UT}) were estimated by multiplying the unitary cost by the amount required by each utility item. Similarly, the costs associated with raw materials (C_{RM}) and waste treatment (C_{WT}) were estimated based on the unitary cost and the amount required. Specific costs used in the analysis are provided in Table SM2 in the Supplementary Materials.

2.3.3. Economic analysis and TEA indicators

To determine the economic viability of the valorisation route, a discounted cash flow (DCF) analysis was carried out (Kookos, 2018). For this, the parameters reported by Davis et al. (2013) were used, which are presented in Table SM3 of the Supplementary Materials. For the calculation of asset depreciation, seven years were assumed based on the

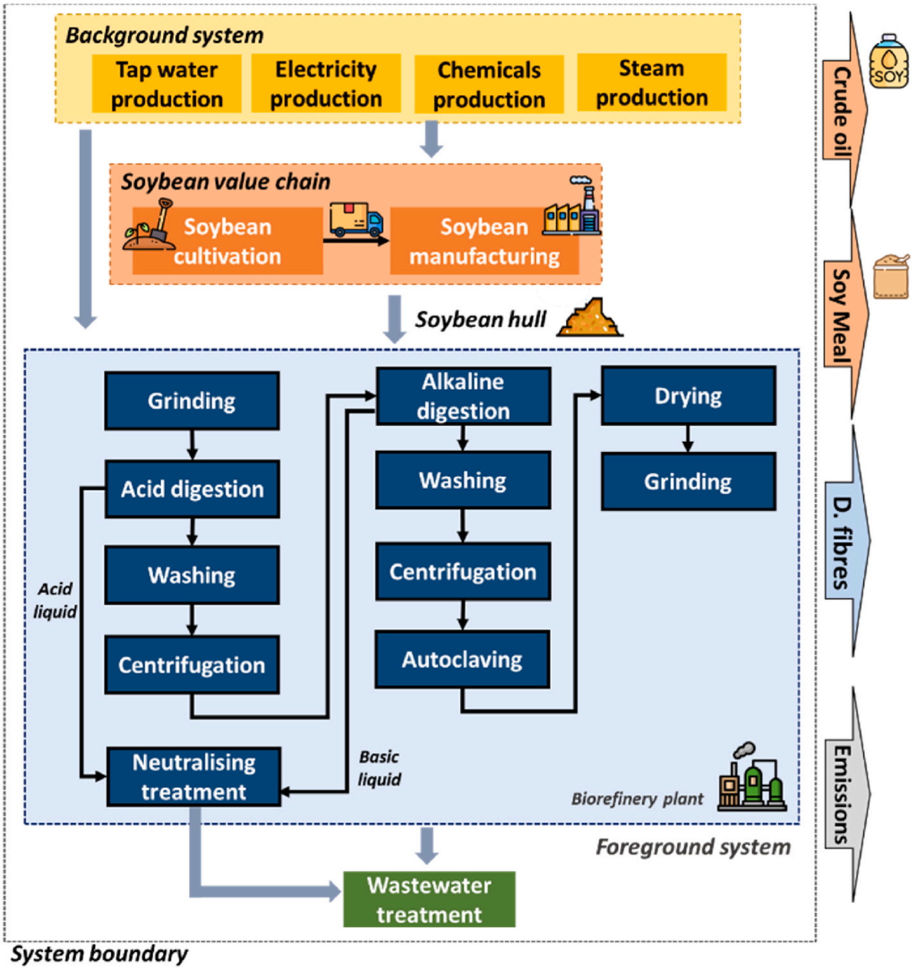


Fig. 2. System boundary of the dietary fibre production from soybean hulls.

Modified Accelerated Cost Recovery System (MARS) (Ladakis et al., 2022). The minimum selling price (MSP) per kg product was estimated by determining the market price of the product where the Net Present Value (NPV) is zero at the end of plant lifetime. The TEA indicators used for the profitability assessment were the MSP, the NPV, the Optimal Plant Capacity (OPC) leading to a minimum COM, the Minimum Feedstock Requirements (MFR) representing the amount of feedstock required to satisfy the OPC, and the Discounted Payback Period (DPP). The OPC corresponds to the capacity level at which the COM or MSP values reach a plateau and then remain constant. For this, different production scales were evaluated, from 4 to about 87 kt y^{-1}. The DPP is the time required, after start-up, to recover the fixed capital investment (FCI) with all cash flows discounted to time zero (Turton et al., 2018).

