Ecodesign of new circular economy scheme for Brewer's side streams

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Abstract

When designing a new circular economy system, many aspects must be considered in order to benefit from all possible environmental improvements. The selection of the right market or use of the resulting product is of paramount importance to ensure the final implementation of the solution.

With this purpose this study has undertook the selection of a market that could absorb the large amounts of by-products generated in breweries, the optimisation of the logistics for the collection of by-products, and the ecodesign of a valorisation process and the facility needed to set up the full value chain.

This analysis has resulted in the ecodesign of a valorisation process of brewery's side streams aiming the production of ingredients for the formulation of aquacultures feeds.

Life Cycle Assessment has been used to find an efficient and sustainable processing scheme and to ecodesign a Model Recovery Plant that uses brewery's by-product as a second-generation feed stuff to produce ingredients for aquafeed.

The overall ecodesign of the new circular economy scheme for Brewer's side streams reached a reduction of the environmental footprint of 6 % in the resulting aquafeed products that account for the biggest part of the aquaculture footprint.

1 Introduction

European Union is one of the largest beer producers in the world with 402 million Hl and more than 11,000 breweries in 2019 (Brewers of Europe 2021). The brewing process produces large amounts of side streams, being the largest volume of wastes the brewers' spent grains (BSG) (80 % of total solid by-products), followed by brewers' yeast (BY) (10 %). In this scenario more than 6 million tons of BSG (15-20 kg of BSG per 1 Hl of beer) and 1 million tons of BY (1.5-3.0 kg of BY per 1 Hl of beer) are annually generated in Europe. The management of these side streams is variable among brewers, but BY is generally mixed and treated with wastewater, while BSG is used in fresh for animal feed (70 %), landfilled (20 %) or used for biogas production (10 %) (San Martin *et al.* 2021a). This implies an important environmental impact that, only regarding greenhouse gases emission, accounts 513 kg CO_2 equivalent by ton of waste landfilled and 83 kg CO_2 equivalent by ton of wastewater treated.

One of the potentials uses of these by-products is the productions of ingredients for the formulation of animal feeds. Life BREWERY project (https://lifebrewery.azti.es/) has ecodesigned a new circular economy scheme based on a sustainable solution for valorising brewery by-products as a second-generation feedstuff to produce new feed ingredients for aquaculture.

This decision is supported by the EU commission that indicates in its “Reflection Paper Towards a Sustainable Europe by 2030” that the development of sustainable aquaculture remains essential, and the inclusion of new ingredients sourced from by-products might help to reduce the aquaculture footprint.

Current results of LIFE-BREWERY project have demonstrated that brewers' by-products stand as a valuable alternative for replacing fish meal in aquaculture feed, due to their availability in Europe, their nutritional characteristics and the validation of the proposed valorisation process and products. The proposed scheme includes the steps to transform brewer's by-products in aquaculture feed ingredients. In short, the process consists in an enzymatical hydrolysis, to improve the ingredients digestibility, and an innovative and low energy demanding drying process (San Martin *et al.* 2020).

The resulting products have been tested and validated with three fish aquaculture species: Sea bream, as a model of a Mediterranean aquaculture specie; Senegalese sole, as a model of Atlantic specie; and Trout, as a model of a freshwater specie (Nazzaro *et al.* 2021).

On the other hand, several studies have promoted the consumption of aquaculture products over meat because of their lower environmental impacts, and so the overall approach is even more favourable from a holistic point of view.

Thus, the use of an Ecodesign approach is of paramount importance to maximize the reduction of the environmental impact of the proposed valorisation scheme to assure the best integration of the processes.

2 Material and methods

Ecodesign methodology is focused on increasing the efficiency and reducing the environmental impact of those aspect related to operational and investment requirements, such as energy, water and material requirements and outputs such as wastes, wastewater and other emissions.

Based on the requirements established by the valorisation process, an Ecodesign of a Model Recovery Plant (MRP) has been carried out by integrating all the functional and operational needs, considering the European environmental requirements and following Ecodesign criteria for the whole life cycle of the plant "from cradle to grave" (San Martin *et al.* 2019).

The use of Ecodesign criteria means that environmental impact will be considered in the same level as those which traditionally have been considered (cost, time & quality) with the aim of reducing the environmental impact of the plant throughout its whole life cycle.

The base of this methodology is to include the environmental attribute from the beginning of the ideation of the valorisation process and the MRP, when the degrees of freedom are sufficient to include improvement actions or strategies with high potential to reduce the overall environmental impact. To identify, quantify and compare environmental impacts linked to the management and infrastructure required of brewer´ spent grains and brewers´ yeast, Life Cycle Assessment (LCA) appears as an internationally recognized methodology.

