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THESIS TITLE

Comparative environmental evaluation in bakery and brewing sectors with the use of brewery spent grain and unsold bread in a circular economy context

Thesis in
Formulation and Product Innovation

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ABSTRACT

This study assessed the environmental impact of beer and bread production in the context of a circular economy using the LCA application with Open LCA software. It consists in evaluating and comparing of innovative products like brewery spent grain breads and beers made by unsold bread. A “cradle to gate” approach was chosen. The supply chain considers the cultivation phase, milling, malting and production of ingredients (salt, yeast and hops). It provides an insight into whether it is environmentally sustainable to use spent grains and unsold bread to produce the same product category. The most important hot spot for both productions is cultivation. In bread production, the hot spots are bakery and proofing steps (energy required) and in brewery the packaging by far followed by boiling and hopping (because of not recycling glass bottles and heat demand). In addition, along BSG stabilisation process the hot spots are drying and co-product transportation. The most impactful products turn out to be conventional ones. In some cases, they have lower impacts than products which have co-products as ingredients, for example, high protein flour breads because the process efficiency. Organic products have lower impacts in some impact categories but it has to be analysed. Usually, in organic products land use and marine eutrophication are significantly reduced after the use of co-products. Comparing traditional baguette with brewery spent grain bread and a standard beer with the “bread beer” the results are favourable to the innovative production. This is a broad study and helps to give a general idea of which product is better from an environmental point by making comparisons between several products. CML-IA baseline and ReCiPe Midpoint (H) 2016 are compared, the second one resulted more suitable because it gives more details in terms of environmental impacts especially for the brewing part. However, at the end of analysis the product impact hierarchy is maintained with both methods. The last step was to compare the whole systems, circular and traditional. A sum between environmental impact categories is made. It concludes that the circular system underlines few impacts with less values comparing to the traditional system like freshwater ecotoxicity, land use, marine eutrophication, mineral resource scarcity, stratospheric ozone depletion and terrestrial acidification; fine particulate matter formation; global warming; ozone formation, human health; ozone formation, terrestrial ecosystems and terrestrial eutrophication. In conclusion, were found positive results about circular economy. However, further studies are needed for example chemical-physical final product analisi and sensory evaluation and also several aspects have not been considered in the model, assumptions are a big limitation il LCA studies.

ABBREVIATIONS

A: Acidification

ADff: Abiotic depletion (fossil fuels)

AD: Abiotic depletion

AB: Avoided barley

AOX: Chlorinated organic compounds

AX: Arabinoxylans

BOD: Biological oxygen demand

BSG: Brewery spent grain

CE: Circular economy

CF: Carbon footprint

CS: conventional system

CFU: colony-forming unit

COD: Chemical oxygen demand

E: Eutrophication

EIC: environmental impact categories

EU: European Union

FE: Freshwater ecotoxicity

FEutr: Freshwater eutrophication

FPMF: fine particulate matter formation

FRDP: Fossil resource depletion potential

FRS: Fossil resource scarcity

FSC: Food supply chain

FU: Functional unit

FWAE: Fresh water aquatic ecotoxicity

GHGE: Greenhouse gases emissions

GW: Global warming

GWP: Global warming potential

HCT: Human carcinogenic toxicity

HM: Heavy metals

HNCT: Human non-carcinogenic toxicity

HPF: High protein flour

HT: Human toxicity

IR: Ionizing radiation

IRSTV: Institute De Recherche En Sciences Et Techniques De La Ville, Nantes
ISO: International Organization for Standardization
LCA: Life cycle assessment
LCC: Life cycle costing
LCIA: Life cycle impact assessment
LEAP: Long-range Energy Alternatives Planning
LU: Land use
MAE: Marine aquatic ecotoxicity
ME: Marine ecotoxicity
MEutr: Marine eutrophication
MRS: Mineral resource scarcity
OLD: Ozone layer depletion (ODP)
OF, HH: Ozone formation, Human health
OF, TE: Ozone formation, Terrestrial ecosystems
PEF: Product Environmental Footprint
PO: Photochemical oxidation
SCFAs: Short-chain fatty acids
S-LCA: Social life cycle assessment
SOD: Stratospheric ozone depletion
TA: Terrestrial acidification
TE: Terrestrial ecotoxicity
TS: Traditional system
TSS: Total suspended solids
TTL: Triple top line
XOS: Xiloligosaccharides
WECCE: without environmental charging circular economy
ECCE: environmental charging circular economy
WC: Water consumption

a. INTRODUCTION

0. Motivation and goal scope

The work is commissioned by the Institute De Recherche En Sciences Et Techniques De La Ville, Nantes (IRSTV) with the collaboration of Ecole Centrale De Nantes and Oniris-Nantes University.

The economic, social and environmental importance of the agri-food sector is well known. The challenge is how to provide a growing population with good, safe, healthy food while decreasing the pressure and impacts on ecosystems, resource and human health. Life cycle assessment (LCA) is the appropriate method to identify, with high degree of detail, environmental hotspots, compare techniques, crops and inform with scientific data the decision makers at both, firm and political level. However, LCA application in the agri-food sector is a complex and challenging endeavour (Notarnicola et al., 2015).

Lastly, a comprehensive study on the circularity between brewing and breadmaking is deemed essential. In this way, the evaluation of the distinct pathways identified could help to clarify the choices of future economic actors wishing to start a new business or of any researcher or manager wishing to participate in a project to exploit spent grain and to manage unsold bread in food.

This thesis purpose (partnership with Oniris École Nationale Véterinaire, Agroalimentaire et de l'Alimentation – Nantes and École Centrale de Nantes) is to use the LCA method to compare the environmental impact of alternative uses of brewery spent grain (BSG) in bread making and the use of stale/unsold bread in beer production. The project is carried out in a circular economy context. The idea was born on one hand from a strong interest in environmental preservation (a very hot topic nowadays). On the other hand, from the passion for the brewery sector, from the importance of the brewing and baking industry in EU and worldwide (Capitello & Maehle, 2021; Martin-Lobera et al., 2022; Roy et al., 2009). 8 million tonnes in Europe and 40 million tonnes worldwide of BSG are produced annually. Recovering these products is a key opportunity in the current context of sustainable food transition, as it is an important source of protein, fibre and other nutrients for human nutrition (Petit et al., 2020). The same argument can be made for stale/unsold bread: food waste generates significant economic losses globally and bread is the most wasted food product in developed countries. It is estimated that bread production generates about 100 million tonnes per year, 65% of which is consumed in Europe (Martin-Lobera et al., 2022). It is difficult to quantify the precise amount of wasted bread, but it has been approximated that, globally, 10% of all manufactured bread is wasted (Narisetty et al., 2021).

It focuses to a small industry scale (craft local breweries and local bakeries) but, maybe in the future, it can be transferred to a big scale production using the same method. The re-use of co-products for human consumption remains one of the noblest alternatives to be pursued as illustrated in figure 1 (Metcalfe et al., 2017).

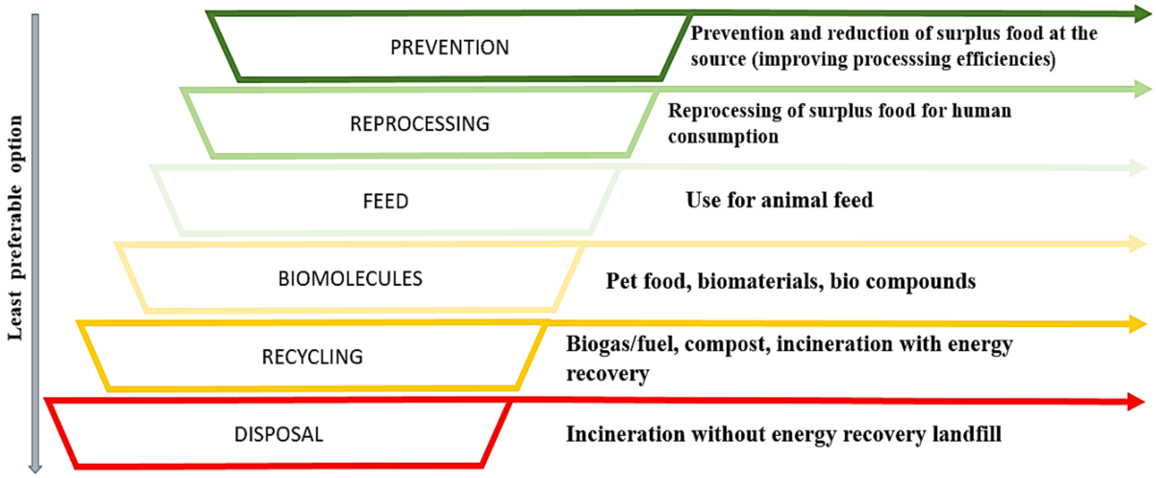


Figure 1. Upcycling food hierarchy. Adapted from Metcalfe et al., 2017

Looking at the increasing pace of the world population, in 2050, three times as much energy will be consumed as the planet can return in one year (United Nations, 2022). Therefore, the 17 Sustainable Development Goals were drawn up in 2015 with the aim of achieving them by 2030. Promoting prosperity by protecting the planet through environmental, social and economic aspects is the priority of these goals (United Nations, 2022). We need to reformulate our system and build a transition to a sustainable economy to reach the European target of carbon neutrality by that year. This is where the circular economy can play an important role. First and foremost, in order to understand which strategies to undertake, we need a standardised and reliable method that allows us to compare various production scenarios between innovative and conventional methods. The LCA method is the one that possesses these characteristics (Roy et al., 2009).

1. Sustainability situation – current context

1.1 Food wastage – Food losses / Co-products management

Annual waste production is expected to increase by 50% by 2050 (Kaza et al., 2018) and material consumption is expected to become twice as high as today (Borowski, 2020). Food production and waste (it is estimated that one third of the total food produced each year is lost or wasted along the food supply chain (FSC)), contributes to resource depletion, global warming and biodiversity loss (Gustavsson et al., 2011). New policies at the European level are gaining increasing visibility. For example, the Circular Economy Action Plan, the Farm to Fork strategy, both included in the European Green Deal (European Commission, 2019).

- ➢ The definition of food waste is:
  - The total amount of food diverted from human consumption.
- ➢ Difference between losses and waste:
  - Food losses are generated during the initial stages of the supply chain. Agricultural processes, transport, process industry, handling and storage.
  - Food waste is the food wasted during the final stages of the supply chain: retail and consumption (FAO, 2013).

Usually, by-products and co-products have a lower value than the main product. Many authors think that by-products can contribute to obtain food products with nutritional claims or extraction of other high value ingredients (Ong et al., 2018). Thanks to a specific add value prosses, it is possible. The factor to be verified is the environmental impacts (the purpose of this study). Consequently, in the future, an economic evaluation by Life Cycle Costing (LCC) and a social evaluation by Social Life Cycle Assessment (S-LCA), should be carried out (Tamasiga et al., 2022). McDonough and Braungart (McDonough & Braungart, 2002) proposed the Triple Top Line (TTL), figure 2. The TTL aims to maximise economic performance with social and environmental aspects without compromises. According to the study, company profit can increase if these three factors increase. Economy, ecology and equity must be maximised and not balanced. The change of mindset is necessary to bring companies closer to the circular economy and sustainable development. Indeed, companies should extend the Triple Top Line to supply chain partners (e.g. farmers, suppliers, retailers) to achieve a circular supply chain (Brown et al., 2019). Companies should collaborate and create an exchange network regarding waste and raw materials, they should work symbiotically (Maranesi & De Giovanni, 2020; Salomone et al., 2020).

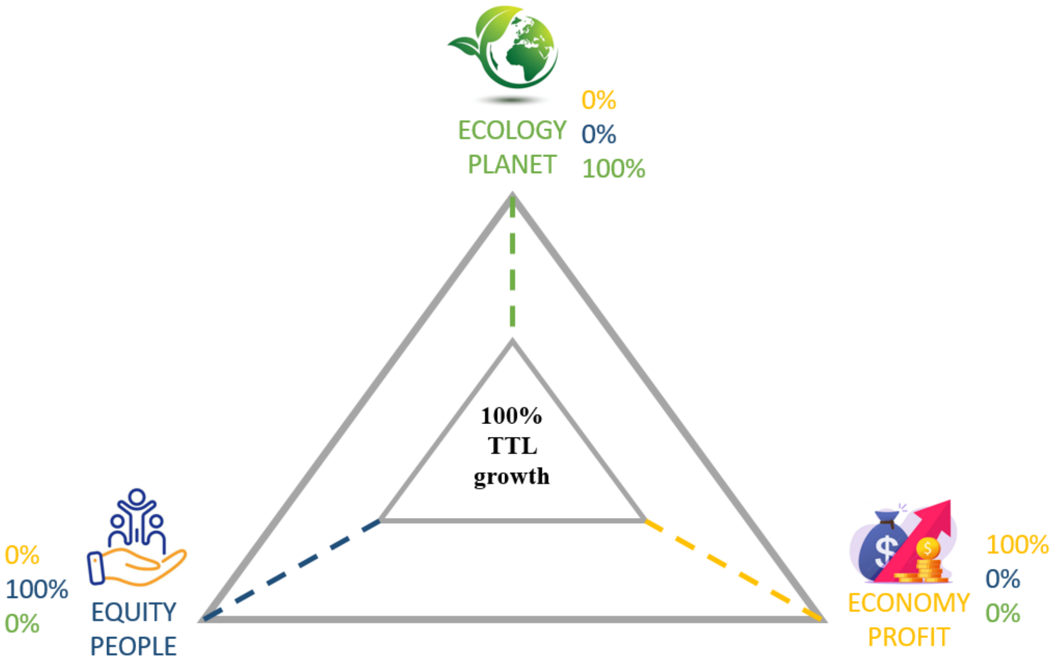


Figure 2. Fractal triangle representing the Triple Top Line that aims at generating value in each category maximizing economy, ecology and social equity. Re-adapted from McDonough & Braungart, 2002

1.2 Circular economy – Waste valorisation

The linear take-make-waste economy is replaced by a circular economy (CE). The regeneration of natural systems and the preservation of used products, supplies and materials while reducing waste and pollution are the goals of the circular economy. Reduce; recover; reuse and recycle replace the notion of end-of-life in processes. There are three different operational levels of the CE: the micro-level (products, businesses, and consumers), the mesolevel (industrial level) and the macro-level (cities and other geographical units). In this case study reference is made to a micro-level. The purposes of CE are to prevent environmental degradation and to ensure the economic and social well-being of present and future generations. Reducing food waste is one of the most critical sustainability issues in the food sector (Zhang, 2022); (Tamasiga et al., 2022).

The Circular Economy (CE) aims to achieve a zero-waste society. The goal is to create interconnected economies in which new products and applications are obtained from "waste" used as inputs. This concept is the basis of industrial symbiosis. The circular system characterises the cradle-to-cradle approach, enabling the development of the three pillars: economy, ecology and equity. In fact, environmental sustainability is not enough. The food produced must be palatable and economically viable (Galanakis, 2020). CE enables the reduction of resource and energy use, waste generation and greenhouse gas emissions. It enables the development of energy-efficient systems, promotes the use of renewable energy and closes energy and material cycles. Sustainable development benefits both current and future generations (Tamasiga et al., 2022).

Valorising by-products and wastes in the context of the CE is therefore crucial, (Teigiserova et al., 2020). The high homogeneity and high concentration of such products makes it possible to obtain high value-added products (Ong et al., 2018).

These can be subjected to extraction processes to obtain important molecules (for food additives or pharmaceutical products). Some valorisation options are preferred as they provide greater environmental benefits reuse of waste and food by-products for human consumption. (Chiaraluce et al., 2021). The concept of CE is a promising idea to address sustainability issues in the food sector by offering a restorative and regenerative production and consumption scheme in the food segment. However, it may be a narrative device or a new form of greenwashing and faces validity challenges at this time (Zhang, 2022).

Another form of recycling is upcycling, which consists of generating high-value products from waste materials, so as well as preventing food waste and loss, it is a way of maximising the value of agricultural inputs and actions taken to produce food (Sung, 2015). The CE cannot be implemented if it is not produced “cum grano salis”. In fact, products must be circular, regenerative and easily recyclable when they reach the end of their life (McDonough & Braungart, 2002).

1.3 Eco-design

Eco-design is the systematic integration of environmental considerations into product and process design. It is a systematic integration of environmental aspects in the development of a product with the aim of reducing negative environmental impacts during its life cycle with a superior or equivalent service. Only if the product is designed to be sustainable can the environmental impact be levelled out. In this way, it uses fewer resources and has a lower impact, reduces emissions and pollution, and optimises the steps in the production chain. At the same time, it ensures that product quality and safety are maintained. In this way, it provides economic, social and environmental benefits (Hauschild et al., 2018).