2.4. Life cycle assessment

2.4.1. Aim and scope

The aim of this research is to estimate the potential environmental burdens of the extraction of dietary fibres from soybean hulls obtained from the oil industry under a biorefinery approach. For this purpose, a cradle-to-biorefinery-gate boundary was followed (see Fig. 2); where activities of feedstock extraction, soybean cultivation and processing, and DF extraction in the biorefinery plant have been considered. It is important to mention that the hulls are obtained directly from the processing industry, so there is no process for their treatment before the biorefinery. The functional unit (FU) was expressed in terms of mass, i.e., 1 kg of DF product (85% content). Furthermore, a comparative assessment with current alternatives is also considered to determine the potential environmental advantages of fibres extraction from soybean.

2.4.2. Life cycle inventory

The life cycle inventory (LCI), which considers the mass and energy balances of the biorefinery platform, is presented in Table SM4 of the Supplementary Materials. In the modelling, steam demand is assumed to come from cogeneration systems (based on wood sources) to avoid the consumption of fossil resources. The background processes were obtained from the Ecoinvent® v3.8 (Wernet et al., 2016) and the Agri-footprint® v6 (2022) (Blonk Agri-footprint, 2015) databases. The latter was used particularly to obtain inventory data for the by-product soybean hulls, which is one of the products (in addition to crude oil and meal) of the soybean manufacturing industry. This system considers soybean activities and associated transports, electricity, water, among others. In addition, this inventory process assumes an economic distribution with an allocation factor of 5.8% for hulls. The manufacturing process is assumed to take place in Italy, as this country is the main soybean producer in Europe (Divéky-Ertsey et al., 2022). Thus, it is assumed that the biorefinery plant is integrated with the soybean processing plant, which rules out the transport of the hulls. Furthermore, as the sodium chlorite dataset was not available in Ecoinvent® v3.8, sodium chlorate was used instead, since $NaClO_2$ is a derivative of sodium chlorite.

2.4.3. Life cycle impact assessment

The ReCiPe 2016 (H) V1.07/World (2010) (H) method (Huijbregts et al., 2017) was considered to determine the potential impacts of the product system. The environmental indicators were Global Warming (GW); Particulate Matter (PM); Terrestrial Acidification (TA); Freshwater (FE) and Marine (ME) Eutrophication; Freshwater Ecotoxicity (FET); Human Carcinogenic Toxicity (HT); Land Use (LU); Fossil Resource Scarcity (FRS), and Water Consumption (WC). In addition, the cumulative energy demand (CED) (Low Heating Value) v1 (Hischier et al., 2010) was applied, as it is one of the most appropriate indicators for energy demand (Entrena-Barbero et al., 2023).

2.4.4. Sensitivity analysis

A sensitivity analysis was carried out taking into account four main alternatives. Firstly, a change in the allocation factor in the economic distribution of the burdens related to the hulls. It could be possible that the market price of the hulls can change, for instance, due to an increase in the demand for this feedstock to produce the DF product. Therefore, an increase of 10% was assumed. This scenario is referred to as DF-EF.

Secondly, the baseline scenario considers that the hulls are produced from a crushing plant that also produces oil and meal as co-products. In this case, it was evaluated that the hulls are sourced from an Italian factory producing oil, molasses, and soybean protein concentrate. This dataset was also obtained from the Agri-footprint® database and considers an economic allocation approach with a factor of 0.98% for hulls, which is the main difference from the baseline, as the food factory elaborates more products. This scenario is referred to as DF-HMU.