The LCA is a method to assess the environmental impacts of a product, process or activity encompassing the whole value chain (cradle to grave). Moreover, its goal is to compare all environmental effects assignable to products and processes by quantifying resources use (inputs as energy, water and raw material) and environmental emissions (outputs as emissions to air, water and soil) associated with the system and assessing how these material flows affect the environment.

The general procedure of conducting an LCA is standardised in ISO 14040 (International- Organization-for-Standardization-(ISO) 2006a) and ISO 14044 (International-Organization-for- Standardization-(ISO) 2006b). An LCA consists of the following four phases:

- The Goal and Scope Definition (**phase 1**) includes a description of the goal of the study and covers the description of the target study. The intended audience is determined. The environmental aspects to be considered in the impact assessment and the interpretation and the functional unit, to which all emissions and resource uses are referred to and which determines the basis for the comparison, are defined.
- The elementary flows occurring in a process, the amount of semi-finished products, auxiliary materials, water and energy of the processes involved in the life cycle are determined and inventoried in the Inventory Analysis (**phase 2**). These data are set in relation to the functional unit. The outcome consists of the cumulative resource demands and the cumulative emissions of pollutants.
- The Inventory Analysis provides the basis for the Impact Assessment (**phase 3**). Applying current impact assessment methods, such as climate change impact according to IPCC (2013), on the inventory results leads to impact indicator results that are used and referred to in the interpretation.
- The results of the inventory analysis and the impact assessment are analysed and commented in the Interpretation (**phase 4**) according to the initially defined goal and scope of the LCA. Final conclusions are drawn, and recommendations are stated.

LCA is an iterative technique that allows to be increased the level of detail in successive iterations.

3 Results and discussion

The ecodesign of the new circular economy scheme proposed by the LIFE-BREWERY project is a holistic approach which deals with several aspects of the system:

1. Defining the circular economy scheme: Explore different alternatives in order to identify a suitable sector where the valorised raw material could substitute current non-sustainable ingredients,
2. Logistic optimization: ecodesign of an optimized distribution approach of by-products from the brewery to the final user or disposal facility,
3. Process ecodesign: Definition of a highly efficient process to valorise the brewery by-products and transform them in sustainable ingredients for aquaculture feeds,
4. Ecodesign of an efficient facility.

3.1 Defining the circular economy scheme

While the valorisation of any by-product is backed by most European strategies toward a more sustainable world and it is part of many principles of the 17 Sustainable Development Goals, the selection of a correct market or product might influence the final feasibility and profitability of the proposed solution, and therefore, its real implementation.

Aquaculture is one of the pillars of the EU's Blue Growth Strategy and its development can contribute to the Europe 2020 Strategy. However, aquafeeds are highly dependent on fish meal (FM) and fish oils (FO), consuming about 65 % of the FM and 83 % of the FO annually produced (Tacon *et al*. 2008). Alternative ingredients to reducing aquaculture’s dependence on marine resources are needed (Turchini *et al*. 2012). Furthermore, the use of alternative ingredients, such as soybean or rapeseed have demonstrated to reduce the environmental impact per tonne of aqua-feed up to 43 % in Global Warming potential (GWP) related to Green House Gases (GHG) (Samuel-Fitwi *et al*. 2013b; Stone *et al*. 2007).

In fact, the proposed solution is a win-win alternative for both sectors, brewing and aquaculture. Several studies have promoted the consumption of aquaculture products as one of the animal-protein products with less environmental impact, having a climate change potential impact significantly lower than other sources of animal protein (Lamb: 20.44 kg CO_2 eq/kg product > Beef: 15.23 kg CO_2 eq/kg product > Pork: 4.62 kg CO_2 eq/kg product > Gilthead Seabass: 4.4 kg CO_2 eq/kg product > Salmon: 4.14 kg CO_2 eq/kg product > Broiler: 2.33 kg CO_2 eq/kg product > Rainbow trout: 1.36 kg CO_2 eq/kg product) (García García et al., 2016; Hamerschlag and Venkat, 2011; Samuel-Fitwi et al., 2013a).

Moreover, aquaculture is projected to be the prime source of seafood by 2030, as demand grows from the global middle class and wild capture fisheries approach their maximum take.

Therefore, there is a need to ensure a more sustainable aquaculture to mitigate the environmental impacts linked to this growth. According to several publications (Bohnes and Laurent, 2019; Philis et al., 2019; Bohnes et al., 2019; Cidad and Ramos, 2021; Naylor et al. 2021) efforts should be focused on reducing the impact of fish feed production, since it is the major contributor to the total aquaculture environmental impact.