1.4 Sustainability – Oriented innovation

Companies must change their business model if they want to implement the CE. All the environmental issues we are experiencing (climate change, resource depletion, environmental degradation, loss of biodiversity) are literally new opportunities to stand out from the competition. Innovation is at the heart of this initiative. However, it is essential to engage executives, employees, managers and corporate decision-makers to incorporate TTL and circular design into the company's objectives. Therefore, researchers and the public administration should inform and encourage these actions through disclosure and legislation (Galanakis, 2020; Joyce & Paquin, 2016).

2. LCA approach

One of the largest industries in the world is certainly the food industry. Consequently, it is a large energy consumer. Greenhouse gas emissions, which have increased dramatically due to the huge consumption of energy, have caused global warming. It happens especially during the production, storage and distribution of food. Consumers in developed countries are increasingly demanding safe food with a low environmental impact. Life cycle assessment (LCA) is a tool for assessing the environmental effects of a product, process or activity throughout its life cycle, known as cradle-to-grave analysis. As a result, awareness can influence legislative bodies and governments to make the best decisions. Although there are already studies on the methodology, it is important to pursue this avenue because these are often incomplete, difficult to compare or related to product niches (Roy et al., 2009).

2.1 LCA Origins

The term LCA was originated in the 1960s and 1970s, when humans began to consider climate change and resource scarcity. Harold Smith's report to the 1963 World Energy Conference regarding energy requirements to produce chemical intermediates can be considered one of the earliest examples. Several studies on global patterns were published in the late 1960s in “Limits to Growth”, in which an attempt was made to predict the effects of an increase in world population and its effect on the demand for raw materials and energy. Strict controls on the energy consumption and emissions of industries began to counteract environmental adversity. The continued rapid consumption of fossil fuels and the onset of climate change have prompted meticulous controls on the energy consumption and emissions of industries. In 1969, a group of researchers from the Midwest Research Institute (MRI) conducted a study on behalf of Coca-Cola to compare different types of beverage containers, with the aim to determining which was the most environmentally friendly and therefore the least harmful. The studies continued both in the United States and in Europe, with packaging systems focus. Thanks to the introduction of two important innovations (communicative transparency and quantitative assessment of impacts on various environmental issues), the interest in LCA increased in the 1980s (Hauschild et al., 2018).

By the end of the decade, however, studies on the same product were not comparable, often with conflicting results due to the lack of an official method. For these reasons, the emergence of an unambiguous and standardised methodology proved to be of paramount importance. The SETAC congress in Smuggler Notch in 1993 (Vermont - USA) coined the term LCA. In 1998, SETAC established guidelines for the drafting of an LCA, subsequently incorporated into ISO 14040. Specifically, the standards currently dealing LCA are ISO 14040:2006 (Environmental management - Life cycle assessment - Principles and framework) and 14044:2006 (Environmental management - Life cycle assessment - Requirements and guidelines). ISO 14040:2006 provides an overview of the practices, applications and limitations of LCA; ISO 140044:2006 provides guidelines for the impact assessment phase of LCA, the interpretation phase of the results and the assessment of the nature and quality of the data collected (Hauschild et al., 2018; Jury, 2022). Figure 3 shows the main important steps of LCA along the timeline. Also emphasising the importance of summits and conferences since the 1990s like Rio 1992; Johannesburg 2002; Kyoto protocol 2005; COP 15 Copenhagen 2009 and COP 21, Paris 2015 (European Commission. Joint Research Centre, 2016).

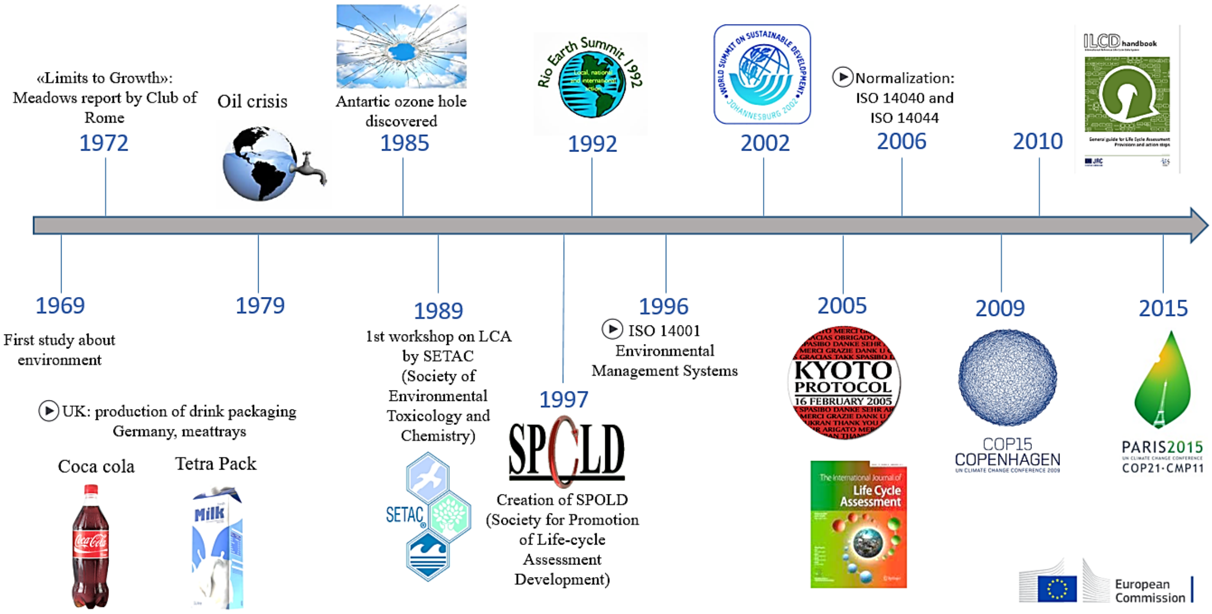


Figure 3. LCA timeline. Readapted from (Jury, 2022).

2.2 LCA phases

In figure 4 and 5 the fundamental steps of LCA are schematised (Roy et al., 2009; European Commission. Joint Research Centre, 2016).

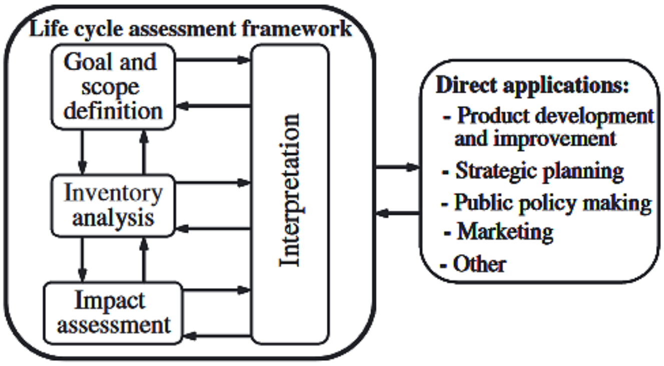


Figure 4. Stages of an LCA (Roy et al., 2009)

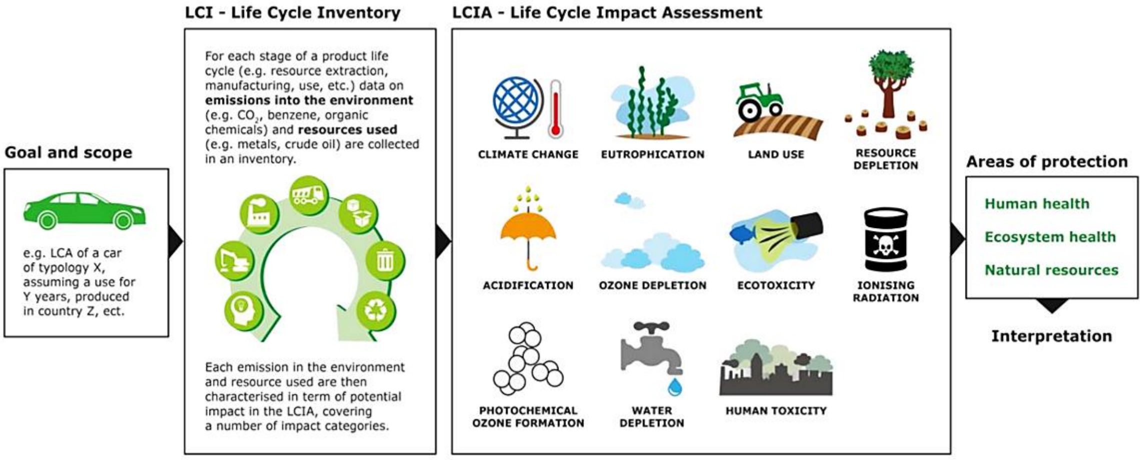


Figure 5. Graphic illustration of LCA phases (European Commission. Joint Research Centre, 2016)

2.2.1 Goals and scopes

It is the most important component of an LCA because the study is conducted according to the statements made in this phase; therefore, the purpose of the study must be defined. The expected product of the study, the boundaries of the system (characterised by an input-output diagram, here all the activities of the system's life cycle are included), the functional unit (FU, provides a unit to which the inventory data can be normalised, depends on the impact category and the objectives of the investigation) and the assumptions constituted that first step. The functional unit is often based on the mass of the product under investigation. However, the nutritional and economic values of the products and the land area can also be used (ISO, 2006).

2.2.2 Inventory

It is composed by different sub-steps: data collection procedures; data collection; calculation procedure and allocation. Especially for data collection, this is the most time-consuming phase. If it has good databases (usually many databases are already in place when the software is purchased) data collection can be less time consuming. In addition, if manufacturers, suppliers, and customers are willing to provide information, the time is further reduced (they are approached mainly for data specific to the product). Database data are often used for general information (not specifically about the product) for example: production of usually used products such as plastics, glass and cardboard, electricity and coal production, and disposal. These data include inputs (energy, water, raw materials, etc.) and outputs (Products, co-products and emissions) of processes and waste generation. Different types of emissions are present, here are some examples: air emissions (CO_2, CH_4, SO_2, NO_x and CO), to water and soil (total suspended solids: TSS, biological oxygen demand: BOD, chemical oxygen demand: COD and chlorinated organic compounds: AOX) (ISO, 2006; Roy et al., 2009).

2.2.3 Impact assessment

The life cycle impact assessment (LCIA) aims to understand and evaluate environmental impacts based on the inventory analysis, within the framework of the goal and scope of the study. In this phase, the inventory results are assigned to different impact categories, based on the expected types of impacts on the environment. Impact assessment in LCA generally consists of the following elements: classification, characterization, normalization and valuation. Classification provides for assigning the results of the inventory analysis to the different impact categories, in a way that identifies which results obtained influence the different categories. The characterization stage, on the other hand, allows the results of the life cycle inventory analysis to be transformed into common units of measure and aggregated to each impact category through the characterization factors. For example, an LCI result might be the volume of greenhouse gases emitted by an industrial plant; the associated category indicator might be the infrared radiation power. Through a mathematical model, the characterization factor, i.e., the global warming potential for each greenhouse gas (kg CO2 equivalent/kg gas) is defined, and then the results of the inventory analysis are all converted back into an indicator result, that can be, kg CO2 equivalent. Normalization expresses potential impacts in ways that can be compared (e.g., comparing the global warming impact of carbon dioxide and methane for the two options). During normalization, potential impacts are expressed so that they can be compared (for example, comparing the global warming impact of carbon dioxide and methane for the two options).

Impact categories include global effects (global warming, ozone depletion, etc.); regional effects (acidification, eutrophication, photo-oxidant formation, etc.); and local effects (nuisance, working conditions, effects of hazardous waste, effects of solid waste, etc.). The relative importance of the environmental loads identified in the classification, characterization, and normalization steps is assessed in the next step, the evaluation. It is assigned a weighting that allows comparison (ISO, 2006; Roy et al., 2009).

2.2.4 Data interpretation

The goal is to obtain conclusions that can support one decision instead of another and provide an easily understandable result. It is a systematic technique to identifying and quantifying, verifying, and evaluating information derived from the LCI and LCIA results. Significant environmental issues are identified to draw conclusions and recommendations consistent with the objective and scope of the study. For example, recommendations on the design of products, processes and activities, in the use of raw material in waste management and processing (Roy et al., 2009).

2.3 Strengths and weaknesses

The main strength of the LCA is its comprehensiveness, both in terms of its life cycle perspective and its coverage of environmental issues. Thus, it is possible to compare environmental impacts of very complex processes that take place in different locations and at different times. However, to achieve completeness, simplifications are also necessary. Not all data can be collected on site. Therefore, completeness can also be a weakness (Hauschild et al., 2018). It is more correct to say that LCA calculates impact potentials because of this uncertainty in modelling the flows and because they are aggregated in time (tomorrow or 20 years from now) and space (limited to countries). The “best estimate” is the principle followed by LCA. It is a strength because it generally allows for unbiased comparisons, as it means that the same level of precaution is applied throughout the impact assessment modelling. A limitation of this approach is that it is based on average process performance and does not allow the risks of rare but very problematic events, such as oil spills at sea or accidents at industrial sites, to be considered (Hauschild et al., 2018).

As a result, nuclear energy, for example, appears quite environmentally friendly in the LCA because the small risk of a devastating disaster, such as those in Chernobyl, Ukraine or

Fukushima, Japan, is not considered. Ultimately, LCA can report which product system is better for the environment, it cannot say whether better is 'good enough'. It is an important assessment, it is the issue of this current study, but is does not mean it is good enough. Researchers try to estimate if innovation processes are better than conventional processes. The characteristics described above make LCA suitable for answering some questions and unsuitable for answering others (Hauschild et al., 2018).

3. Overview of brewery and bread making / life cycle evaluation

3.1 LCA in the brewery sector

3.1.1 Brewery production

Beer is the most widely consumed alcoholic beverage in the the world. On a global scale this commodity is the fifth most consumed beverage behind tea, carbonates, milk and coffee (Morgan et al., 2021). The brewing process combines a variety of ingredients depending on the style of beer. However, the four most popular cultivated grains are barley (usually tow-row barley), wheat, oats and rye, usually used after maltation process (Morgan et al., 2021). The remaining three raw materials for beer production are water (not excessively hard drinking water with a sub-acidic pH value is used); the hop (the female inflorescences, which contain “lupulin”, a yellow resinous powder consisting of bitter resins and essential oils) and the yeast (usually *Saccharomyces* and genus) (Stewart et al., 2017). There are several stages in the production of beer:

- *Malting* focuses on the germination of the caryopsis of barley or other cereals following by dehydration. The aim of this process is to allow the development of enzymes that will be exploited during the mashing/saccharification phase. The tissue of the cereal changes: the aleurone layer partially degrades but remains metabolically active; the starchy endosperm provides sugars following hydrolysis; the embryo, on the other hand, develops, taking advantage of the hydrolysis of starch and the migration of other polymeric and nutritional substances. This phenomenon leads to the development of acrospires and rootlets. The steps of malting are steeping, germination, drying, deradication and cleaning; figure 6. During these steps, many chemical and biochemical changes take place within the caryopsis. The first step favours the raising of humidity to 42-48%, after which the caryopses are placed in containers in which they will germinate. During this phase, the activation of hydrolytic enzymes (amylolytic, proteolytic and cytolytic), the initiation of chemical reactions and physical changes (loss of structure) take place. This phase is clearly visible for the development of new organs (Stewart et al., 2017).