Thirdly, since alkaline digestion involves the use of KOH, it was assumed that the production of this chemical takes place in Europe and in a facility using renewable sources with a share of 30% hydro, 30% wind and 40% solar. In addition, KOH is produced from potassium chloride in a facility that uses a cogeneration system for its heat demand. This scenario is DF-KOH. Finally, the DF-HMU and DF-KOH scenarios were combined as the last alternative, called HMU + KOH.

3. Results and discussion

3.1. Techno-economic results

3.1.1. TEA indicators

As mentioned above, different production scales were analysed to determine the production level at which the constant value of FCI per kg of DF was reached. In this regard, Fig. 3 presents the results obtained for the indicators FCI, MSP and COM. These outcomes indicate that a plateau was observed for a production capacity of about 56 kt y^{-1}. Consequently, the OPC indicator corresponds to this capacity level.

As for the FCI indicator, the values range from about $9.9 to 138.2 million per year of production, and decrease from $2.3 to $ 1.6 per kg of product as plant capacity increases. Furthermore, the COM indicators of the biorefinery platform range from $13.7 to 204.6 million, which means that per kg of product ranged from $3.2 to 2.4. In addition, Fig. 3 shows the MSP for dietary fibre at the different plant capacities. As can be seen from it, the value of the MSP indicator like the previous ones has a range of values from 3.5 $\$\bullet kg^{-1}$ at the lowest capacity scale to about 2.6 $\$\bullet kg^{-1}$ where the value of the MSP indicator reaches the plateau.

3.1.2. TEA indicators at the optimum plant capacity

The estimated equipment size, the cost of purchasing equipment cost and the FCI at the OPC level for the dietary fibre extraction is presented in Table SM5 of the Supplementary Material. As for the FCI indicator, the total value corresponds to $91.3 million. This value is mainly due to the neutralisation and water recovery stage, which accounted for approximately 65% of the FCI value. In addition, each of the two digestion processes accounted for approximately 12% of the total FCI value. Regarding the MSP indicator, the value was 2.6 $\$\cdot kg^{-1}$ of product at optimum capacity. The current price is quite varied in the Asian market, with supplier offering competitive prices of 686 $\$\cdot ton^{-1}$ (MadeinChina, 2023) or in a range of 3.24–9.85 $\$\cdot kg^{-1}$ (Alibaba, 2023) with a DF content above 60%. In the Indian market it is possible to find a market price of about 0.91 $\$\cdot kg^{-1}$ (75 Indian rupee) with a DF content of 65–70% (Indiamart, 2023). In the case that a soybean processing plant could integrate this biorefinery at the optimum capacity, the MSP could be reduced to 2.3 $\$\cdot kg^{-1}$ as it would not require the purchase of the hulls. The NPV indicator differed as a function of the percentage of profit above the minimum selling price (see Fig. 4). For instance, the NPV increases from $46.4 to $183.1 million when the price between 5% and 20% above the MSP, respectively, at a discount rate of 10%.

In addition, the COM indicator achieved an annual value of $ 135 million, or $2.4 per kg of DF product at the optimal capacity. In terms of raw material costs, the total value reached an amount of approximately

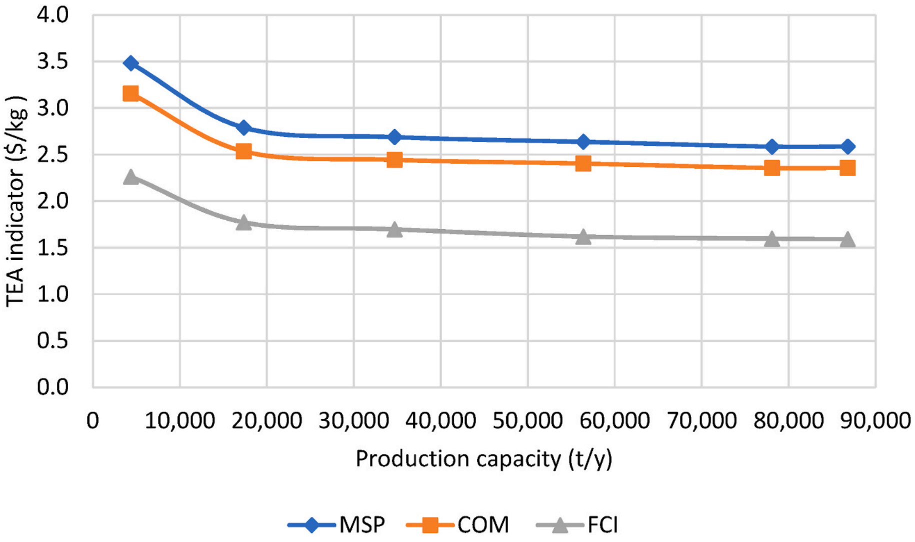


Fig. 3. MSP, COM and FCI indicators according to the production scales analysed.