3.2 Logistics optimization

In a valorisation process of by-products the logistic for the collection of the by-product or the situation of the processing plant could have an important environmental impact that should be minimized through the ecodesign. The objective is to reduce the mass per distance factor, and in the valorisation of brewer's by-products, it implies reducing as much as possible the distance between by-products generation points and the valorisation facility, due to their high moisture content and the important weight reduction during the valorisation process.

In this study, the processing plant has been located as close as possible to the by-product generation point being this solution the most favourable. This is due because the scenario allows to foresee a plant that only need to process a single generation point that is sufficient to reach the critical mass to ensure the economic viability of the solution.

However, if one is evaluating the solution to collect by-products from small breweries, the selection of the optimal location and the collection routes should be optimized by using geographic information system assisted tools such as the GISWASTE tool (San Martin *et al.* 2021b). The tool will propose a facility location within the specified criteria (such as available space, or distance to main routes) and design collection routes that minimise the fuel consumption, that is directly related to the logistic footprint. The tool might also discard some generation points if the established profitability parameters are out of range. For these generation point that are too far away from logistics routes, dehydration *in place* could be a solution, although it may increase the cost of the processing.

3.3 Process ecodesign

3.3.1 Goal and scope definition

The goal of the study is to evaluate and compare through LCA methodology the environmental impact of current management systems of brewers´ spent grains and brewers´ yeast with the ecodesigned management system proposed by BREWER project (Table 1).

Table 1: Current and ecodesigned management option of BSG and BY assessed in this study.

Brewers´ spent grain (BSG)	Brewers´ yeast (BY)
· Landfill (Current management) · Incineration (Current management) · Valorisation: wet feed ingredient for livestock (Current management) · Valorisation: dried aquafeed ingredient (Ecodesigned management)	· Wastewater treatment (Current management) · Valorisation: dried aquafeed ingredient (Ecodesigned management)

The functional unit of this study is the management of **1 ton of brewers´ co-products** and the system boundaries follow a cradle-to-grave approach. As such, for landfill disposal, transport from brewery to dump and long-term emissions from the aerobic decomposition of organic material are included; for the incineration, the transport to the incineration plant and burning of organic material in the industrial furnace; for valorisation as wet livestock feed, transport of the co-products to the dairy farm and the substituted rapeseed meal are included; and last but not least, for the valorisation as dried aquafeed, transport of the co-products to the dehydration facility, an innovative and low energy demanding drying process (San Martin et al., 2020) and the transportation to the aquaculture company are included (**Figure 1**). Additionally, the substituted aquafeeds ingredient (mainly maize and soybean meal (> 80 %)) have been also included as avoided products.

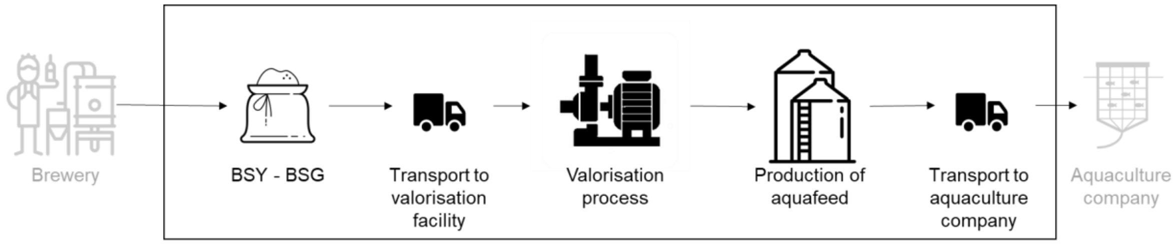

Figure 1: System boundary of the brewers´ by-products valorisation process.

Inventory data for current management pathways, incineration and landfill of organic co-products and the treatment of organic wastewater, were obtained from Ecoinvent 3.5 commercial dataset (Wernet et al, 2016): "Biowaste {GLO}| treatment of biowaste, municipal incineration", "Biowaste {RoW}| treatment of biowaste, open dump" and "Wastewater from potato starch production {RoW}| treatment of, capacity 1.1 E10 l/year" respectively.

Inventory data regarding amount of energy consumption, water consumption and process efficiency of the valorisation process of brewers´ co-products as aquafeed ingredients was collected during the demonstration trials preformed in LIFE BREWERY project. Data for the valorisation as wet feed in livestock was collected from the Product Environmental Footprint Category Rules of Beer study, published in the European Single Market from Green Product site (De Smet et al., 2018). Background inventory data (i.e. electricity or water production or cultivation and production of substituted feed ingredients) was obtained from the Ecoinvent 3.5 and Agrifootprint databases.

The environmental impact has been selected following the International reference Life Cycle Data system (ILCD) methodology (Table 2). This protocol was released by the European Commission, Joint Research Centre in 2012. It supports the correct use of the characterization factors for impact assessment as recommended in the ILCD guidance document "Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors (EC-JRC, 2011)".