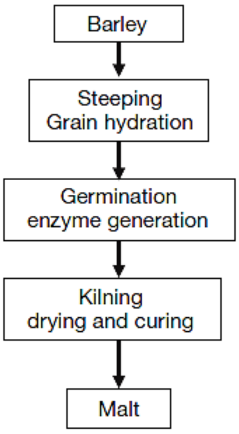
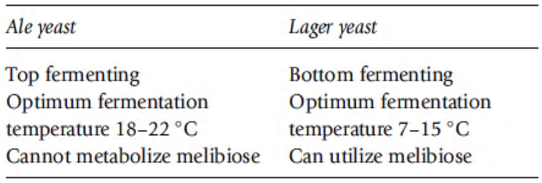


Figure 6. Typical barley malting process (Stewart, 2016)

- *Mashing* consists of reactivating the enzymes in the malt, which will hydrolyse the starch and proteins to form mainly soluble and fermentable components. The purpose is to extract starch, proteins (not a large portion, it can cause worth instability), peptides, lipids and other minor components from the partially ground malt, hops and other additions. It is necessary to make these extracts well accessible to the yeasts through the reactivation of enzymes. There are specialised enzymes depending on the macromolecule: starch is split into fermentable sugars, proteins into amino acids and small peptides, and lipids into short-chain fatty acids and sterols. Temperatures of around 65-70°C are reached. These components are separated from the not soluble part by filtration (Stewart et al., 2017).
- In the *boiling process*, hops, various extracts, syrups or other sugars are added in order to obtain a low microbial load and flavour. Filtering, boiling and hopping: when the mashing is finished, the matrix is filtered to obtain a clear wort, then it is boiled (100°C) and hopped as described in the section on hop raw materials (Stewart et al., 2017).
- *Fermentation*: alcoholic fermentation establishes a wide range of styles. The key is yeast nutrition, fermentable sugars, nitrogen in the form of amino acids, oxygen, vitamins and minerals. It will produce ethanol, CO_2, various aromas (esters and higher alcohols) and heat. It involves the transfer of the wort into tanks to which yeast is added, the latter being able to produce ethanol and in certain cases also characteristic aromas. This is followed by the maturation process. Both the process (in terms of duration and mode) and the type of yeast count in this phase. Today, mainly two types of yeast are used, resulting in two different macro-types of beer. *Saccharomyces cerevisiae* (Ale; Porter; Stout) and *Saccharomyces carlsbergensis* (Pilsner; Munich; Boch; etc.). Spontaneously fermented beers are also present, i.e., yeasts of natural origin (Lambic). Table 1 shows the main

differences (Livens, 2016). Primary fermentation occurs when the wort is cooled and the yeast consumes the oxygen in the fermenter and then moves on to the anaerobic phase. When the process finishes (3 to 7 days depending on the strain), the "young beer" is obtained, which then passes into maturation tanks (3 to 6 weeks at approximately 2 °C). The beer is practically ready to be sold. The preceding description is validated for bottom-fermenting beers, whereas for top-fermenting beers, maturation often takes place in the same containers in which the beer is placed on the market (e.g. Hefe-Weizen or Belgian beers stored in bottles) (Zangrando et al., 2002).



Ale yeast	*Lager yeast*
Top fermenting	Bottom fermenting
Optimum fermentation temperature 18–22 °C	Optimum fermentation temperature 7–15 °C
Cannot metabolize melibiose	Can utilize melibiose

Table 1. Fermentation parameters of the two yeast types (Livens, 2016)

- Bottles, cans and kegs are generally used for *packaging*.

The figure below shows all the stages of a classic brewing process Figure 7 (Encyclopaedia Britannica, -)

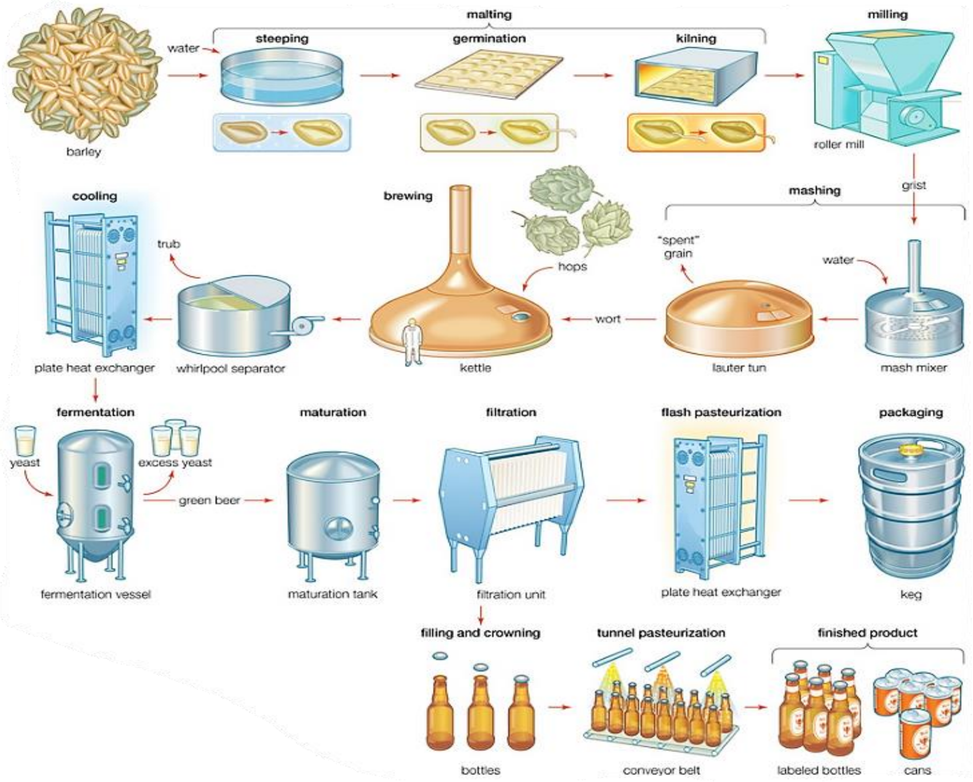


Figure 7. Industrial beer flow chart (Encyclopaedia Britannica, -)

3.1.2 LCA in brewery process

This study talks mainly about craft breweries. Several academic studies have been conducted to assess the environmental footprint of beer production. They have mainly focused on multinational companies (Morgan et al., 2021). However few studies, have focused on small producers which face different challenges than large corporations (Amienyo & Azapagic, 2016; Morgan et al., 2021).

The five stages of the product life cycle are shown below. Figure 8 is an example of Life Cycle Inventory (Cordella et al., 2008).

- The acquisition of raw materials (so first cultivation, then upstream processing and upstream transport of these raw materials)
- Production (brewery activities)
- Distribution (packaging and downstream transport)
- The use by the consumer,
- The disposal and recycling (Cimini & Moresi, 2018).

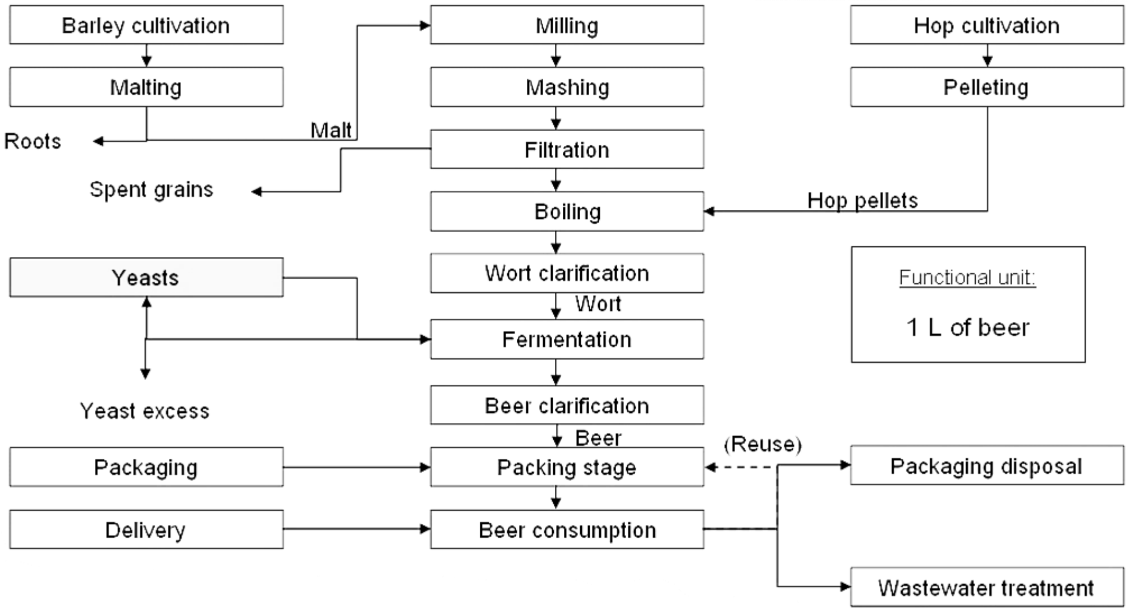


Figure 8. Example of beer life cycle scheme (Cordella et al., 2008)

The critical points for the environment are cultivation, packaging and retail and home refrigeration as highlighted by some studies (Morgan et al., 2021). The main LCA categories implicated by beer production, namely Eutrophication Potential (nitrogen, phosphorus, contributing to nutrient pollution), Global Warming potential (CO2 equivalents contributing to climate change) and Acidification Potential (sulphur dioxide, nitrogen oxide contributing to acid rain) (Hospido et al., 2005). Figure 9 shows the various contribution (Heller, 2017).

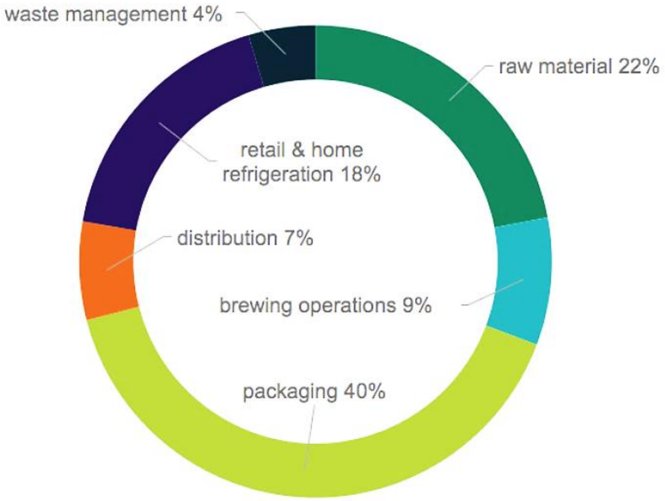
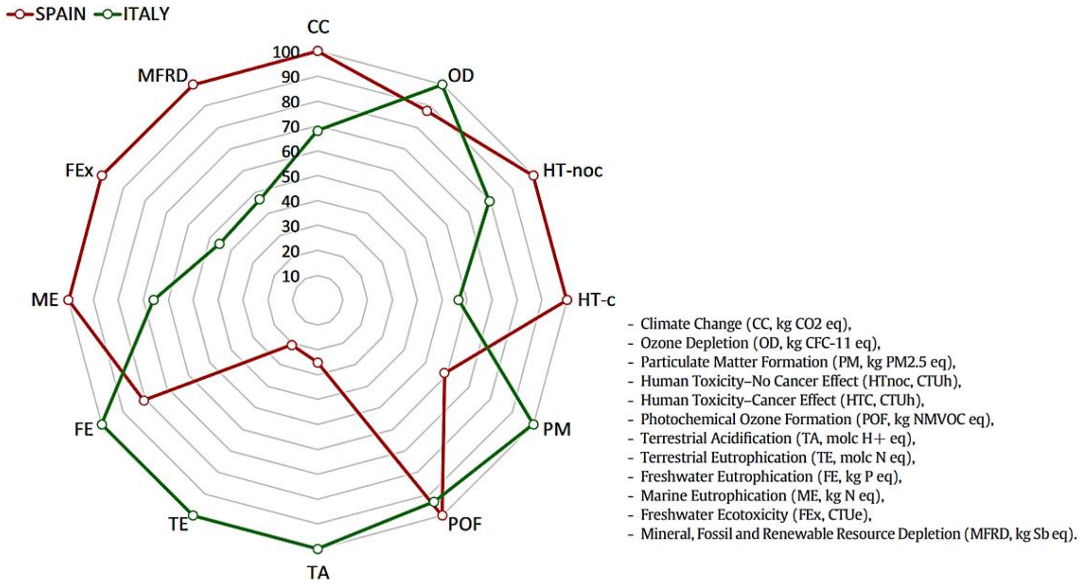


Figure 9. Carbon foot print by life cycle phase of beer (Heller, 2017)

Barley is an impactful agricultural input. This is because the cultivation of barley emits pollutants into the soil, water and atmosphere. Malted barley generates 57% of the total global warming potential emissions of all raw materials, with liquefied carbon dioxide at 11% and light fuel oil at 10%. It must be considered that these raw materials must be transported then. The emissions and thus the environmental impact generated vary depending on the proximity of the raw material plant to the brewing plant (Holland, 2021). Agricultural barley production contributes significantly to the carbon footprint of beer, it is also the main source of eutrophication emissions. There is variability in environmental impact depending on cultivation practices and regions. A study on the Italian Peroni lager estimated that the use of organic barley grown in Italy instead of conventionally grown barley would reduce the carbon footprint of beer by 11%, while importing conventional barley from 1500 kilometres away (by truck transport) would increase the greenhouse gases emissions (GHGE) of beer by 9%. Importing organic barley, again from 1500 kilometres, decreases the GHGE of beer by 6%. The differences, however, are due to regional production differences and transport (Cimini & Moresi, 2016).

In another similar study the results of the comparative LCA show that the organic cultivation of barley is the most environmentally sustainable (but not production-efficient) solution, whereas the conventional cultivation of barley is the most production-efficient (but not environmentally sustainable) solution. Production efficiency and environmental sustainability may also depend on qualitative elements (crop quality and adaptation to specific soil and climatic conditions). An economic allocation was considered (Tricase et al., 2018). An interesting study compares barley production in Italy and Spain. Spanish production has lower yields than Italian one. The use of machines with a wide working width, mineral fertilisers spread over the field, and a cultivation system that takes place on large areas (300-400 ha) provide the worst environmental results especially for impacts related to the consumption of mineral fertilisers. Italian production, on the other hand, presents a higher impact for environmental impacts related to emissions associated with the application of organic fertilisers. The lower formation of particulate matter, acidification and eutrophication is in favour of Spanish cultivation, but this is negatively affected by low yields. Italian barley production is more environmentally sustainable. There is a graphical compression in figure 10. From this study it emerges that yield and efficiency of field activities have a profound effect on systems, so management practices together with high yield are the predominant processes to focus on (Lovarelli et al., 2020).



- Climate Change (CC, kg CO2 eq),
- Ozone Depletion (OD, kg CFC-11 eq),
- Particulate Matter Formation (PM, kg PM2.5 eq),
- Human Toxicity–No Cancer Effect (HTnoc, CTUh),
- Human Toxicity–Cancer Effect (HTC, CTUh),
- Photochemical Ozone Formation (POF, kg NMVOC eq),
- Terrestrial Acidification (TA, molc H+ eq),
- Terrestrial Eutrophication (TE, molc N eq),
- Freshwater Eutrophication (FE, kg P eq),
- Marine Eutrophication (ME, kg N eq),
- Freshwater Ecotoxicity (FEx, CTUe),
- Mineral, Fossil and Renewable Resource Depletion (MFRD, kg Sb eq).

Figure 10. Relative comparison between Spanish and Italian barley grain production

Although hops are an important ingredient, they do not make a large contribution to the environmental footprint of beer. Another study compares conventional beer production with malted barley and the use of a new enzyme that allows beer to be brewed directly from 100% unmalted barley (Kløverpris et al., 2009). Avoiding the malting process saves energy and produces less barley, but the environmental burden of producing the enzyme remains to be considered. The resulting analysis showed no clear difference between the two products (Heller, 2017).

Barley malt processing is energy intensive. It also causes a significant discharge of wastewater, which would have to be further treated due to its hazardousness (as most countries require), so it means additional energy inputs (Holland, 2021).

Usually, reusable kegs have less impact than glass bottles (Cordella et al., 2008). Cimini and Moresi compared five packaging scenarios. The 0.33 L glass bottles sold in a multi-pack provided the largest carbon footprint (figure 11). In addition, a high share of energy demand was highlighted by packaging in a comparative study of two beer styles, lager and ale. Lager has a higher carbon footprint due to the need for electricity for cooling during fermentation and maturation (Cimini & Moresi, 2016; De Marco et al., 2016). Packaging is a major burden from an environmental point of view, although it can be reduced if bottles are subjected to reuse instead of recycling or disposal (Heller, 2017).

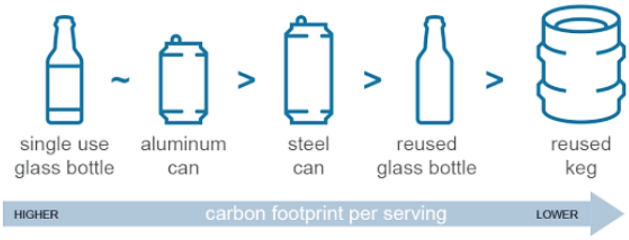


Figure 11. Packaging formats from most to least impactful (Heller, 2017)

Downstream distribution is a significant hot spot for overall craft beer footprints due to the use of small commercial vans rather than larger trucks, especially about GWP (carbon footprint) and FRDP (Fossil resource depletion potential). Due to the high consumption of oil for drying hops in this study, high impacts were highlighted, highlighting the potential for improving the efficiency of some upstream processes. Overall, these micro-breweries had a lower contribution from packaging than larger breweries studied previously, due to a greater reliance on reusable kegs and casks for localised distribution. It is not clear whether microbreweries are less efficient than large breweries in terms of on-site energy consumption per litre of beer (Morgan et al., 2021). Another study shows different results about packaging. For developing an environmental product declaration, the LCIA shows the life cycle impacts of consuming 12 bottles of beer. The results show that the ingredient and brewery phases are the main contributors to the impacts, while the packaging phase may only be significant for some breweries. Analyses show that variations in barley production have a moderate impact on the overall environmental impact of the product and that the duration of cold storage in refrigerated trucks and retail outlets has a moderate to high influence on ozone depletion results (Lalonde et al., 2013).