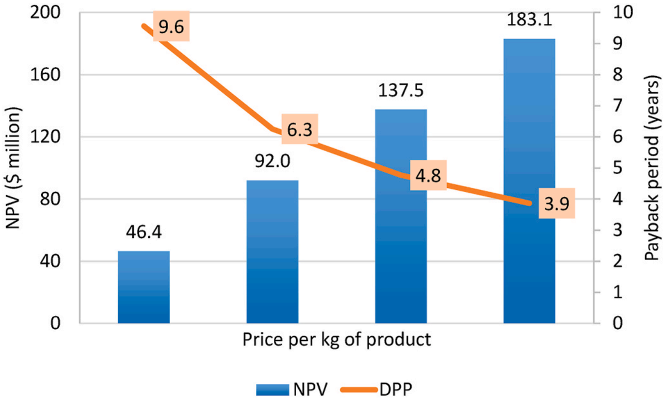


Fig. 4. NPV and DPP indicators based on the market price of DF product.

$ 75 million, where the chemical KOH accomplished the greatest share of about 66% of the total, and soybean hulls represented 19% of this item. The costs associated with labour and utilities were $8 and $2 million per year, respectively, with the latter's largest item being low pressure steam. The payback period for the biorefinery platform at OPC ranged from 9.6 to 3.9 years (see Fig. 4). Furthermore, the MFR indicator describing the minimum amount of feedstock at the OPC level was about 103 kt y^{-1} of soybean hulls.

Table 1
Impact category of the DF extraction (FU: 1 kg DF product).

Impact category	Unit	Total
GW	kg CO_2 eq	8.76
PM	g $PM_{2.5}$ eq	11.44
TA	g SO_2 eq	30.56
FE	g P eq	2.81
ME	g N eq	4.35
TET	kg 1,4-DCB	11.32
FET	kg 1,4-DCB	0.08
HT	kg 1,4-DCB	0.14
LU	m^2a crop eq	6.74
FRS	kg oil eq	1.57
WC	m^3	0.19

3.2. *Environmental assessment*

Table 1 shows the environmental profile of the extraction of DF from soybean hulls. The contribution analysis of the valorisation route is presented in Fig. 5. From this analysis it can be seen that alkaline digestion and soybean hulls production are the main contributors to the hulls-based DF product. In particular, alkaline digestion was the hotspot in eight out of 11 impact categories, while hull production was the critical process in three categories, such as ME, LU and WC.

3.2.1. *Global warming*

The burdens in this category were mainly caused by the alkaline digestion and soybean hulls production stages, which accounted for a similar share of about 47.2% and 44.2% of the total CO_2eq emissions, respectively. About half of the greenhouse gas emissions were fossil CO_2, which were mainly identified in the alkaline digestion process. Fossil methane (CH_4) and dinitrogen monoxide (N_2O) emissions had a low contribution, each representing a share of less than 5% of the total GHG emissions. The CH4-related loads mainly belong to alkaline digestion (86.5%), due to the production of KOH, caused by the electricity generation. In addition, most of the N_2O emissions were identified in the soybean cultivation phase, with about 85% of the total.