Table 2: Environmental impact categories, unit and reference assessed in the current study

Impact category	**Unit**	**Reference**
Climate change	kg CO_2 eq	IPCC 2013
Ozone depletion	kg CFC-11 eq	World Meteorological Organization 1999
Ionizing radiation HH	kBq U^{235} eq	Frischknecht et al. 2000
Photochemical ozone formation	kg NMVOC eq	Van Zelm et al. 2008
Particulate matter	disease incidence	Fantke et al. 2016
Human toxicity, non-cancer effects	CTUh	USEtox model, Rosenbaum et al. 2008
Human toxicity, cancer effects	CTUh	USEtox model, Rosenbaum et al. 2008
Acidification	molc H^+ eq	Seppälä et al. 2006 and Posch et al. 2008
Freshwater eutrophication	kg P eq	ReCiPe version 1.05
Marine eutrophication	kg N eq	ReCiPe version 1.05
Terrestrial eutrophication	mol N eq	Seppälä et al. 2006 and Posch et al. 2008
Freshwater ecotoxicity	CTUe	USEtox model, Rosenbaum et al. 2008
Land Use	Pt (Dimensionless)	Soil quality index based on LANCA (EC-JRC)*
Water use	m^3 depriv.	Boulay et al. 2016
Resource use, minerals and metal	kg Sb eq	CML 2002, Guinée et al. 2002 and Van Oers et al. 2002
Resource use, fossils	MJ	CML 2002, Guinée et al. 2002 and Van Oers et al. 2002

*Beck et al. 2010 and Bos et al. 2016

3.3.2 Life Cycle Inventory

The following input-output inventory data have been considered for the impact assessment of the brewers´ by-products valorisation processes (Table 3).

Table 3: Life cycle inventory of 1 ton of brewers´ co-products (spent grains and yeast) valorisation as aquafeed and wet feed.

		BSG AS AQUAFEE	**BSY AS AQUAFEED**	**BSG AS WET FEED**
Output product				
Feed ingredient	kg	233.85	124.78	1.00
Avoided product				
Maize gluten feed	kg	77.63	43.45	
Soybean meal	kg	61.08	33.98	
Soybean protein feed	kg	18.51	7.53	
Fish oil	kg	8.91	5.75	
Fishmeal	kg	16.33	6.65	
Maize feed	kg	37.74	21.79	
Rapeseed meal	kg			0.29
Inputs from technosphere				
Brewers' spent by-product	tn	**1.00**	**1.00**	**1.00**
Heat	kwh	522.05	101.24	
Electricity	kwh	63.93	59.38	
Transport to valorisation	kgkm	2.50E+05	2.49E+05	
Transport to aqua	kgkm	1.17E+05	6.24E+04	0.50E+02
Outputs to technosphere				
Wastewater	L	444.62	707.96	

3.3.3 Life Cycle Impact Assessment

As observed in the Table 4, and considering that certain feed ingredients are substituted, the valorisation of BSG could potentially reduce the overall environmental impacts attributed to the management of 1 ton of BSG. Indeed, 274 kg of CO_2 eq. are avoided when choosing this management option.

The valorisation process (dehydration) consumes high amounts of energy which has a significant impact on the environment (+ 200 Kg CO_2 eq.). However, due to the avoidance of fishmeal and soymeal cultivation and production (- 474 Kg CO_2 eq.), the overall environmental impact obtains a negative value.

Table 4: Environmental impact characterization of the valorisation of 1 ton of BSG as aquaculture feed ingredient.

Impact Category	**Unit**	**Valorisation of BSG**	**Processing BSG**	**Substituted ingredients**
Climate change	kg CO_2 eq	-2.74E+02	2.00E+02	-4.74E+02
Ozone depletion	kg CFC-11 eq	-2.43E-06	2.32E-05	-2.57E-05
Ionising radiation	kBq U^{235} eq	1.14E+01	1.96E+01	-8.25E+00
Photochemical ozone formation	kg NMVOC eq	-1.03E+00	3.19E-01	-1.35E+00
Particulate matter	disease inc.	-1.73E-05	2.95E-06	-2.03E-05
Human toxicity, non-cancer	CTUh	-6.54E-06	1.11E-06	-7.65E-06
Human toxicity, cancer	CTUh	-1.68E-07	4.65E-08	-2.15E-07
Acidification	mol H^+ eq	-1.99E+00	4.37E-01	-2.43E+00
Eutrophication, freshwater	kg P eq	-2.95E-02	3.55E-02	-6.50E-02
Eutrophication, marine	kg N eq	-1.73E+00	9.29E-02	-1.82E+00
Eutrophication, terrestrial	mol N eq	-8.45E+00	9.27E-01	-9.37E+00
Ecotoxicity, freshwater	CTUe	-8.92E+03	1.59E+03	-1.05E+04