A few solutions from the literature:

- Reduce GHG emissions from barley cultivation through ‘conservation agriculture’ (Holland, 2021). Greenhouse gas emissions and other negative impacts on crops can be mitigated with conservation agriculture. The demand for fertilisers is reduced through precision applications (it takes a lot of energy to produce them). Minimum tillage practices can also help reduce emissions. These good practices also tend to increase water retention and soil fertility. Consequently, optimising energy and using renewable energy in the management of these raw materials would be a recommended choice (Holland, 2021).
- Use renewable energy, electric equipment and machinery in breweries and for transport, substituting renewable energy can have a massive impact on the greenhouse gas emissions generated by brewery operations, instead of using conventional energy sources such as fossil fuels and nuclear power. In fact, renewable energy releases no emissions whatsoever.
- Use raw materials with high % recycled or alternative material content (Holland, 2021). Aluminium cans are a better option if glass bottles are only used once. Bottles and cans can have recycled content as an option. For bottles it is 1/3 and for cans it is 85%, for paper and cardboard there are already 100% recycled options available and there are non-fossil raw materials that can be used for plastic films used in packaging. (Holland, 2021)
- The use of larger vehicles could be a very effective mitigation option for this hotspot, but would require the transport of larger volumes, potentially only achievable through collaboration with other local companies. (Morgan et al., 2021)
- Increase water efficiency and reuse wastewater for non-product purposes. For every barrel of beer produced in the United States, seven barrels of water are required, i.e. a water efficiency ratio of 1:4. The size and type of packaging affect water use: smaller packages (330 ml bottles) tend to require more water per litre of beer than larger packages (kegs). The brewing process requires the use of a lot of water in the product and simultaneously generates a lot of water waste. Smaller breweries have a lower efficiency ratio for water use than large breweries. The waste water generated by breweries amounts to approximately 70% of the water entering the facility (Holland, 2021). A suitable scenario would be to invest in water efficiency. This means investing in new technology, maintenance and ensuring that staff are aware of good brewery cleaning practices. In

addition to reducing direct pollution, it will also reduce energy consumption. The reuse of treated wastewater is another option that can be implemented. (Holland, 2021).

3.2 LCA in the bread sector – general impacts

3.2.1 Bread production

One of the fastest growing food industries in the world is the baking industry. Bakery products such as bread, biscuits and rusks are the most popular bakery items. Bread is a staple food rich in flavour and nutrients. It is an important part of the human diet, but for many people it is much more than just a food (Monika et al., 2019). Since bread is the staple food of the daily human diet, various attempts at innovation have been made to enrich it with nutrients.

The most widely used ingredient is 00 (white) wheat flour. White flour is nutritionally poor (in spite of its high calorie content due to the large amount of carbohydrates) and needs to be enriched with fibre, protein, vitamins and minerals to overcome the problem of malnutrition (Monika et al., 2019). In figure 13 is reported a typical industrial bread making flow chart (Malik, 2016). The basic process involves mixing the ingredients (flour, water, salt, yeast and other ingredients) until the flour is transformed into a dough, followed by baking the dough into a loaf (Cauvain, 2012). The steps of breadmaking are:

- *Mixing*: the various ingredients are mixed; it allows the development of a protein (gluten). Each dough has an optimum mixing time, depending on the flour and mixing method used. Too much mixing produces a dough that is very extensible with reduced elastic properties. Undermixing may cause small unmixed patches which will remain unrisen in the bread. This will give a final loaf with a poor appearance inside.
- *Rising* (fermentation): in this phase, the dough is left to ferment. The dough is slowly transformed from a rough, dense mass (not very extensible and with poor gas-holding properties) into a smooth, extensible dough with good gas-holding properties. Gluten established an articulated network, yeast cells grow, and alcohol and carbon dioxide are formed.
- *Kneading/moulding* into loaf shapes: the dough releases large gas holes. It can be left to rise again and kneaded. During the final rising (proving), the dough fills with more gas bubbles again and finally the dough is transferred to the oven for baking.
- *Baking*: The baking process transforms an unpalatable dough into a light, readily digestible, porous flavourful product. The heat expands the gases and the cells enlarge, increasing the volume of the dough. This expands these cells and overall, the solubility of

the gases is reduced. The oven heat changes liquids into gases by the process of evaporation and thus the alcohol produced evaporates. Heat also influences the rate of yeast activity. As the temperature rises the rate of fermentation increases, and until the dough reaches the temperature at which yeast dies (approximately 46°C). At 60°C, the stabilisation of the crumb begins. The starch granules swell outer cell wall of the starch granule breaks down and the starch inside forms a thick gel-like paste, which helps form the dough structure. At 74°C, the gluten filaments turn into a semi-rigid structure (breadcrumb resistance). Enzymes die at this temperature (alpha amylase works up to 75°C). The yeast has denaturalised at around 46°C so it cannot utilise the extra sugars produced by the enzymes. These sugars are then available to sweeten the crumb and produce the attractive brown colour of the crust. Until this internal temperature is reached, the loaf is not fully baked. As the moisture is removed, the crust heats up and eventually reaches the same temperature as in the oven (100°C). Subsequently (at 160°C), browning reactions occur that provide the typical crust colour.

- *Cooling - slicing and wrapping:* In bakeries, bread is cooled rapidly when it comes out of the oven. The crust temperature exceeds 200°C and the core temperature of the crumb is around 98°C. The loaf is filled with saturated steam, which must be given time to evaporate (Cauvain, 2012). The main stages of bread production are illustrated in the figure 12 (Malik, 2016).

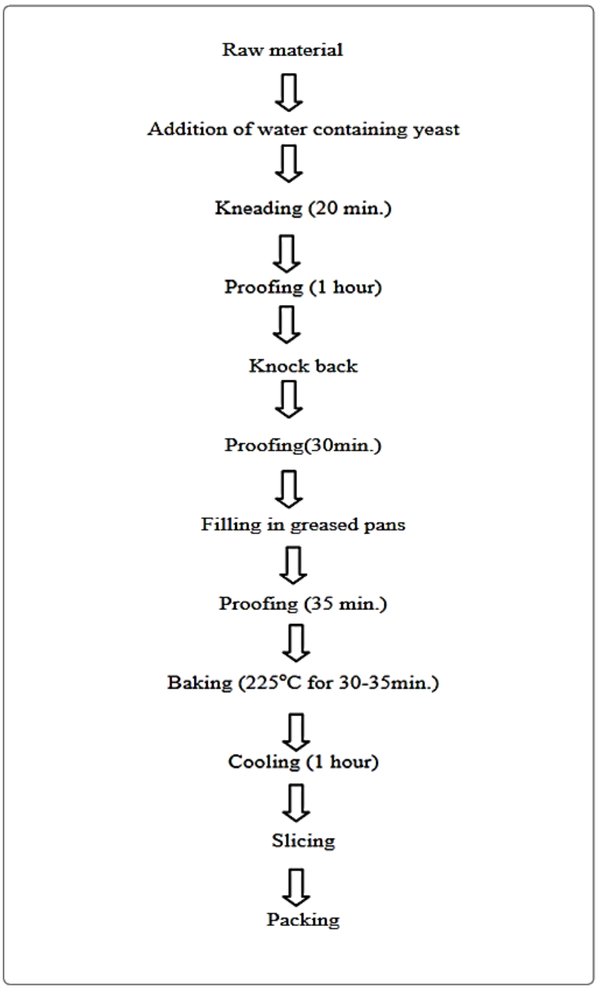


Figure 12. Typical industrial bread making flow chart (Malik, 2016)

In breadmaking process, the goal is always the conversion of wheat flour into an aerated foodstuff. Although there are many methods of bread making, a series of largely common steps can be grouped together (Cauvain, 2016):

- The mixing of wheat flour with water, together with yeast, salt and other specific ingredients in appropriate ratios;
- Kneading: development of gluten structure through the application of energy during mixing and subsequent hydration of proteins;
- Development of air bubbles within the dough during mixing;
- Maturation or ripening: continuous structural change of the gluten. The rheological properties of the dough change by improving its ability to expand as gas pressure increases with the generation of carbon dioxide during fermentation;
- development or creation of aromatic compounds in the dough;
- The division of the dough mass into pieces;
- A preliminary modification of the shape of the pieces;

- A short delay in processing to further modify the rheological properties of the dough pieces;
- The final shaping of the dough pieces;
- The fermentation (proofing) and expansion of the pieces;
- Final expansion of the dough pieces and fixing of the final bread structure during baking;

All of those operations that in practice deal with the formation of a large dough bulk provide the main differences in different baking processes: mixing and kneading, air incorporation, and the creation and development of the gluten structure. The dividing and shaping processes make small contributions to product quality, and the processes of proving and baking are common to all breadmaking processes. Since it is mixing stages, which determine most of the bread quality (Cauvain, 2016).

3.2.2 LCA in bread making

The complexity of agricultural and food systems often limits environmental studies on food products. Nevertheless, the number of data and products has increased over the years. Mass consumer products are very important, so improving their production means greatly reducing global impacts (Ingrao et al., 2018).

The use of fertilisers and pesticides, issues related to the use of increasingly less available agricultural land (especially in Europe) and the consumption of fossil fuels are the most impactful practices. Many studies refer to agricultural practices that are often the most environmentally burdensome steps in cereal supply chains (Notarnicola et al., 2015). A scenario that combines organic wheat production, industrial milling and a large bread factory is indicated as the most advantageous way to produce bread. There is a more pronounced difference when considering industrial supply chains and smaller realities compared to organic and conventional methods. Eight different scenarios were compared in this study, and it turned out that organic production was the least impactful but it requires more area than conventional wheat production. However, special attention should be paid to the role of transportation (of grains, flour and purchased bread). Typical impact categories considered in studies of wheat products are global warming, acidification, eutrophication, ozone depletion, ecotoxicity and abiotic depletion (Braschkat et al., 2004). Usually in these types of studies, the functional unit is assumed as the mass (kg) of bread. This other study also confirms that organic farming is less impactful by showing that conventional practices cause around 16% more CO2 equivalent emissions than conventional ones. It also pointed out that transport over a distance of 2000 km has a global warming potential (GWP) comparable to that of the entire bread production excluding transport (Meisterling et al., 2009).

Kulak et al. demonstrate that a correlation between sustainability and low-input agriculture could not be demonstrated, and the reduced use of inputs often resulted in lower yields, which in turn had a negative impact on environmental performance. Due to site-specific conditions and individual management decisions, it was difficult to compare different systems. The study showed that switching to alternative supply chains does not always guarantee environmental benefits. in fact, the distribution phase could counterbalance the positive aspects of small-scale, low-input systems (Kulak et al., 2015).

Eutrophication (due to nitrogen loss from fields and nitrogen compound emissions in fertiliser production and the use of tractors) is especially due to cultivation (Roy et al., 2009). The main challenge for wheat cultivation is not only to fulfil the need for more productive agricultural and food systems but also to make them more sustainable: in other words, producing ‘more with less’ (Notarnicola et al., 2015).

Studies show that when conventional and organic wheat are transported the same distance to market, the conventional wheat produces more CO_2-eq than the. The transport distance of the wheat, as well as the mode of transport of the finished product, may cancel out or increase the advantage of organic wheat. Regarding the issue of irrigation, they show that with low N-fertiliser consumption, the environmental impacts with the irrigated system are greater than with rainfed systems (this is not a widespread system).

The formation of photo-oxidants and energy use is highest in the cooking phase (Roy et al., 2009).

It is necessary to consider the entire life cycle of the product because of the importance of the upstream and downstream phases from an environmental point of view. For example, the impact of the consumption phase was found to be significant depending on consumer behaviour (whether the bread is refrigerated or toasted) (Espinoza-Orias et al., 2011). Still the same study (in the UK; cradle-to-grave approach) evaluated the CF (carbon footprint) of a standard 800 g loaf of sliced bread, produced with wheat flour on an industrial scale and consumed at home. They realised that the CF of the bread depends on the thickness of the slices, the packaging and the types of flour. For example, the CF varies from 1.11 kg CO_2 eq/bread for wholemeal bread cut into thick slices to 1.24 kg CO_2 eq/bread for white bread cut into medium slices. For bread packed in plastic bags, the results vary from 0.98 kg CO2 eq/pound for thick sliced wholemeal bread to 1.10 kg CO2 eq/pound for medium sliced white bread (Espinoza-Orias et al., 2011).

When other impact categories are included in the assessment, similar trade-offs between impact categories can be expected; even the choice of different FUs can lead to different results. Therefore, some studies include a sensitivity analysis with different functional units, mainly mass (1 kg of dry matter) or area (1 ha of cultivated land). Defining the functional unit in terms of mass is not always a good measure of the quality of the food produced; the energy (MJ) and protein (kg) content may be of more interest, as reported by (Notarnicola et al., 2017).

The differences between industrial and domestic baking are not too wide. The main differences are the transport of the wheat flour from the mill and the mix of electricity used during the production process. This is due to economies of scale in the production of bread in large quantities. Although industrial bread production uses more machines at different stages of the process, the allocation of this energy is more efficient than in home baking (Bimpeh et al., 2006). Among conventional bread types, when evaluated with a mass-based FU, the French Baguette, the Greek Pita and the Italian Focaccia are the most sustainable. In the case of French bread, this is mainly due to a mix of electricity based on nuclear energy and wheat production that results in very high yields (7 t/ha). The shape of each bread can also influence energy consumption: small or elongated loaves tend to have a greater surface area exposed in the oven during baking and therefore require less energy for the evaporation of liquids from the dough. When evaluated with a FU based on nutritional values, as this group of bread types has similar nutritional values, the results are similar to those for a FU based on mass. The use of electricity in the life cycle of French bread, based on a mix of electricity centred on nuclear energy, also makes the baguette among the best in terms of greenhouse gas emissions (Notarnicola et al., 2017). Figure 13 shows the various steps in a typical LCA study concerning industrial bakery.

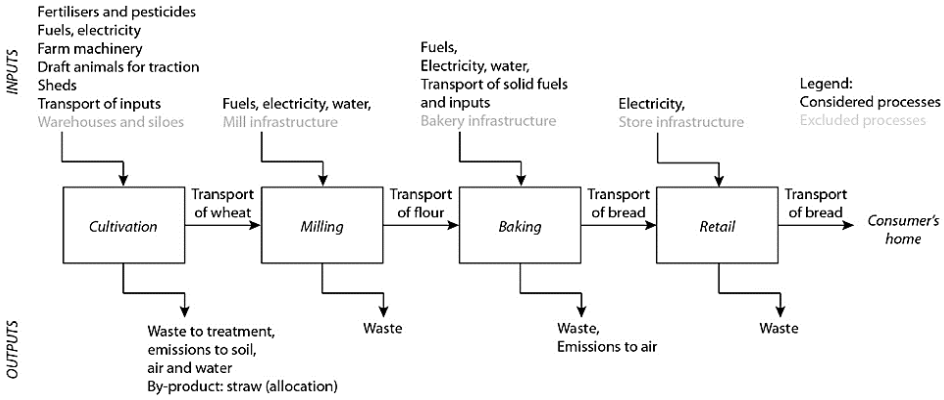


Figure 13. Common system boundaries of bread LCA (Kulak et al., 2015)

4. Brewery spent grain

4.1 Brewery spent grain formation in brewery process

Brewing produces significant amounts of organic waste material, the most abundant of which is formed after the mashing process (85 % of all residues produced by the brewing industry). Residual grains are removed after separation of the liquid produced during mashing. BSG are the insoluble, undegraded part of the malted barley. The production of 100 L of beer generates about 20 kg of BSG (Rachwał et al., 2020); (Czubaszek et al., 2022). A schematic representation of the process leading to the production of brewery spent grain from barley grains is shown in figure 14. The brewing process leaves within the spent grain washed and water-insoluble proteins, residues from the cell wall of the husk, pericarp, and seed coat. Depending on the type of beer to be brewed, the BSG may consist of the residues of malted barley or other malted and unmalted grains. So, its composition can vary (Mussatto et al., 2006). Most often, it is placed in wet form in tanks or containers as soon as it leaves the mashing tunnel at the end of the soaking phase. Their management is often economically problematic and their environment accumulation is challenging. The food industry is trying to find new applications that change the traditional approach to "waste" products and make them "co-products". There is a potential in these by-products, although attempts are being made to exploit new strategies for their utilisation, their use is still limited. Due to their properties, they can be used to design new food and feed products from waste or to recover functional components (Rachwał et al., 2020). 8 million tons in Europe and 40 million tons worldwide is the amount of BSG. As the number of microbreweries around the world increases, spent grain recovery represents a huge opportunity in the current context of sustainable food transition. A great interest for human consumption is developing (Petit et al., 2020).