3.2.2. *Particulate matter formation and terrestrial acidification*

For the PM category, the alkaline digestion stage stood out with about 66.7% of the total, followed by soybean hulls production (18.6%). Sulphur dioxide and particulates <2.5 μm were the main emissions in this category, with 40.6% and 33.9% of the total, respectively, which were mainly observed in the alkaline stage. For the acidification category, alkaline digestion accounted for almost half of the impacts (47.1%), followed by loads related to hulls production (37.4%). Sulphur dioxide was also the most relevant substance, sharing half of the total impacts, which were observed in the alkaline digestion stage (64.1%). Soybean cultivation then placed ammonia emissions in second place, with a contribution of about 27% of the total SO_2eq.

3.2.3. *Eutrophication related categories*

Different hotspots were identified in the categories related to eutrophication. In the FE indicator, alkaline digestion stood out with 56.1% of the total impacts, while burdens related to hulls production highlighted in marine eutrophication (87.5%). In the case of the FE category, phosphate and phosphorus contributed 90.5% of the impacts, mostly observed in alkaline digestion and the cultivation stages.

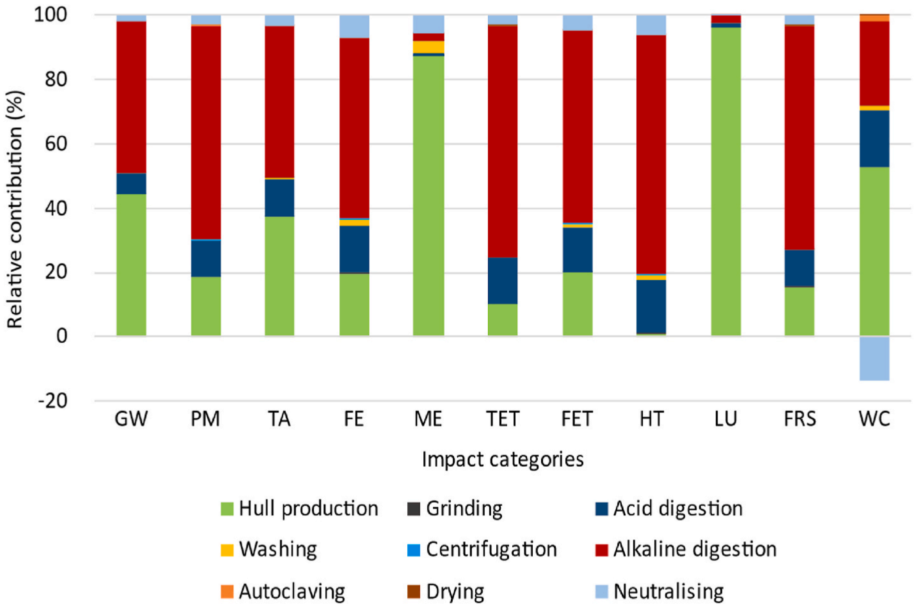


Fig. 5. Contribution analysis in the life-cycle profile of soybean hull-based DF.

Regarding the ME indicator, the hulls production stage contributed the most impact (87.5%), due to nitrate emissions (95.5%) mainly generated by the crop fertilisation process.

3.2.4. *Ecotoxicity and human toxicity categories*

Alkaline digestion was the main hotspot accounting for 71.7% and 59.9% of the total burdens in the TET and FET categories, respectively. In terms of terrestrial ecotoxicity, about half of the emissions were related to the substance copper, mainly identified in alkaline digestion (84.8%). Then, burdens related to zinc emissions played a minor role with a similar contribution (about 43–45%) in both digestion processes. Emissions in the FET category were related to zinc (55.3%) as the most relevant, followed by nickel and copper with less than 10% contribution each. In the human toxicity category, the alkaline digestion stage reached a share of 74.3% of the impacts, where chromium VI emissions were the most significant, representing 90.8% of the burdens in this category.

3.2.5. *Land use, fossil resource scarcity and water consumption*

Almost all impacts were associated with the production of soybean hulls (96.1%) in the land use category. In general, these burdens were due to the annual occupation of the crop (64.4%), and the conversion of forest land (25.5%). In terms of fossil resource scarcity, alkaline digestion accomplished the greatest contribution with 69.6% of the total impacts. The burdens were caused by the demand for natural gas (31.9%), coal (hard) (31.4%) and crude oil (14.6%). With respect to the WC category, hulls production was the most water consumer stage with more than half of the impacts, followed by the alkaline stage. In addition, the negative contribution in this category (e.g., Fig. 5) corresponds to the water returned to the Technosphere through wastewater treatment after the neutralisation process.