Land use	Pt	-4.30E+04	1.12E+03	-4.42E+04
Water use	m^3 depriv.	-9.31E+01	-5.20E+00	-8.79E+01
Resource use, fossils	MJ	2.34E+02	3.03E+03	-2.79E+03
Resource use, minerals and metals	kg Sb eq	-9.65E-05	1.47E-03	-1.57E-03

As with BSG, the valorisation of BY as aquafeed ingredient could potentially reduce the overall environmental impact. Indeed, as could be observed in Table 5, 176 kg of CO_2 eq. is avoided per ton of BY valorised when choosing this management option. The valorisation (drying) process consumes high amounts of energy for the dehydration which has an impact on the environment (+ 70 Kg CO_2 eq.). However, due to the avoidance of fishmeal and soymeal cultivation and production (- 246 Kg CO_2 eq.), the overall environmental impact obtains a negative value.

Table 5: Environmental impact characterization of the valorisation of 1 ton of BY as aquaculture feed ingredient

Impact Category	**Unit**	**Valorisation of BY**	**Processing BY**	**Substituted ingredients**
Climate change	kg CO_2 eq	-1.76E+02	7.07E+01	-2.46E+02
Ozone depletion	kg CFC-11 eq	-2.92E-06	8.93E-06	-1.18E-05
Ionising radiation	kBq U^{235} eq	1.14E+01	1.58E+01	-4.39E+00
Photochemical ozone formation	kg NMVOC eq	-5.48E-01	1.58E-01	-7.06E-01
Particulate matter	disease inc.	-9.30E-06	1.66E-06	-1.10E-05
Human toxicity, non-cancer	CTUh	-3.45E-06	6.27E-07	-4.07E-06
Human toxicity, cancer	CTUh	-9.33E-08	2.11E-08	-1.14E-07
Acidification	mol H^+ eq	-1.06E+00	2.52E-01	-1.31E+00
Eutrophication, freshwater	kg P eq	-3.74E-03	2.84E-02	-3.21E-02
Eutrophication, marine	kg N eq	-9.44E-01	5.56E-02	-9.99E-01
Eutrophication, terrestrial	mol N eq	-4.60E+00	5.22E-01	-5.12E+00
Ecotoxicity, freshwater	CTUe	-5.01E+03	8.04E+02	-5.81E+03
Land use	Pt	-2.32E+04	7.65E+02	-2.40E+04
Water use	m^3 depriv.	-6.62E+01	-1.80E+01	-4.82E+01
Resource use, fossils	MJ	-3.18E+02	1.18E+03	-1.50E+03
Resource use, minerals and metals	kg Sb eq	-1.14E-05	8.29E-04	-8.41E-04

3.3.4 Interpretation

When comparing the obtained environmental impact characterisation results with current management options (incineration, landfill and valorisation for livestock animal feeding (wet feed ingredients)), significant impact reduction results are observed (Table 6). For instance, almost 300, 1000 or 150 kg of CO_2 eq could be avoided per ton of BSG generated, when choosing this management option instead of incineration, landfill or valorisation for livestock animal feeding, respectively.

Table 6: Avoided impact when comparing the valorisation of 1 ton of BSG as aquafeed ingredient with current management alternatives (incineration, landfill and wet valorisation).

Impact Category	**Unit**	**vs. incineration**	**vs. landfill**	**vs wet valorisation**
Climate change	kg CO_2 eq	3.13E+02	1.03E+03	1.48E+02
Ozone depletion	kg CFC-11 eq	5.37E-06	2.43E-06	-9.51E-06
Ionising radiation	kBq U^{235} eq	-1.04E+01	-1.14E+01	-1.79E+01
Photochemical ozone f	kg NMVOC eq	1.30E+00	1.26E+00	5.04E-01
Particulate matter	disease inc.	1.99E-05	1.74E-05	-3.62E-06
Human toxicity, non-cancer	CTUh	1.06E-05	7.89E-06	-6.20E-06

Human toxicity, cancer	CTUh	2.57E-07	1.72E-07	-3.60E-08
Acidification	mol H^+ eq	2.24E+00	2.06E+00	-1.09E+00
Eutrophication, freshwater	kg P eq	7.81E-02	1.22E-01	-8.83E-03
Eutrophication, marine	kg N eq	1.87E+00	3.00E+00	-1.12E+00
Eutrophication, terrestrial	mol N eq	9.54E+00	8.45E+00	-4.65E+00
Ecotoxicity, freshwater	CTUe	1.06E+04	3.87E+04	5.97E+03
Land use	Pt	4.33E+04	4.34E+04	-3.49E+05
Water use	m^3 depriv.	1.08E+02	9.31E+01	-3.59E+00
Resource use, fossils	MJ	7.43E+00	-2.34E+02	-9.67E+02
Resource use, m.m	kg Sb eq	9.91E-04	9.65E-05	-3.53E-03

When comparing the obtained impact characterisation results with current management practice as wastewater, significant impact reduction results are observed in the environmental assessment (Table 7). For instance, 177 Kg of CO_2 eq. could be avoided per ton of BY generated, when choosing this management option instead of treatment with wastewaters.