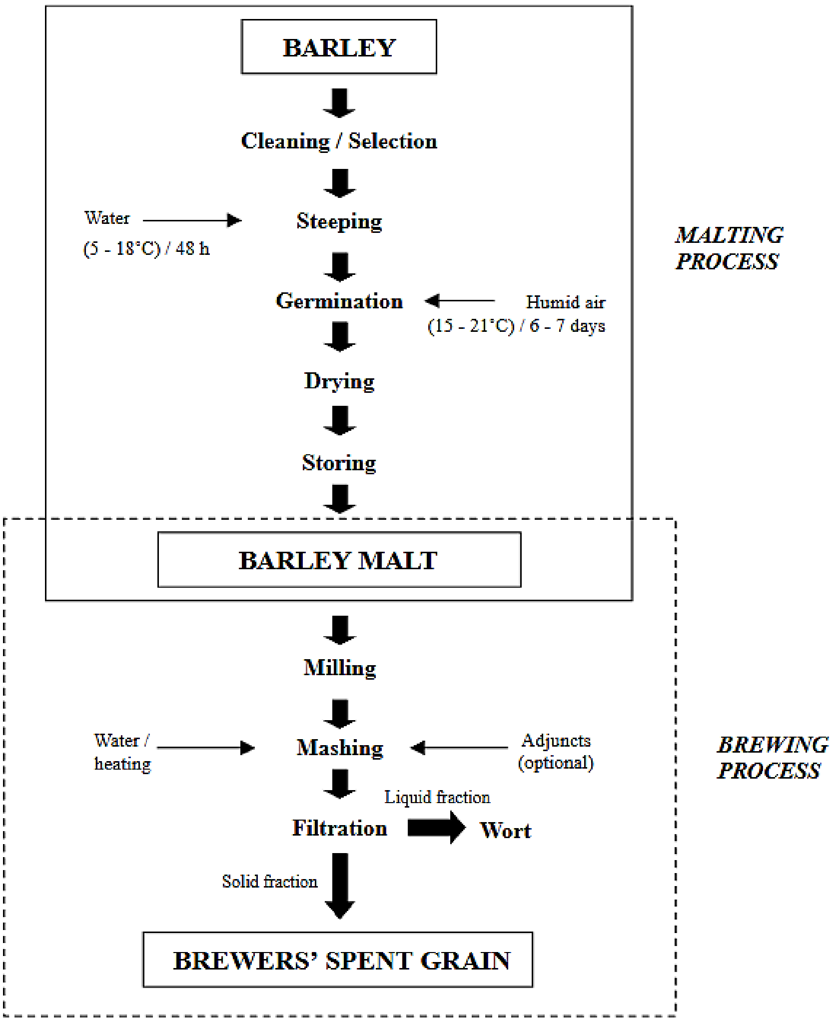


Figure 14. Schematic representation of the process to obtain BSG from natural barley (Mussatto et al., 2006)

4.2 Composition and health benefits of brewery spent grain

Spent grains consist mainly of 15-26% protein and 70% fibre, which consists of 16-25% cellulose, 28-35% hemicellulose and 7-28% lignin (dry weight basis) (Capossio et al., 2022). In addition, it contains arabinoxylans, proteins in the form of hydrolysates and phenolic compounds. The latter have gained increasing attention for their potential health benefits (Lynch et al., 2016). The BSG is a heterogeneous substance. It consists of the seed coating layers, pericarp and husk, which covered the original barley grain. The endosperm may remain more or less starchy and the walls empty aleurone cells, depending on mashing efficiency. In BSG, depending of the brewing type, there may also be some hop residue with a low starch content (Mussatto et al., 2006). In figure 15 is shown structural description of barley (Lynch et al., 2016).

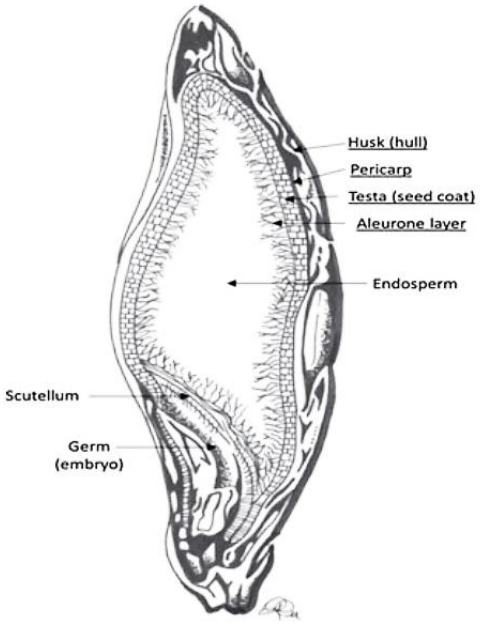
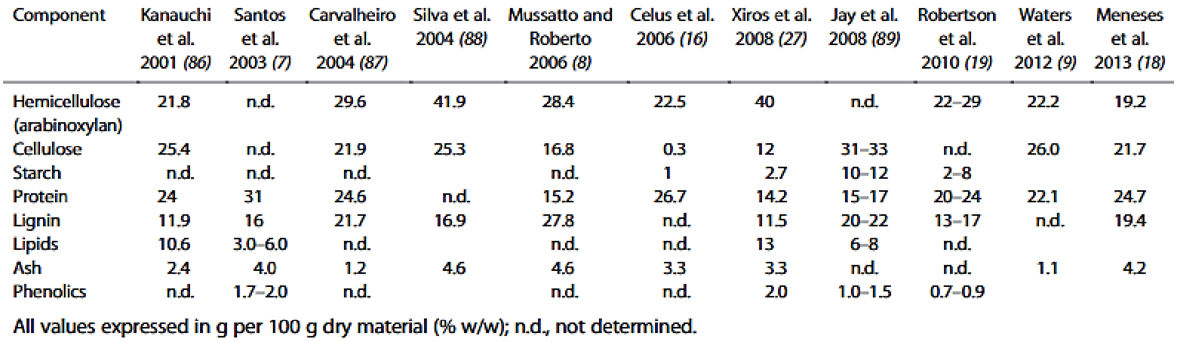


Figure 15. Cross-section of a barley kernel showing the grain coverings (underlined) that constitute brewers' spent grains (Lynch et al., 2016)

The amount of BSG produced is about 14 kg/ hL of must, with a moisture content of 75% to 90%. The ash content in the spent wort is between 2.3 and 7.9% (Rachwał et al., 2020). The high fiber content (it makes up about half of the composition of BSG on a dry weight basis) and protein make BSG an attractive raw material for food and non-food applications. Hemicellulose (consisting mainly of arabinoxylan) is the main constituent of BSG fibre and can be present up to 40% on a dry weight basis. β-D-glucans and starch may also be part of the composition. Another significant constituent of BSG is lignin (accounts for about 10-28% of the total dry weight) (Lynch et al., 2016). The protein level may vary, generally present to 20 % on dry weight. Essential amino acids account for about 30% of the total protein content, with lysine most abundant (14.3%). That amount is significant because lysine is often deficient in grain-based foods (Czubaszek et al., 2022). Lynch et al. reviewed many studies to get a complete picture of the composition of BSG derived from malt. They show it in table 2 and in figure 16 (Lynch et al., 2016).

Minerals, vitamins and amino acids are also found in BSG. Mineral elements include calcium, cobalt, copper, iron, magnesium, manganese, phosphorus, potassium, selenium, sodium and sulphur, all in concentrations below 0.5 %. Vitamins include (ppm): biotin (0.1), choline (1800). The net and gross calorific values of BSG were 18.64 MJ/kg and 20.14 MJ/kg dry mass, respectively (Mussatto et al., 2006). This by-product is also rich in oligo and polysaccharides and phenolic compounds. Among the phenolic acids, BSG has the highest content of ferulic acid (1860-1948 mg g) and p-coumaric acid (565-794 mg g^{-1}), as well as synaptic, caffeic and syringic acids (Rachwał et al., 2020).



Component	Kanauchi et al. 2001 *(86)*	Santos et al. 2003 *(7)*	Carvalheiro et al. 2004 *(87)*	Silva et al. 2004 *(88)*	Mussatto and Roberto 2006 *(8)*	Celus et al. 2006 *(16)*	Xiros et al. 2008 *(27)*	Jay et al. 2008 *(89)*	Robertson et al. 2010 *(19)*	Waters et al. 2012 *(9)*	Meneses et al. 2013 *(18)*
Hemicellulose (arabinoxylan)	21.8	n.d.	29.6	41.9	28.4	22.5	40	n.d.	22–29	22.2	19.2
Cellulose	25.4	n.d.	21.9	25.3	16.8	0.3	12	31–33	n.d.	26.0	21.7
Starch	n.d.	n.d.	n.d.		n.d.	1	2.7	10–12	2–8		
Protein	24	31	24.6	n.d.	15.2	26.7	14.2	15–17	20–24	22.1	24.7
Lignin	11.9	16	21.7	16.9	27.8	n.d.	11.5	20–22	13–17	n.d.	19.4
Lipids	10.6	3.0–6.0	n.d.		n.d.	n.d.	13	6–8	n.d.		
Ash	2.4	4.0	1.2	4.6	4.6	3.3	3.3	n.d.	n.d.	1.1	4.2
Phenolics	n.d.	1.7–2.0	n.d.		n.d.	n.d.	2.0	1.0–1.5	0.7–0.9		

All values expressed in g per 100 g dry material (% w/w); n.d., not determined.

Table 2. Chemical composition overview of brewer's spent grain (BSG) (Lynch et al., 2016)

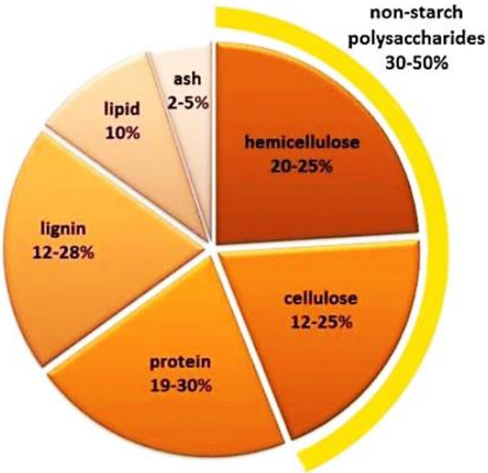


Figure 16. Typical barley BSG composition (Lynch et al., 2016)

As explained above, the nutritional value of BSG can vary considerably because its composition depends on many factors: genetic properties of the barley, the type of barley, the harvest date of the barley from which the malt was produced, the malting and mashing conditions and the quality and type of additives used during the brewing process (Cimini & Moresi, 2021).

Ingestion of BSG, or derived products, offers health benefits associated with increased faecal weight, accelerated transit time, increased cholesterol and fat excretion, and reduced gallstones. The addition of spent grains to rat diets is beneficial for intestinal digestion, relieving both constipation and diarrhoea. These effects have been attributed to the glutamine-rich protein content and high content of no cellulosic polysaccharides (arabinoxylan, 20-47%)

and smaller amounts (less than 1%) of (1/3, 1/4)-b-glucans. intake of foods containing BSG also found a decrease in cholesterol (Mussatto et al., 2006). In the following paragraph, the various components are described from a functional point of view for human health.

Arabinoxylans (AX):

- A significant portion of the water-extractable AX that enters the large intestine can act as a prebiotic. It is fermented by the colonic microflora, of which important Bifidobacteria and Lactobacilli are part. A healthy population of these bacteria is considered important for maintaining gut health;
- Bifidobacteria produce short-chain fatty acids (SCFAs) through fermentation of dietary fibre. SCFA production is generally considered beneficial because it protects the host from pathogens, induces immune responses, reduces cholesterol synthesis, stimulates colonic blood flow, improves muscle contractions, and may protect the colon from cancer development;
- Known prebiotic called xyloligosaccharides (XOS) are derived from the breakdown of AX, they are perhaps the reason for the prebiotic activity of AX;
- The ingestion of AX can help modulate postprandial glycaemic response;
- It can increase bulk viscosity, delaying gastric emptying, reducing intestinal motility and thus inducing a delay in glycaemic and insulin response. To achieve this effect, it is recommended to consume 8 g of AX-rich fibre for every 100 g of available carbohydrate.

Lignin:

- According to the European Union Commission, lignin is included as a component of dietary fibre when it remains closely associated with the original plant polysaccharides;
- This complex polymer has generally been considered an inert compound in the human gastrointestinal tract and resistant to the metabolic activities of gut microbiota; Recent studies suggest that the gut microbiota is able to partially degrade lignin and metabolise the released compounds.

β-glucans:

- Consumption of whole foods has been associated with reduced risk of coronary heart disease, and β-glucan is believed to be an important nutritional component;
- The effect of β-glucan is due to its soluble nature and ability to form a gel-like network. There is an increase in gastrointestinal viscosity resulting in decreased reabsorption of bile acids and increased synthesis of bile acids from cholesterol, with a net cholesterol-lowering effect;

- At least 3 g per day of barley β-glucan is recommended to achieve this cholesterol-lowering effect;
- Modulation of the immune system is also considered a mechanism by which dietary fibre produces beneficial effects on the host. An inflammatory response is associated with an increased risk of developing colorectal cancer. Increased dietary fibre intake has been shown to reduce pro-inflammatory effector levels.

Proteins:

- Essential amino acids account for about 30 percent of the total protein content, and lysine is abundant. This finding is significant because lysine is often deficient in grain-based foods;
- Isolated protein hydrolysates produce antioxidant and antihypertensive effects;
- Hydrolysates can act as functional ingredients for the management of diabetes and hypertension.

Husk barley Phenolic compounds and hydroxycinnamic acids:

- Antioxidants and scavenging DPPH;
- Anti-carcinogenic effect;
- Anti-apoptotic effects on immune cells;
- Process immune modulatory effects;
- It significantly reduced the damage induced by hydrogen peroxide.

In conclusion, the consumption and incorporation into food products, or indeed, the use of this brewing by-product is an inexpensive source of health promoting compounds (Lynch et al., 2016; Mussatto et al., 2006).

4.3 Spoilage, stabilisation and storage

Spoilage: moist BSG contains a large amount of water and fermentable sugars. BSG is a very unstable material and is likely to deteriorate rapidly due to microbial activity, e.g., after 30 days of storage at room temperature have been isolated Aspergillus, Fusarium, Mucor, Penicillium, and Rhizopus (Mussatto et al., 2006). Also, the transport of wet BSG is very impactful, energy consuming and costly. If this material is to be used at a later stage, it must be stabilized and stored under appropriate conditions after production. It is suggested to lower the moisture content to ~10% to extend the storage time. (Lynch et al., 2016). Although BSGs have proved useful for many practices, it is very complicated to stabilise them, both because of timing and energy consumption (hence cost and environmental impacts) (Cimini & Moresi, 2021).