3.2.6. *Cumulative energy demand indicator*

Table 2 shows the results related to the cumulative energy demand indicator. This table indicates that the fossil source contributed the most (84.6%) to the non-renewable energy alternatives. On the other hand, the biomass source represented 57.7% of the renewable energy demand in the production of DF. In addition, the analysis of contribution of these categories is displayed in Fig. 6. From this, it is possible to observe that alkaline digestion was the stage that stood out in all categories with a share range of 49.3–91.1%. The energy demand of this process is mainly due to the production of KOH in almost all sources, except in the case of biomass, where steam production (from cogeneration systems) was the main contributor.

Table 2
CED indicator of the dietary fibre extraction.

CED category	Total (MJ)
Non-renewable, fossil	67.88
Non-renewable, nuclear	12.35
Non-renewable, biomass	0.01
Renewable, biomass	7.82
Renewable, wind, solar, geothe	1.62
Renewable, water	4.12

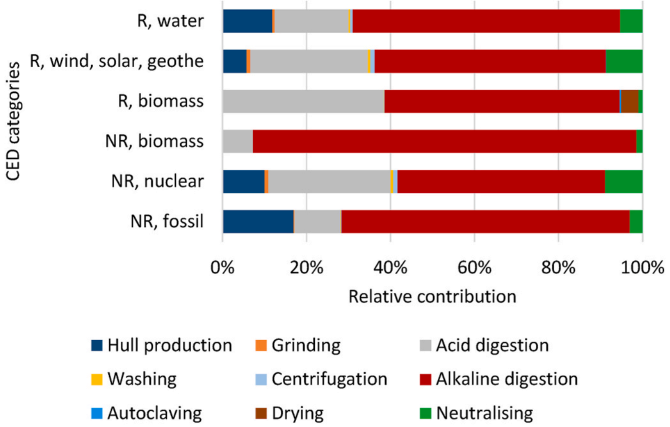
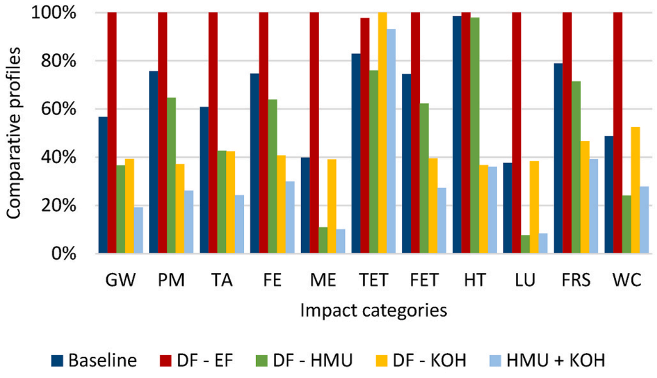


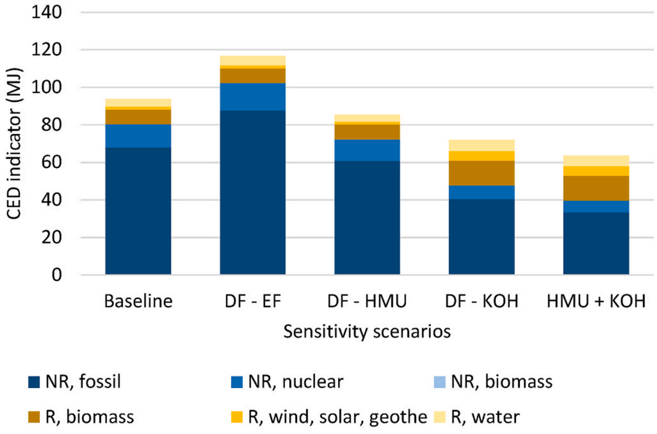
Fig. 6. Contribution analysis in the CED indicator of soybean hull-based DF (NR: non-renewable, R: renewable).