Table 7: Avoided impact when comparing the valorisation of 1 ton of BY as aquafeed ingredient with current management alternative (wastewater).

Impact Category	**Unit**	**vs. wastewater**
Climate change	kg CO_2 eq	1.77E+02
Ozone depletion	kg CFC-11 eq	2.96E-06
Ionising radiation	kBq U^{235} eq	-1.14E+01
Photochemical ozone f	kg NMVOC eq	5.51E-01
Particulate matter	disease inc.	9.36E-06
Human toxicity, non-cancer	CTUh	3.46E-06
Human toxicity, cancer	CTUh	9.44E-08
Acidification	mol H^+ eq	1.07E+00
Eutrophication, freshwater	kg P eq	4.08E-03
Eutrophication, marine	kg N eq	9.49E-01
Eutrophication, terrestrial	mol N eq	4.61E+00
Ecotoxicity, freshwater	CTUe	5.03E+03
Land use	Pt	2.32E+04
Water use	m^3 depriv.	2.77E+01
Resource use, fossils	MJ	3.28E+02
Resource use, m.m	kg Sb eq	2.68E-05

As far as the main environmental impact of food waste recovery is related to the energy consumption and wastewater generation of the processing plant (Salemdeeb *et al*. 2017), the reduction of the impact within the solution could lead to great improvement of the whole final feed ingredient, and thus also of the final aquaculture product. After the assessment of the global solution the main environmental impacts evaluated are: climate change, acidification, eutrophication terrestrial and land use, which have been selected following the International reference Life Cycle Data system (ILCD) methodology.

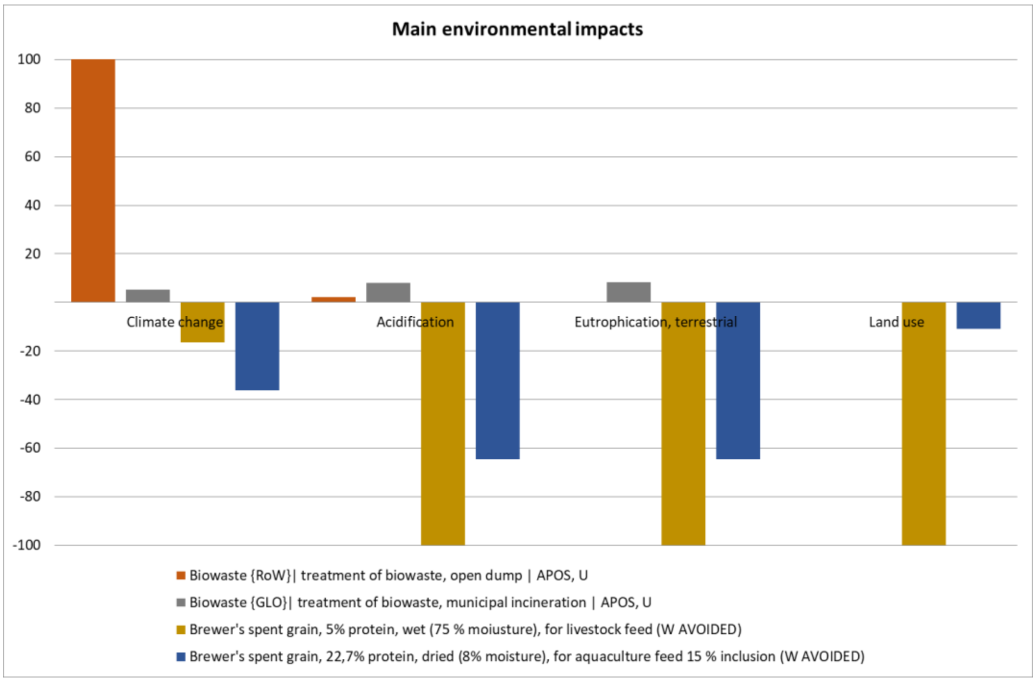

Figure 2: Main environmental impact characterization of the 4 different management alternatives of 1 ton of BSG: Landfill, Incineration, Valorisation for livestock animals feeding, and Valorisation for aquafeeds. Climate change (kg CO_2 eq.), acidification (mol H^+ eq.), Eutrophication terrestrial (mol N eq.) and Land use (Pt).