Stabilisation: there is chemical solutions like acid solutions (lactic, acetic, formic and benzoic acids) and the use of a mixture of benzoate, propionate and sorbate at a concentration of 0.2-0.3% (w/w) can be used to extend the aerobic stability of BSG by 4-5 days. However, it is unthinkable to apply these methods to an end consumer (Lynch et al., 2016)

Physical methods:

- Drying: this is the most common process and often the one that offers the best compromise despite being energy intensive (Lynch et al., 2016). Because of the oven and rotary-drum drying use. It reduces the volume of the material; no alteration of the composition takes place; however, it must be conducted at temperatures <60 °C because higher temperatures can generate unpleasant flavours(Mussatto et al., 2006); the temperature of the grains near the dryer outlet can increase, leading to roasting or burning of the dried grains (Lynch et al., 2016).
- Freeze-drying: it reduces the volume of material and there is no compositional alteration. However, it is not economically viable because of the large amount of energy requirement (Lynch et al., 2016); (Petit et al., 2020).
- Freezing: It is inappropriate because of large stored volumes, it reduce the volume of material; there is an alteration of arabinose content (Mussatto et al., 2006).
- Pickling: it extends product life without too much sensory alteration. It was studied only for animal feed (Jackowski et al., 2020).
- Use of superheated steam: it is less energy intensive than oven drying; it improved drying efficiency and enhanced the recovery of valuable organic compounds. Steam velocity through the sample, as well as temperature were seen as important factors in drying of the BSG, while only very high temperatures (180 °C) were shown to affect starch gelatinisation. (Lynch et al., 2016).
- Extrusion: mixing of different type of BSG according to obtain flour. The high polyphenol content, high antioxidant capacity, significant insoluble fibre content and starch content (soluble fibre) make BSG suitable for extrusion and inclusion in the form of extrudates into functional food formulations (Ivanova et al., 2017; Steinmacher et al., 2012).
- Lactic ferments: they provide food safety and extended shelf life. *Lactobacillus Curvatus* was used by Petit et al., 25 g of culture per 1 kg of product. It is able to prevent the growth of undesirable bacteria such as pathogens and degradation. The culture is applied by spraying a bacterial suspension onto the surface of the product. It is in the form of a dry whitish or brownish powder and can be stored for at least 18 months at -17 °C even if transported at room temperature. The shelf life of the cultures at 5 °C does not exceed 6

weeks. The strain remains alive but does not multiply in the product below the minimum growth temperature (Petit et al., 2020).

- The authors of a study combined the mechanical drying (with mechanical tools) and the thermal drying (pure dehydration) to reduce the drying energy requirement, this study was also for animal nutrition (Iñarra, 2022).
- Storage: some studies compared different methods of BSG storage, with respect to microbial proliferation and modification to polysaccharides and phenolic acid components.
- Fresh material is conservated at 20 °C: fresh BSG had low levels of aerobic mesophilic and thermophilic bacteria (102–103 CFU g^{-1}). The microbial population increased 1000-fold, to ∼106 CFU g^{-1}, by day 5. Loss of sugars postulated to be due to microbial hydrolytic and surviving endogenous enzyme activities, which would be particularly active during the cooling of the BSG postproduction (Lynch et al., 2016).
- Refrigerated at 4 °C: over 16 days, the numbers of aerobic bacteria remained below 105 CFU g^{-1}; loss of sugars postulated to be due to microbial hydrolytic and surviving endogenous enzyme activities, which would be particularly active during the cooling of the BSG postproduction (Jackowski et al., 2020; Lynch et al., 2016).
- Autoclaved at 120 °C for 1 h: no evidence of microbial activity; solubilisation of polysaccharides and associated phenolics. It was seen as being effective for long-term BSG stability; however this can result in compositional changes (Lynch et al., 2016).
- Frozen storage: no evidence of microbial activity; no changes in composition but energy consuming (Lynch et al., 2016).
- Micronising and dry milling techniques can be used to transform BSG into flour. this process combines milling and sifting to fractionate the raw material into portions with a range of different particle sizes (Barron et al., 2012; Karlsen et al., 2022; Nocente et al., 2021)

4.4 Brewery spent grain potential applications and focus on bread production

Figure 17 shows how the food waste hierarchy specified by Directive 2008/98/EC could be applied to manage the disposal of BSG according to circular economy template (Cimini & Moresi, 2021). The noblest action for the reuse BSG is to include them in the formulation of new products.

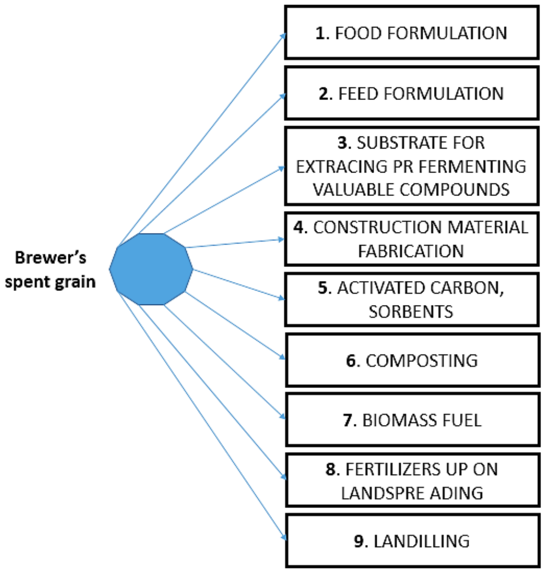


Figure 17. Potential uses of BSG. Adapted from (Cimini & Moresi, 2021)

As the figure 17 shows, there are other important strategies. In the table below (table 3), referring to the hierarchy, the authors (Cimini & Moresi, 2021) have strictly listed the main scenarios about the use of BSG.

Food waste hierarchy	**Main BSG reuses**	**Remarks and references**
1	Partially exhausted raw material	It can be recovered from the uppermost layers of BSG discharged after lautering. Since it contains undigested starch, it might be integrated with appropriate doses of fresh malt and reused in the subsequent wort batch to produce low-alcohol or alcohol-free beers (Zürcher and Gruss, 1990).
	High-protein and high-fiber containing ingredient	It was used to: (a) Enrich soft wheat flour and formulate: (i) breads (Steinmacher *et al.*, 2012), (ii) breadsticks (Ktenioudaki *et al.*, 2012), (iii) cookies (Kissell *et al.*, 1979; Petrovic *et al.*, 2017), and (b) Enrich hard wheat semolina to prepare several dry pastas (Cappa and Alamprese, 2017; Nocente *et al.*, 2019). (c) Reduce fat content in some meat products: (i) frankfurters (Özvural *et al.*, 2009), (ii) smoked sausages (Nagy *et al.*, 2017), (iii) chicken sausages (Choi *et al.*, 2014), and (iv) chicken patties (Kim *et al.*, 2013).
	Main substrate for probiotic beverages	Upon suspension of 200 g L-1 of pre-ground BSG in sterile water, and fermentation of the resulting medium with Bacillus subtilis WX-17 (i.e., rod-shaped, Gram-positive bacteria generally recognized as key health promoter), it was recovered as a liquor rich in viable cells (7.2 × 109 CFU mL-1), several essential amino acids, and citric acid cycle intermediate metabolites, and with a high antioxidant activity (Tan *et al.*, 2020).
2	Feed additive	BSG can be used to feed: (i) cattle (Cimini and Moresi, 2016),

		(ii) pigs (Kerby and Vriesekoop, 2017), (iii) aquaculture fish (Nazzaro *et al.*, 2021), (iv) poultry (Rachwał *et al.*, 2020), and (v) edible insects (Mancini *et al.*, 2019).
3	Source of proteins	The recovery of proteins, as such or hydrolyzed to formulate vegan foods, asks for quite complex extraction and purification processes using alkaline (Du *et al.*, 2020) and/or acid solutions (Qin *et al.*, 2018), subcritical water at 200°C and 40 bar (Du *et al.*, 2020) or 185°C and 50 bar (Alonso-Riaño *et al.*, 2021), hydrothermal pretreatment at 60°C, ultrasound-assisted enzymatic pretreatment (Yu *et al.*, 2020), or steam explosion (Rommi *et al.*, 2018).
	Source of polyphenolics	Recovery of polyphenolics was performed using quite different processes, namely alkaline hydrolysis, enzymatic hydrolysis, acetone–water, or ethanol–water extraction as such or assisted by ultrasound or microwave, or supercritical carbon dioxide extraction (Jackowski *et al.*, 2020; Karlović *et al.*, 2020; Rachwal *et al.*, 2020; Stefanello *et al.*, 2018).
	Source of arabinoxylan (AX)	Such polysaccharide consists of two monomers (xylose and arabinose) and may be recovered from BSG using the integrated process as set up by VIeira *et al.* (2014) where increasing concentrations of KOH or NaOH allowed ~83% of total proteins and ~70% of total arabinoxylan to be extracted sequentially. The efficiency of such a process was further improved with the help of ultrasound (Reis *et al.*, 2015) or microwaves (Coelho *et al.*, 2014).
	Source of multicomponent extracts	These were recovered by submitting BSG or other brewery wastes to water leaching under moderate conditions (Almendinger *et al.*, 2020). Their carbohydrate or amino acid concentration was generally smaller than 10 mg per g DM or 2 mg per g DM, respectively. Thus, their biological activity should be significantly enhanced to be properly utilized in cosmetic products (Almendinger *et al.*, 2020).
	Source of cellulose nanofibers	Such nanofibers could be used as emulsion or dispersion agents in food preparations (Rachwal *et al.*, 2020). Their recovery from dried BSG required quite a complex procedure consisting of the following steps: primary alkaline treatment with 0.1-M NaOH at 60°C for 2 h to get rid of proteinaceous matter; bleaching of the lignocellulose residue with 0.7% (w/v) sodium chlorite at a boiling point for 2 h; filtering and residue resuspension in 5% (w/v) sodium bisulfite at room temperature for 1 h; filtering and washing with distilled water; secondary alkaline treatment with 17.5% NaOH at room temperature for 8 h; washing and dispersion in water at 1.5% (w/v); and final homogenization at 700–800 bar for 20 cycles (Mishra *et al.*, 2017). However, no information about their processing costs is available.
	Microbial growth substrate	It was used as a growth substrate for several microorganisms, such as *Escherichia coli*, actinobacteria, *Bifidobacterium adolescentis*, *Lactobacillus spp.*, and yeasts in alternative to expensive nitrogen sources, such as yeast extract and peptone (Cooray *et al.*, 2017; Rachwał *et al.*, 2020).
	Mushroom substrate	It was used to cultivate mushrooms, such as *Pleurotus ostreatus*, *Lentinula edodes*, and *Hieracium erinaceus*. The trials carried out at the Mycoterra Farm (Westhampton, MA, USA) suggested not only that BSG should be handled with care to avoid cross-contamination of laboratory environment but also that grain savings from BSG substitution were not so significant to support such a use financially, especially in spawn stages (Mycoterra Farm, 2015).
	Bioproduct substrate	BSG was used as substrate for several bioproducts (Rachwał *et al.*, 2020), such as succinic acid (Cooray *et al.*, 2017), microbial oil (Saenge *et al.*, 2011), fatty acids and carotenoids (Zalynthios and Varzakas, 2016), xylitol (Mussatto

		and Roberto, 2008), pullulan (Singh and Saini, 2012), or citric acid (Femi-ola and Atere, 2013).
	Microbe-immobilizing carrier	It was used to immobilize yeasts (Brányik *et al.*, 2001).
4	Additive for bio-composites	BSG was used as an environment-friendly reinforcement or filler component in: 1. polyurethane foam composites, even if the foam matrix was found to be less compatible than that using ground tire rubber (Formela *et al.*, 2017); 2. food packaging trays made of BSG, potato starch, glycerol, and chitosan or glyoxal in replacement of expanded polystyrene, even if their flexural strength (~3.8 MPa) decreased to 0.4 MPa after contact with water (Ferreira *et al.*, 2019); 3. clay bricks as substitute for sawdust at 5–15% of dried BSG in brick making (Ferraz *et al.*, 2013); addition of just 3.5% (w/w) of BSG yielded stronger, more porous, and less dense bricks than standard ones in large-scale tests (Russ *et al.*, 2005); 4. wood polymer composites by twin-screw extrusion of pre-dried BSG at 120–180°C, this lowering the specific mechanical energy consumption by 20% and improving their thermal stability (Hejna *et al.*, 2021).
5	Activated carbon	BSG, as such or pelletized, was converted into biochar via pyrolysis and micro-gasification under high-temperature (400–500°C) and low-oxygen conditions with an average yield of 18.6% (w/w) (Sperandio *et al.*, 2017). Activated carbon from BSG exhibited adsorption capacity for metallic ions, phenolic compounds, and color quite similar or even effective than that of their commercial counterparts (Mussatto *et al.*, 2010).
6	Composting	A proper dosage of wet BSG with a lignocellulosic bulking agent (e.g., wheat straw) and sheep or pig manure favored its appropriate composting (Assandri *et al.*, 2021).
7	Biomass fuel	BSG could be used as a: (i) solid biomass having a lower calorific value (LCV) of 13.7 ± 0.7 MJ kg-1 at ~8% (w/w) moisture content, and a positive economic return, its estimated production cost and its market price being €110–140 kg-1 and €230–270 kg-1, respectively (Sperandio *et al.*, 2017); (ii) hydrochar, a coal-like product obtained by hydrothermal carbonization in a closed reactor at 180–280°C and 2–6 MPa for 5– 240 min (Jackowski *et al.*, 2019); (iii) substrate for production of bioethanol upon acid pretreatment and inoculation of single or mixed microbial cultures, such as *Pichia stipitis* and *Kluyveromyces marxianus* (White *et al.*, 2008), *Saccharomyces cerevisiae* and *Aspergillus oryzae* (Wilkinson *et al.*, 2017), and *Fusarium oxysporum* (Xerus *et al.*, 2008); (iv) substrate for BSG anaerobic digestion in continuously stirred bioreactors yielding from 0.56 g (Wang *et al.*, 2015) to 0.81 g (Vitanza *et al.*, 2016) of biomethane per gram of total organic matter, even if both yields and kinetics were implemented by resorting to microwave-assisted alkaline pre-treatment (Kan *et al.*, 2018) or by supplementing 5% biochar (Dudek *et al.*, 2019) or trace elements (Bougrier *et al.*, 2018).
8	Organic fertilizer	BSG might be used as: (i) organic fertilizer because of its P, K, protein, cellulose, lignin, and hemicellulose contents; the mixture of BSG (5 Mg ha-1) and NPK fertilizer (200 kg ha-1) affecting positively the growth of maize and increasing soil aggregation (Nsoanya and Nweke, 2015);

		(ii) biofertilizer useful against soil-born insects; once BSG is inoculated with the spores of entomopathogenic fungi Beauveria bassiana the accumulation of 10 metabolic compounds in the fermented biomass is found to be effective against Galleria mellonella larvae (Qiu *et al.*, 2019).
9	Landfilling	Wet BSG is landfilled by 7–10% of the UK craft breweries (Kerby and Vriesekoop, 2017).

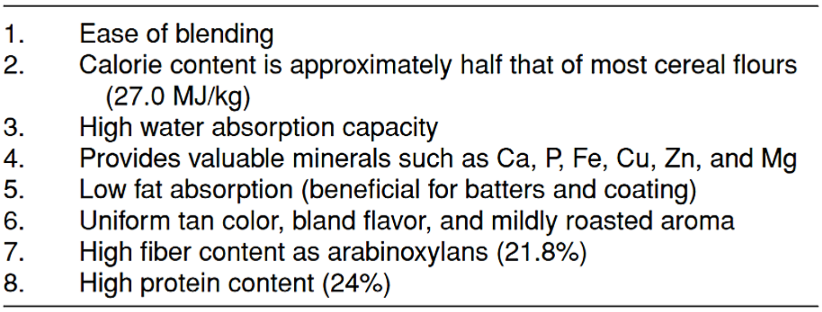
Table 3. Main potential uses of brewer's spent grain (BSG) as classified according to the food waste hierarchy (Cimini & Moresi, 2021).

As previously reported, BSG is generally dried after must production and then (in many cases) ground to convert it into a form more suitable for application in food products (Lynch et al., 2016)

Sieving, extrusion baking and hydrolysis are some steps that can be applied to BSG before formulation on food. The first one separates the ground BSG into fine (<212 μm), medium (212-425 μm) and coarse (425-850 μm) fractions before flour application. The second one has been applied to BSG as an aid for incorporating it into various baked goods or snacks. Extrusion can also be used as a means of reducing the moisture content of BSG before use. The third one is an innovative process involving the application of cellulase and protease enzymes during the extrusion process (called reactive extrusion). Compared with extrusion in the absence of enzymes, reactive extrusion successfully modified BSG, as evidenced by the increase in solubility index and reducing sugars and the decrease in water-holding capacity.

10 and 40% on a dry weight basis are the levels of BSG applied in products. It generally leads to increased levels of fibre and protein and decreased levels of starch. If the percentage of BSG is greater than 20%, the addition of such amounts generally has a negative effect on the structure, texture, volume, and colour of the final product, and thus on sensory characteristics and final consumer acceptance. It is known that the addition of fibre generally results in darker products with lower volume, higher hardness, and denser texture (Lynch et al., 2016). It is confirmed by Cimini and Moresi. They report that fortification of food products with BSG had no effect on the taste, smell and texture of the final product chosen, as well as on its appreciation by the end consumer, provided it was no higher than 25-30% (w/w) in bread and snacks. Naturally, these fortified foods have a higher fibre content and a lower glycaemic index (Cimini & Moresi, 2021).