3.2.7. *Sensitivity analysis*

Fig. 7a displays the results obtained in the sensitivity analysis. It shows that an increase of only 10% in the economic allocation factor for hulls can drastically increase the environmental profile. Of these four alternatives, this case was the worst in almost all impact categories, except of TET but marginally (2% lower). Compared to the baseline, the



(a) Environmental profiles of soybean DF based on sensitivity scenarios



(b) CED indicator according to sensitivity scenarios

Fig. 7. Sensitivity analysis of the DF profile and CED indicator (DF-EF: increase of 10% in the economic factor allocation; DF-HMU: Hulls with multiple four co-products; DF-KOH: Renewable energy for KOH; HMU + KOH: Combination of DF-KOH and DF-HMU scenarios; R: renewable; NR: non-renewable).

DF-EF scenario reached values in the GW and WC categories of almost double, with 15.4 kg CO_2eq and 0.38 m^3, respectively. Besides, the largest increases were identified in LU and ME categories.

When soybean hulls are sourced from a manufacturing industry with a higher number of co-products (i.e., DF-HM), the environmental profile of the DF product improved in all categories with respect to the baseline. GHG emissions were reduced by around 35%, while a significantly decrease was observed in the LU (80%) and ME (78%) categories. For the DF-KOH scenario, two categories showed an increase in their values compared to the baseline. Terrestrial ecotoxicity and land use change increased by about 21% and 2%, respectively. In the former, this growth was caused by the higher burdens of the KOH production profile of Europe compared to the rest of the world, because of the potassium chloride production; while the latter was due to heat demand in potassium chloride production being provided by cogeneration systems. On the other hand, the most significant reductions were identified in HT (63%) and PM (51%), while fossil scarcity was reduced by around 41%. In addition, the HMU + KOH scenario was the best alternative in most categories, except in TET, LU and WC. An increase in the TET category of about 12% over the baseline was only found, while significant decreases were reached in categories such as LU (78%), ME (75%), GW (66%), and PM (65%).

In terms of changes in the CED indicator (see Fig. 7b), the HMU + KOH scenario encompasses the best performance in energy terms. Compared to the baseline situation, this scenario reduces demand for fossil fuels by about 51%. However, it significantly increases the demand for renewable energy sources, especially wind and solar, by about 215%, which is to be expected due to a complete mix of renewables in electricity generation. As well as a growth of about 70% in biomass demand. A 10% variation in the allocation factor (i.e., DF – EF scenario) resulted in a total increase from 93.8 to 116.8 MJ per kg of product (about 24%).

3.3. Comparison with literature studies

As mentioned above, only the work of Khanpit et al. (2023) has a close approximation to this work combining LCA and TEA approaches: the extraction of DF from agri-food waste. These authors evaluated the techno-economic implications and the environmental burdens of soluble dietary fibre concentrate (SDFC) production from citrus peel waste under 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 consisted of manufacturing 40 kg of SDFC per batch and the functional unit was 40 kg of SDFC. Their results showed that US and MC were the worst and the best strategies, with 145 and 49 kg CO_2eq, respectively (Khanpit et al., 2023). Regarding the economic dimension, they estimated an NPV (at a rate of 7%) of −43.4 to 20 million rupees, where the negative value corresponds to the ultrasonication alternative that cannot be implemented at the evaluated production scale. Furthermore, a payback period between 2.3 and 6.1 years was estimated, with a gross margin of between 26.2 and 55.7% for the profitable alternatives (e.g., MC, AC, AM, and EX).