Considering that certain feed ingredients are avoided, the valorisation of brewers´ by-product spent grains potentially reduces the overall environmental impacts. Indeed, regarding climate change impact category, 274 kg of CO_2 eq. are avoided when choosing this management option. The management itself consumed high amounts of energy which has a significant impact on the environment (+ 200 kg CO_2 eq.). However, due to the avoidance of fishmeal and soymeal cultivation and production (- 474 kg CO_2 eq.), the overall environmental impact obtains a negative value.

Moreover, with the proposed solution, the valorisation of brewers' by-product spent grains, would lead to a potential saving on greenhouse emissions of about 1000, 300 and 150 kg of CO_2 equivalents per ton related to current management options landfill, incineration and valorisation for livestock animal feeding, respectively.

Furthermore, the implementation of the ecodesign approach in the facility design allows the reduction of energy demand by the integration of flows and energy uses, as well as the implementation of high thermal efficient systems and thermal and electric power generation in site.

On the other hand, the use of brewer's by products will also contribute to reduce the environmental impact related to aquaculture feed production, by substituting FM or edible crops. In example, considering the production of feed ingredients and their transport to feed mill, the aquafeeds obtained with LIFE BREWERY ingredients show significant benefits comparing with commercial aquafeed, such as the reduction of 6 % of climate change among others. Moreover, LCA studies indicates that more than 90 % of the impact related to the aquaculture product is related to aqua-feed, and thus, within the inclusion of environmentally improved feeds, the impact of the final product could be also reduced (Naylor et al., 2021).

The Ecodesign of the MRP reduces the impact of the valorisation process evaluating not only the avoided impact, but also leading to a more sustainable design of the process, the facilities and the logistics related to this new circular economy scheme.

3.4 Ecodesign of an efficient facility

In most life cycle analysis, facility or infrastructure contribution to the environmental footprint of products its usually neglected due to its little contribution to the overall impact. However, in the LIFE-BREWERY project, life cycle assessment was used for the decision making from the early design stage of the building along with energy simulation strategies. On the one hand, the reduction of heating and cooling energy consumption during use phase, and on the other hand, the selection of construction materials with lower environmental impacts, applicable in a Model Recovery Plant (MRP) located in the North-East of Spain with an estimated processing capacity of 28000 ton of BSG and 5400 ton of BY with a surface of 3200 m^2.

Initial LCA studies centred on the selection of materials with the least environmental impact for the main building elements. Different construction alternatives were analysed separately, in order to reduce the environmental impacts of the construction process. Final studies were complete building analysis to establish overall lifecycle impact of the proposed building, which were used to complete additional value engineering for the final design, optimising the proposal for less impact.

The functional unit was defined as 1 m^2 of gross internal floor area of a logistic warehouse located in Lleida and built in 2020. A lifespan of 60 years was considered. As system boundaries, the analysis included the production of construction materials, transport of the materials to the construction site, construction, use stage (maintenance, replacements, heating and cooling energy consumption) and end of life (EoL).

Life cycle analysis at different stages of the design process including specific element studies, have proven essential for reducing the overall impact of the building. This can be seen in the following Figure 3 in which the environmental impacts of the proposed design and final design are compared with the initial preliminary design. The preliminary design contemplated eco-design concepts, optimising thermal envelope and structure. Further LCA of specific construction elements (structure, facades, windows) resulted in an optimization of the environmental impacts reflected in the Proposed Design. The Final Design incorporates final value engineering which considered costs, energy performance and life cycle impacts of all materials, reducing overall volume of the construction solutions.