Fibre can interfere with gluten network formation and, in addition to limiting water for gluten development, it physically disrupts the gluten-protein matrix. A minor obstacle may be the presence of phytic acid (present in BSG). However, this can be overcome through fermentation; in fact, some lactic acid bacteria and yeasts associated with grains have been shown to possess phytic activity. A generic summary of the physical characteristics that BSG can bring to foods when it is included in the formulation is given in table 4.



1. Ease of blending
2. Calorie content is approximately half that of most cereal flours (27.0 MJ/kg)
3. High water absorption capacity
4. Provides valuable minerals such as Ca, P, Fe, Cu, Zn, and Mg
5. Low fat absorption (beneficial for batters and coating)
6. Uniform tan color, bland flavor, and mildly roasted aroma
7. High fiber content as arabinoxylans (21.8%)
8. High protein content (24%)

Table 4. Properties of BSG flour in foods (Gupta et al., 2010)

As mentioned in the paragraph above, this material can be exploited in many fields and in different products. The current study focuses on the use of BSG in bread production; several studies about the quality of flour and the quality of bread have been published. BSG has been used to produce protein and fibres enriched breads, which could be very useful in poorer regions of the world where food is scarce. However, considering that carbohydrates are the main components, more attention should be paid to its conversion into soluble and fermentable sugars (Gupta et al., 2010). Various nutritional and textural properties of the finished product were studied by Stojceska and Ainsworth. Incorporation of BSG significantly improved dietary fibre by 4 and 9% upon addition of 10 % (w/w) and 30% BSG, respectively. The protein content did not change significantly compared to the control (Stojceska & Ainsworth, 2008). Czubaszek et al. observed that this substitution decreased the gluten yield and worsened the quality (lower sedimentation stability and increased dough softening). Changes were also observed in the starch-enzyme system, resulting in a decrease in the number of falls and maximum dough viscosity (Czubaszek et al., 2022). Breads containing both types of BSG (10 and 20 %) had lower volume and higher yield. In contrast to the previous study, they had higher protein (8.33 to 14.65% crude protein), dietary fibre (from 0.74 to 8.45% crude fibre), fat and ash contents and a lower energy value (53.18 to 34.45% and from 2.66 to 2.24 kcal, respectively) than wheat bread (Czubaszek et al., 2022; Yitayew et al., 2022). The sensory acceptance of bread was significantly influenced by BSG levels; replacing wheat flour with BSG up to 10% was accepted by consumers (Yitayew et al., 2022).

An increase in water absorption by the bread and a better consistency compared to bread made with standard flour can be observed. These products have a higher fibre content, it is true. However, it disturbs dough formation and contribute to reduced gas retention and, consequently, the volume of baked goods. This effect can be eliminated by adding enzymes such as xylanase and lipase when baking bread. Influence this can also affects the loaf volume, its ageing rate and the structure of the crumb. Studies recommend not exceeding 30% BSG flour in the total dough (Jackowski et al., 2020).

In conclusion, the use of BSG as a main bread ingredient would increase the market value of this co-product, thus increasing its economic potential (Waters et al., 2012).

4.5 LCA of Brewery spent grain for human consumption

Numerous strategies are reported for the use of BSG. Therefore, it is necessary to understand which scenarios are better than others and if that scenarios are better than conventional ones. A great help is certainly provided by the LCA approach. A comprehensive LCA study on the production of a bread formulated with BSG has not yet been found. However, Petit et al. have compared which innovative stabilising process (and which one is better) and conventional scenarios, figure 18.

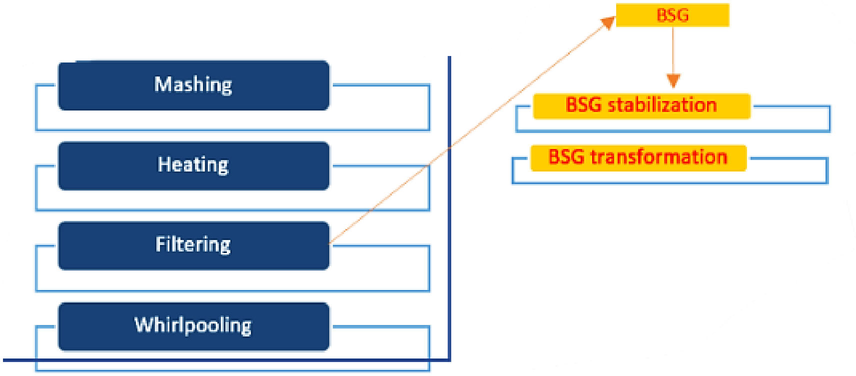


Figure 18. partial flow chart of brewery life cycling, the orange part is for BSG upcycling (Petit et al., 2020).

Many conclusions are accorded with previous studies, like cultivation impacts, transportation and energy consuming treatments (e.g., refrigeration). Nowadays, innovative scenarios have been evaluated as more impactful than conventional ones (e.g., animal feed) as shown in figure 19. This is because the technologies involved (dehydration, lacto-fermentation, freeze-drying and refrigeration) have a non-negligible impact compared to the other phases of the spent grain life cycle. However, for the animal feed scenarios, assumptions are made of avoided impact (grain cultivation and feed production avoided). Thus, the same approach could be used for human food scenarios (Petit et al., 2020).

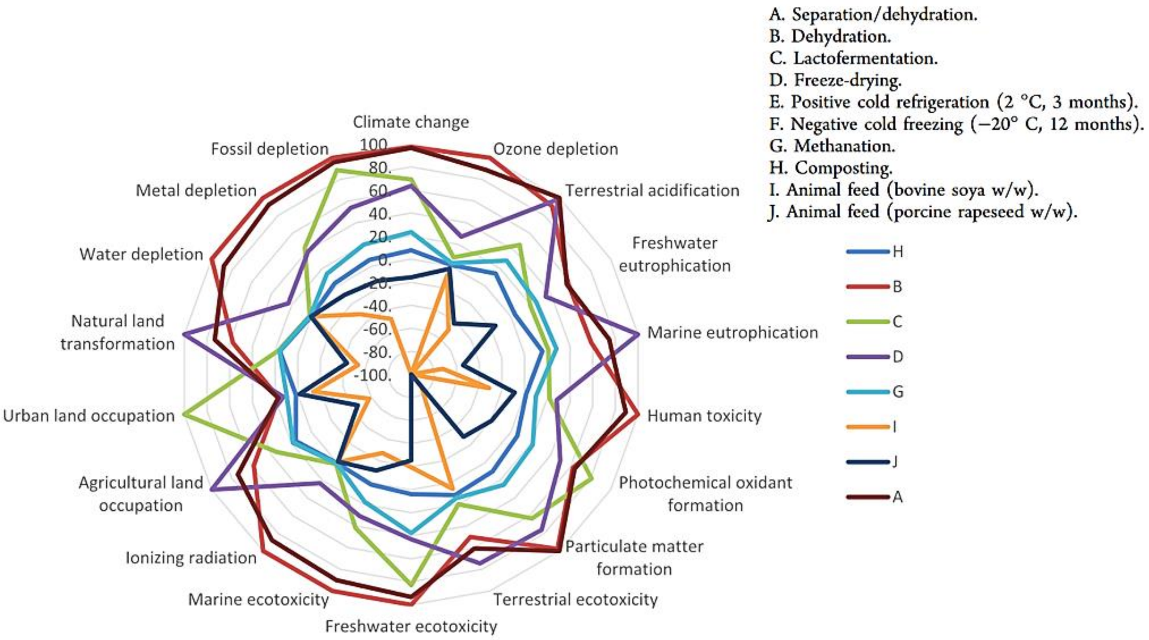


Figure 19. Comparative environmental performance of the different models for recovering the brewed spent grain (Petit et al., 2020)

One of the largest brewers in the United States, Anheuser-Busch InBev, has applied admirable choice. It realised that it must dispose of approximately 1.4 million Mg of BSG per year. Therefore, they have placed a bakery in-house (producing other products in addition to bread). In this way, it can cut down on transport and storage emissions and produce a product with high benefit that can boast nutritional claims. Therefore, more BSG is used in food sector instead of being diverted to the second option of the food waste hierarchy. Obviously, not all small breweries can afford such applications. Consequently, there should be a system-wide and more organised collection and processing (Cimini & Moresi, 2021).

5. Stale/unsold bread

Most developed countries in the world waste large quantities of bread, especially in Europe. Annual global bread production is over 100 million tonnes. According to the analysis of the global bread market, Europe dominates the market with a 53.6% share, followed by the United States (28.6%), Asia Pacific (10.9%) and the Middle East and Africa (6.9%) (Narisetty et al., 2021). 10% of all bread produced is wasted. It is difficult to quantify the exact amount of bread wasted; it is an approximation. Not only the product itself is lost, but also the natural resources used to produce it (the water, land and energy used for the production of raw materials, transport and manufacture) and of course this has an impact on society, the environment and economy (Brancoli et al., 2020). Just to give an idea of a highly developed economy like the UK: bread is the second most wasted food, with as much as 44% of the bread produced going to waste. It is causing huge economic losses and environmental problems. Every day, around 20 million slices of bread are thrown away in the UK, with an annual waste of 292,000 tonnes, which equates to 584,000 tonnes of CO_2 equivalent emissions. This waste must be managed in the best possible way because primarily it is necessary to protect the health of the consumer, being an organic waste, it is easy to contaminate. Therefore, holistic approaches in the supply chain and understanding the steps leading to waste generation could help develop the economy by reducing waste or recycling waste into valuable products (Narisetty et al., 2021).

Production and handling of intermediate products and dough; portioning and dough formation, baking, custom packaging, shipping (storage), and transportation by own means are the wasting steps identified by Goryńska-Goldmann et al. (Goryńska-Goldmann et al., 2020). Due to substandard practices, processing factors, errors during operation, rejection during product quality control, improper handling during storage/packing, and sometimes due to the type of product manufactured bread wastage during the production stage is easy to occur (Goryńska-Goldmann et al., 2020). For example, up to 40% of the bread is lost in the sandwich making process due to the removal of crusts from the loaves. Storage and transport conditions play an essential role in keeping bread in a healthy environment to ensure high quality and good shelf life (this is when bread arrives in supermarkets and retail shops).

Waste at the consumer level plays a key role. People's awareness exacerbates this situation, as they buy more than they need and do not have sufficient knowledge about storage conditions and shelf life. The problem is observed in many European countries (Narisetty et al., 2021). There are several strategies for reusing such material as shown in figure 20; these include our case study, stale bread in brewery production. In addition, bread has been proposed as a substrate to produce chemicals for pharmaceutical companies, the food industry, biofuels and enzymes; as a substrate to produce *Saccharomyces cerevisiae* biomass; and in the production of ingredients for food processing. Bread residues contain a high concentration of starch (more than 70% of dry matter) and protein (up to 14% dry matter), and treatment with amylase, amyloglucosidase and protease easily leads to the release of compounds available for microbial growth (Martin-Lobera et al., 2022).

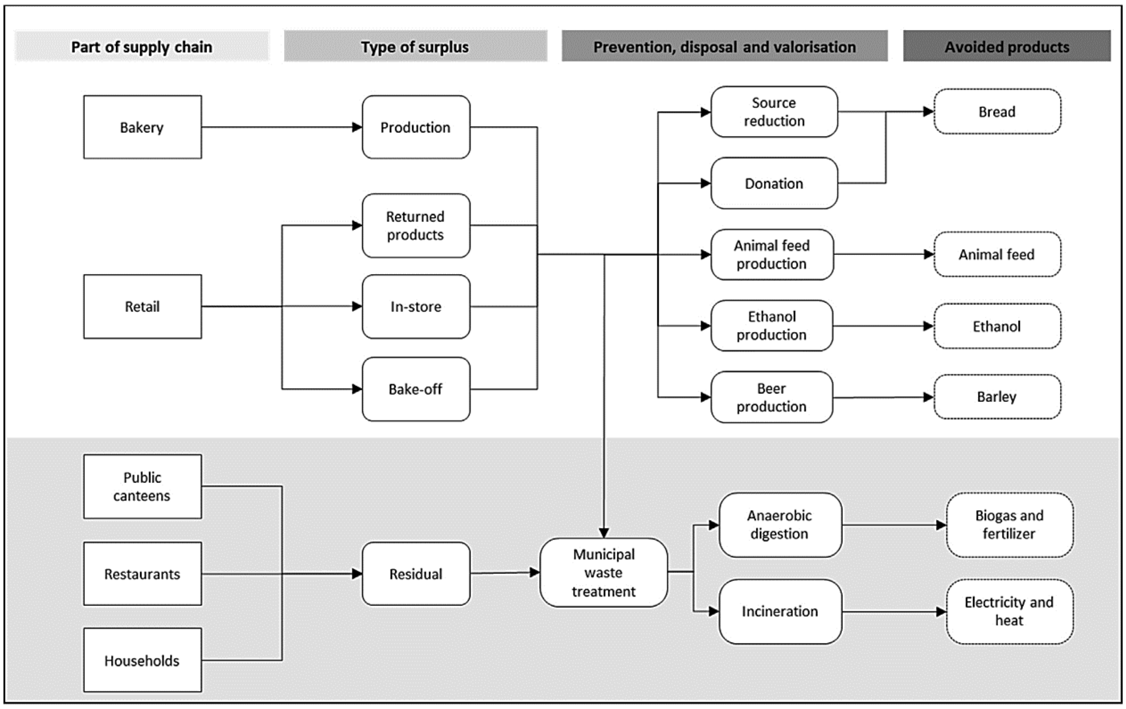


Figure 20. Bread surplus flows, waste treatment and valorisation scenarios, and avoided products. The area highlighted in grey shows common flows of mixed food waste, which are not feasible for the management pathways highlighted in the white area (Brancoli et al., 2020)

During storage, a complex physicochemical process called "staling" occurs, driven mainly by moisture loss and starch retrogradation. Bread is a starchy food and an important source of easily extractable fermentable sugars, which is in direct contrast to lignocellulosic raw materials, for which severe physical, chemical and/or enzymatic pre-treatment processes are required to release fermentable sugars. For this reason, bread is susceptible to microbial attack. Consequently, preservatives that inhibit the growth of spores, molds and/or yeasts are used to reduce spoilage and ensure safety (Martin-Lobera et al., 2022).

5.1 Stale bread in beer production and its life cycle assessment

Taking into account the principles of the circular economy, one solution to avoid bread waste is to divert the flow of surplus bread to a recovery system that can turn it into beer, creating value with what would otherwise be used in less valuable ways (incineration), or even completely wasted (landfill) (D’Angelo, 2022). Projects have appeared around the world involving this strategy. The pioneer was the Belgian brewery Brussels Beer Project, which, in collaboration with Atelier Groot Eiland, produced the first beer from unsold bread in 2013 (Connolly, 2019). Martin-Lobera et al. brewed an ale replacing up to 50 % of the malt weight with different types of bread: wheat bread, whole wheat bread, rye bread, and corn bread. A sensory (visual and taste) comparison with 100% malt ale was also developed. All the beers brewed by partially replacing malt with stale bread, except in the case of cornbread, achieved the same sugar extraction and physicochemical profile similar to the control beer, especially in the case of whole-wheat bread beer. In addition, beer brewed with whole grain bread provided a higher level of bitterness and greater persistence in the mouth. All of these achievements represent great progress and benefit to the brewing industry worldwide (Martin-Lobera et al., 2022).

In the other hand, some breweries in the United Kingdom have begun using bread waste to replace malted barley as a source of sugar for fermentation in brewing. In 2018, between 20 and 25 % of malted barley was replaced with stale bread at 5.1 percent alcohol in the production of Thoroughbred beer. Similarly, in 2017, in the case of Toast Ale, 25-28 % of the original malt was replaced with dried bread (Toast ale saved by saving 15 tons of bread, and its success led it to expand the concept abroad); (*Toast Ale - Raise a Toast. Save the World. Cheers*, s.d.). Replacing more than about 25% of the malt is impractical because barley contains natural enzymes that can break down bread starch into fermentable sugars This means that when the amount of malted barley decreases, the supplementation of external enzymes for gelatinization and saccharification increases, and therefore comparative LCA studies need to be addressed (Narisetty et al., 2021).