In this regard, it is possible to point out the difference identified with this research. Firstly, these authors evaluated soluble DF, whereas here the total proportion of DFs was addressed. Therefore, a comparison of the environmental profile between them could not be appropriate. Secondly, they considered a gate-to-gate approach that could be taken as a partial LCA study, focusing only on the manufacturing phase of the life cycle. Thirdly, orange peels were considered a residual resource, so impacts from the cultivation stage were excluded. However, by excluding this stage the results related to the product profile could be misinterpreted, as the cultivation stage has a relevant contribution in impact categories such as eutrophication, land use and even in global warming, where it accounted for more than 40% of the loads (see Fig. 5). In the techno-economic perspective, the minimum selling price was not estimated, and the market price was set at 200 Indian rupee per kg of product (1 US$ = 78.6 Indian rupee, 2022 (IRS, 2023),). Khanpit et al. (2022) conducted a study that only focused on the life cycle impacts of converting insoluble DF into soluble DF from orange peels waste. However, aforementioned manuscript only considered the manufacturing process (i.e., a gate-to-gate boundary), and evaluated the product system on a laboratory scale, which implies that the results cannot be directly extrapolated to an industrial scale process (Piccinno et al., 2016). In particular, the impacts related to the global warming category were 1.5 and 3.97 kg CO_2eq for the extrusion and ultrasonication strategies, respectively, based on 0.1 kg of fresh orange peels input.

Regarding current or conventional alternatives for fibre production, the Agri-footprint® v6 database was used to identify suitable benchmarks. In this regard, fibre extraction from rice crop was identified. This dataset describes the extraction of protein, starch and dietary fibre from rice using the alkaline method, considering a gate-to-gate boundary. According to the inventory description, the activities include white rice from China, transport to the processing plant, water, heat and wastewater treatment. Furthermore, three allocation approaches are available to deal with the three co-products (protein, starch, and fibre): mass, economic, and energy. Considering the ReCiPe 2016 (H) method, the GW profile ranges between 0.97 and 2.25 kg CO_2eq with economic and mass allocation, respectively; where rice cultivation was the critical factor. These results are quite different from those obtained for soybean hulls, but it is important to note that different boundaries are addressed, which makes comparison difficult. Similar results are obtained for the other categories. From this, it is relevant to say that the crop from which the fibre extraction takes place can be critical for environmental performance, as soybean has a relevant footprint.

3.4. Limitations and future research

The main limitation in the environmental modelling was the use of indirect of sodium chlorate production data instead of sodium chlorite, as the latter was not available in the Ecoinvent® v3.8 database. In addition, no other similar studies were found in the literature, which restricts the possible comparative assessment of the results.

As prospective lines of research, firstly, other extraction methods that do not require the use of chemicals could be investigated. As could be demonstrated in this research, alkaline digestion was the critical process due to the use of the chemical KOH. Thus, the impacts associated with KOH can be reduced by replacing it with other less impactful alkaline activators. For instance, sodium hydroxide (NaOH) has half the impact on global warming of KOH, and has been used in different concentrations for the extraction of dietary fibre from dried cassava pulp (Okrathok et al., 2022). In addition, the environmental consequences of the application of this valorisation pathway to identify the effects of displaced products on the market could be an issue of interest.

4. Conclusions

This research presents a techno-economic and environmental overview of the extraction of dietary fibre from soybean hulls, showing that the alkaline digestion process was the main contributor of burdens in almost all categories. This was driven by the use of the chemical KOH, where electricity generation and potassium chloride production are the hotspots in its life cycle. In addition, soybean cultivation represents the largest contributor in categories such as marine eutrophication, land use and water consumption. While in global warming this stage is also relevant, contributing more than 40% of carbon dioxide emissions. In addition, the allocation approach is important in the profile of soy-based DFs, as a high number of co-products elaborated by manufacturing companies leads to more options for distributing loads upstream, especially when soy cultivation is a critical factor. However, if we consider an economic approach to allocate impacts, and the market price of hulls increases (e.g., due to higher demand), higher impacts related to the fibre production are expected.

In the economic dimension, the investment in fixed capital has a large contribution, due to the neutralisation section of the acid and alkaline streams of the digestion processes. Furthermore, the demand for KOH was the main concern in raw material costs. Nevertheless, the minimum selling price was 2.6 $\$\cdot kg^{-1}$, which is an expected price market.

CRediT authorship contribution statement

Ricardo Rebolledo-Leiva: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Maria Teresa Moreira:** Writing – review & editing, Validation, Supervision. **Sara González-García:** Writing – review & editing, Validation, Supervision, Funding acquisition.

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.

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Appendix A. Supplementary data

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