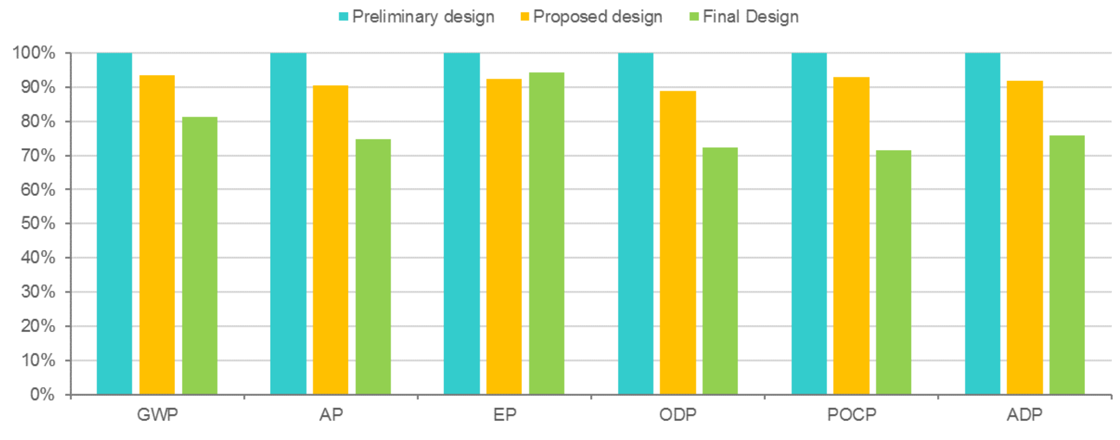

Figure 3: Comparison of Life-cycle assessment between preliminary, proposed and final design. (GWP: global warming, AP: acidification, EP: eutrophication, ADP: abiotic depletion, ODP: ozone depletion, POCP: photochemical oxidant creation)

For the MRP analysed, located in Lleida, energy consumption during use phase was reduced almost 30 % from the preliminary design. Moreover, LCA results of the proposed design revealed that heating and cooling energy consumption during use phase represented from 9 % to 25 % depending on the environmental category, while the impact of construction materials ranged from 54 % to 70 %.

These results highlight the need to consider the whole life cycle of the building in the design of low environmental buildings. When final design was compared to preliminary design a reduction of life cycle environmental impact between in all categories was achieved with reductions higher than 20 % in GWP, AP, ADP, OPC and POCP and higher than 5 % in EP.

Table 8: Environmental impacts of Final building design (Energy in use not included)

	Global warming Kg CO$_2$eq	Acidification Kg SO$_2$eq	Eutrophication Kg PO$_4$eq	Ozone depletion potential kg CFC11eq	Formation of ozone of lower atmosphere Kg Ethenee	Total use of primary energy ex. raw materials MJ
Construction product	1385636.70	4425.10	1121.11	0.07	388.56	12906671.20
Transportation to construction	33577.46	77.28	16.33	0.01	4.23	633899.48
Installation / construction process	70637.50	244.90	145.50	0.01	8.82	1301086.01
Mainenance and material replacement	401842.57	837.83	95.14	0.01	154.71	6423501.67
In-service energy use	316449.75	1530.00	206.15	0.04	75.13	7121880.54
End of life						
External impacts	-246446.72	-438.62	-97.95	0.00	-37.93	-2977980.71
Total	2384241.80	7253.81	1609.14	0.13	641.89	28830993.46
Results per gross internal surface area	745.08	2.27	0.50	0.00	0.20	9009.69
Results per year	39737.36	120.90	26.82	0.00	10.70	480516.56
Result per gross internal surface area and year	12.42	0.04	0.01	0.00	0.00	150.16

Final values indicate a carbon footprint of 2384 ton CO$_2$ eq in the whole MRP life, that contributes to 39.7 ton per year, or 1,19 Kg CO$_2$eq per ton of raw material processed (Table 8).

Spanish regulations do not require reductions in the environmental impact through the life cycle approach, instead only energy consumptions, generation and CO$_2$ emissions are stipulated. However, Leadership in Energy and Environmental Design (LEED) certification scheme, has a credit called Building Life-Cycle Impact reduction, where LCA of the project's structure and enclosure must demonstrates a minimum of 10 % reduction, compared with a baseline building, in at least three of the six impact categories analysed in this chapter, one of which must be global warming potential. The reduction achieved in this research could allow to meet LEED requirements in case of certification would be pursued.

4 Conclusions

Results of the LIFE-BREWERY project have demonstrated that the valorisation of brewers' co-products as aquafeed ingredients is more sustainable than current management practices and can be the basis on a new circular economy scheme.

The valorisation process has been ecodesigned to reduce the environmental impact of the solution. The facility characteristics have been also optimised to reduce the environmental footprint. Further environmental gains could be achieved if the impact of the consumed energy is reduced by, e.g., shifting towards renewable sources of energy. The environmental footprint has also been reduced by optimizing logistics; decreasing distances between the brewery/ies, where the co-products are generated, and the fish feed ingredients processing plant.

Selecting the most appropriate product and market is of paramount importance for the final viability of the proposed solution. The product and market chosen for the resulting products has also been chosen taking into account its environmental impact and its capability of absorbing all the production.

In this regard, the comparison between the aquafeeds obtained with LIFE BREWERY ingredients and commercial aquafeed showed significant benefits, including a 6 % reduction in climate change.

The valorisation of Brewers´ by-products as an ingredient for the formulation of aquafeed has an important favourable effect both in brewers and aquaculture environmental impact. The use of an Ecodesign methodology has improved the preliminary environmental advantages of the scenario leading to a more sustainable circular economy scheme exceeding initial expectations.

Author contributions

B.I. coordinated the research and writing of this article. All authors contributed substantially to the conceptualization of the topic and the writing of the article.

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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