Many other examples can be added-the Knäerzje (Germany, 2019) (*A Toast to Sustainability! German Company Brews Beer from Leftover Bread | Video Ruptly*, s.d.); the Woolworths Supermarket's Loafer (Australia, 2019) (*From bread to beer: Woolworths helps create its first circular economy craft beer «Loafer» - Woolworths Group*, s.d.); MUSA (Portugal, 2020) (*Bread Combo - Cerveja Musa*, s.d.) and Baladin (Italy, 2021) (Baladin Staff, s.d.).

They demonstrate the technical feasibility of brewing with current quality and taste requirements. What will be interesting to explore are the environmental impacts and the social and urban interactions of the system; figure 21.

Figure 21. Example of stale bread mashing and malt (Bondioli, 2016)

Not many LCA studies have been identified in the literature regarding the use of stale bread in brewing. It is practically necessary to compare the innovative approach with the traditional ones through LCA method. In Australia a recipe was developed to replace some of the barley with waste bread. A comparative life cycle assessment (LCA) was performed against a standard beer from the same producer, figure 22 (different scenarios). The footprint of Upcycle Ale (the name of the beer) was found to be 20 % lower than that of a standard craft beer. Due in part to lower demand for barley but mainly because all spent grain from Upcycle Ale production is offered to livestock farmers as feed instead of being disposed of in landfills. Further opportunities for emissions reduction lie in the adoption of renewable energy sources to power the brewing process, as this is the main source of greenhouse gas emissions for both bread beer and standard beer. The study concluded that the use of alternative raw materials does not confer significant differences. BSG placement and use of renewable energy, on the other hand, differ in flavour of environmental impact compared to standard production, figure 23. These results highlight the applicability of LCA to validate and guide circular economy decisions in operational contexts (Almeida et al., 2018).

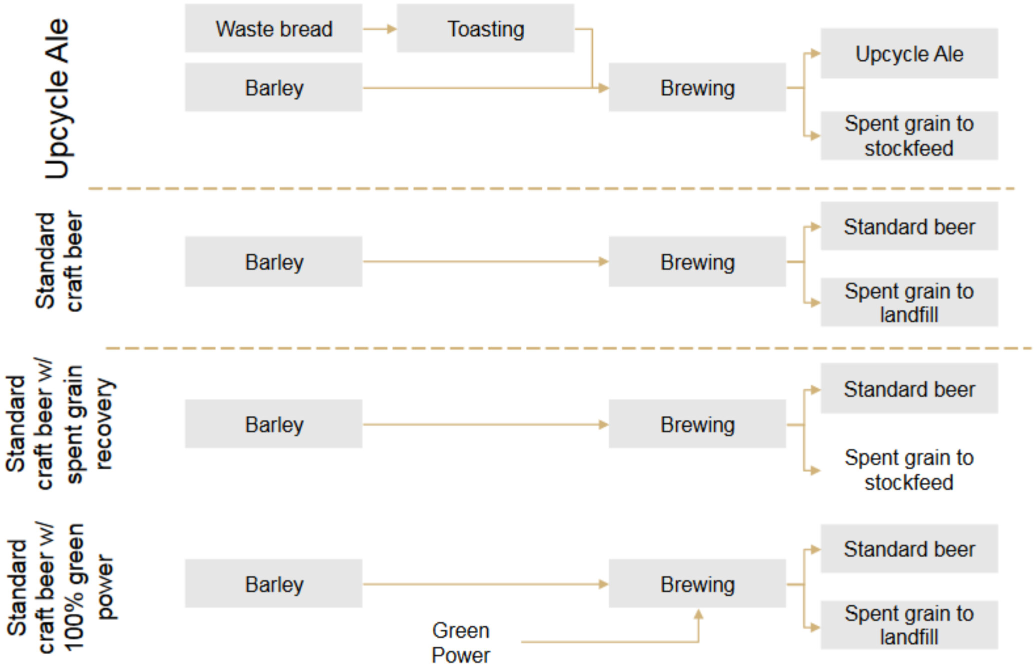


Figure 22. Differences between the life cycle of Upcycle Ale and a standard craft brew (Almeida et al., 2018)

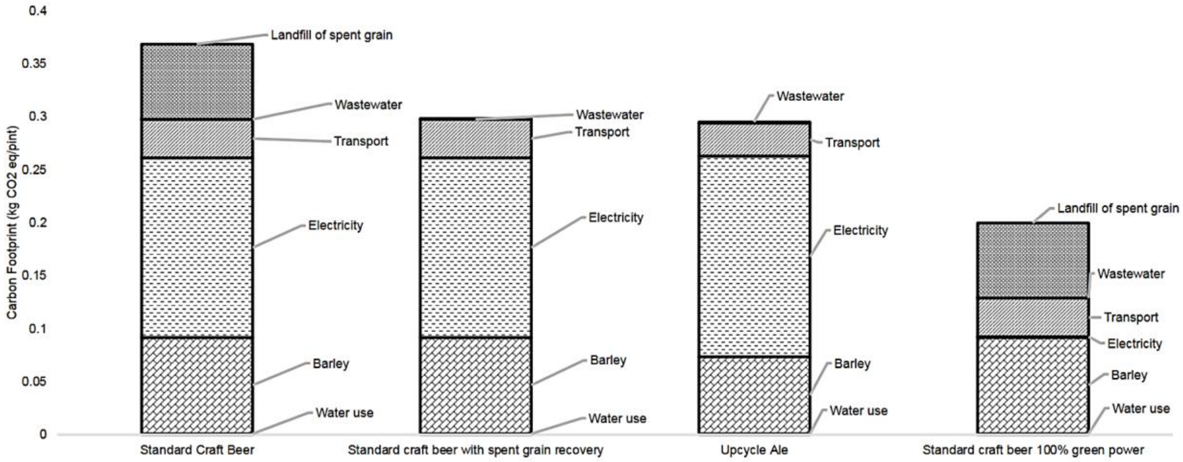


Figure 23. Life cycle carbon footprint of Upcycle Ale compared to a standard craft beer by the same brewer. The stacked bars show the contribution of different inputs and outputs to the life cycle (Almeida et al., 2018)

b. EXPERIMENTAL SECTION

6. Materials and methods

6.1 Data provider companies and the application tool for LCA assessment

The study area includes four small-local companies and one pilot scale at the Oniris University; two companies are in the North-West of France (Les Brassés and Yec'Hed Malt), one in the South-West of France (Waste Me Up) and the last one in Brussels (Brussels Beer Project).

The application tool for LCA is OpenLCA. It is a free, professional Life Cycle Assessment and Footprint software with a broad range of functions and available databases, created by GreenDelta since 2006. OpenLCA is an open-source software, i.e. its source code is freely available and can be modified by anyone. The main feature of openLCA is its flexibility of use, because it allows processes and materials already existing in the database to be modified and adapted to the case study. It is also possible to create processes from scratch. This makes it possible to extend the boundaries of the system when the information obtained are not adequate. Ecoinvent is the main database in openLCA one of the most comprehensive and most used, especially for LCA evaluations involving the European region (openLCA.Org).

6.2 Goal and scope definition

The general goal is to evaluate the environmental impact of two production sectors in a circular economy way: bread and beer production. How the use of waste from one sector impacts the environmental load of the other one. Different options are taken into account in the environmental impact comparison: conventional; organic; virtuous use of BSG and unsold/stale bread in other food formulation (in this case, same food category, bread and beer). The goal is to indicate which variants would cause higher impact, identify the processes hot spots and if the circularity is the best option for this king of system. This is a tool for small breweries, bakeries and new companies that collect and stabilise the BSG. The results can be used by the managers to identify the hotspots and associated mitigation measures to make the processes more sustainable. The functional units considered are 1 kg of bread and 1 L of beer.

6.3 System boundaries

In this study, a cradle to gate approach is considered. It includes the production and distribution of raw materials, packaging, energy, water and transports along the entire supply chain per unit of brewing and baking operations, BSG and unsold bread stabilisation processes as innovative links between traditional approaches.

Primary data are available for all productions steps (malting, brewery, BSG stabilisation, bread stabilisation, and bakery). Secondary data are available for cultivations, for transports and for grain milling in bread production (form Ecoinvent and Agribalyse database available in OpenLCA). Assumptions are made about high protein flour (HPF, made after BSG sifting process after which the fiber part is removed), BSG and unsold bread percentages during beer and bread production according to the literature. Several products are considered and figure 24 resume all that variants: T = transport; rectangles = processes and ovals = row materials, intermediate products and final products.

6.3.1 Beer flow chart description

Beer operations: barley cultivation, malting, milling, mashing, 1° filtration, hop cultivation, boiling and hopping, fermentation, yeast production, maturation, 2° filtration, cooling and bottling (brown colour, figure 24). For blanche beer a wheat cultivation was considered (purple colour, figure 24).

BSG used for animal feed is not included (for traditional steps), the BSG is considered a co-product and allocation was made. The consumption phase and cleaning products are excluded. Hop and yeast production are included. Bottles recycling is not included because it usually takes place after consumption phase which is not part of the study. Below there is a list of traditional beer that we considered:

- Beer 100% barley malt: beer
- Beer 100% barley malt organic: beer org
- Blanche (35% wheat unmalted): blanche
- Blanche organic (35% wheat unmalted): blanche org

6.3.2 Bread flow chart description

Bread operations: wheat cultivation, grain processing, salt production, yeast production, kneading, proofing, dividing, shaping and resting, baking, bread packaging (brown colour, figure 24).

Agricultural machineries production is included and company facilities production is excluded only in global milling process the construction of the hall is considered (data from Agribalyse). Cleaning products, the consumption phase and the avoided plastic production after sifting (fibre) are not considered. Only a mass allocation is done. The global milling process is different according to different type of flour, type 55 and type 150, white and whole meal flour respectively; in this last case the bran and germ utilisation for animal feed is not included, it is made a mass allocation. After the last step the unsold bread is collected and used in the brewery process. Below there is a list of conventional bread products considered:

- Traditional baguette: TB
- Traditional baguette organic: TB org
- Wholemeal bread: W
- Wholemeal bread organic: W org

6.3.3 Co-products stabilisation

The stabilisation part is the key of the project, it links the two traditional productions. The unsold/stale bread stabilisation: collecting (grey colour, figure 24), drying and slicing (blue colour, figure 24). The dried matter is going directly into the mashing step. The BSG obtained from brewery goes through stabilisation: pressing, drying and micronisation before reach the kneading step in bakery process. A further step, sifting, is taken in order to obtain the HPF flour which goes in the kneading step as well (green colour, figure 24).

- Beer bread (35% wheat replacement): b.b. 35 aw
- Beer bread organic (35% wheat replacement): b.b. 35 aw org
- Beer bread (50% malt replacement): b.b. 50 ab
- Beer bread organic (50% malt replacement): b.b. 50 ab
- Beer bread 35% AB: b.b. 35 ab
- Beer bread 35% AB organic: b.b. 35 ab org
- Beer bread 10% AB: b.b. 10 ab
- Beer bread 20% AB: b.b. 20 ab
- Beer bread 40% AB: b.b. 40 ab
- HPF bread (20% of HPF): HPF
- HPF bread organic (20% of HPF): HPF org
- HPF wholemeal bread (20% of HPF): HPF W
- HPF wholemeal bread organic (20% of HPF): HPF W org
- BSG bread (20% of HPF): BSG
- BSG bread organic (20% of HPF): BSG org
- BSG whole meal bread (20% of HPF): BSG W
- BSG whole meal bread organic (20% of HPF): BSG W org

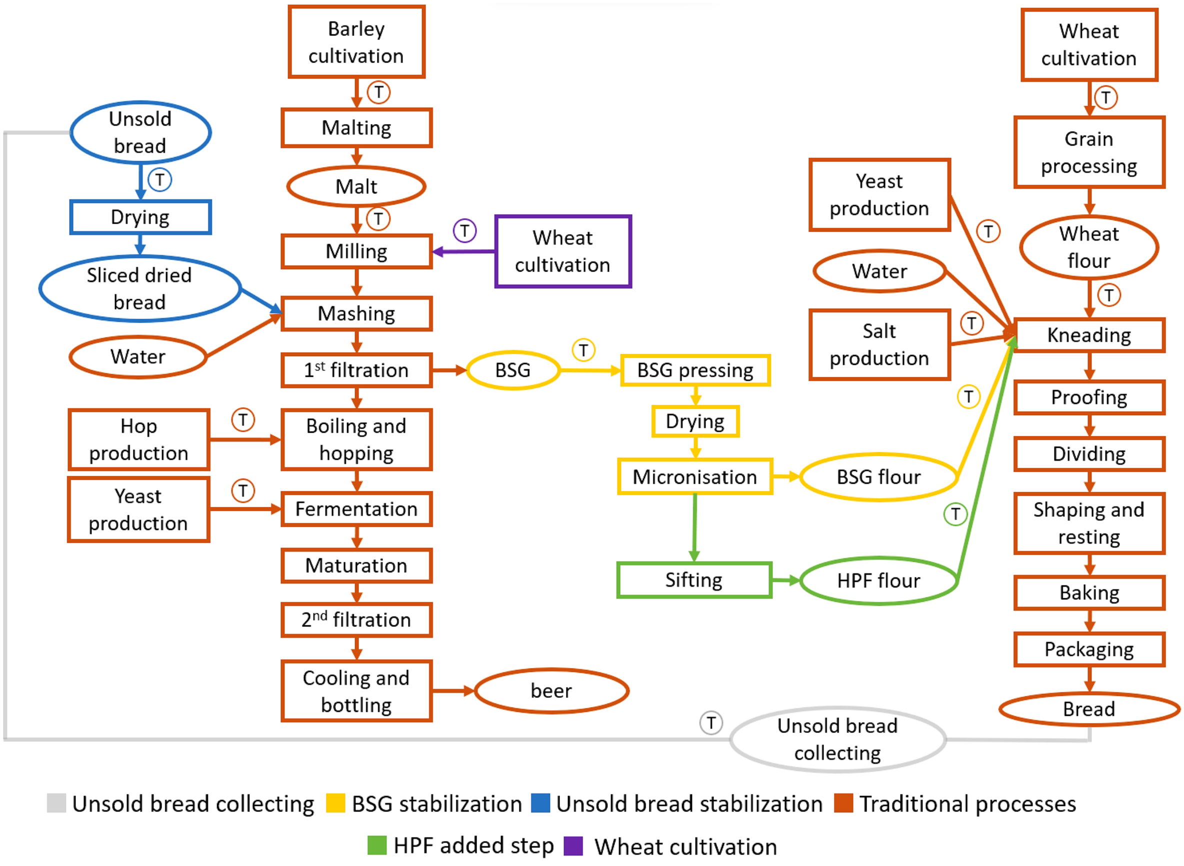


Figure 24. The entire production flow chart, divided into traditional processes, unsold bread stabilization and BSG stabilization

6.4 Life cycle inventory compilation

Activity data are collected by interviews with the owners of the companies. The data are from baker laboratory in Oniris (bread making); Waste me up company (concerning the BSG stabilization); Les Brassés (beer production); Brussels beer project (bread stabilization and conversion rate considering the starch retrogradation) and Yec'Hed Malt (malting). When necessary supplementation by generic data from databases of LCA tool (Ecoinvent and Agribalyse in OpenLCA) with some adjustments from the literature about heavy metals negative emissions (Montemayor et al., 2022) are done. Figure 25 reports the interpreters of this work.

Figure 25. Companies that provided data

6.4.1 Assumptions and critical points

- The brewery and BSG stabilization activities are assumed to be in the same city (thus, not very long distances);
- Background processes and flows such as electricity, head, water supply and transportation are similar for all variants;
- The BSG and the unsold bread was considered without environmental charge;
- In the organic production, the only aspect that changes is the cultivation of grains; the yeast and the hop are from conventional production.
- It is assumed no variability in BSG composition from different processes in order to reduce the work complexity.
- The empty processes/programs in OpenLCA are fitted to data from Ecoinvent;
- For the bags (Waste Me Up): not considered because no suitable data was found;
- The dryer utilized for bread (under 10% of humidity) is the same utilized for BSG.
- The conversional ratio of 1:1.25 for unsold bread (data from Brussels Beer Project considered the amount of starch) is only for avoided barley One part of bread is 1.25 parts of barley. For the avoided wheat is considered 1:1 because the amount of starch is quite similar between wheat and bread;
- Organic wheat and organic barley are from intercropping, after alfa alfa crop and unspecified respectively;

- A conversion ratio between HPF and wheat flour was 1:1 in order to simplify the estimation. So, we are not taking in account the variability of this aspect;
- The distances of ingredients in bread making are chosen randomly (no data available). The distribution is considered in the same city: salt and yeast 30 km and wheat flour 30 km.
- It is assumed that the distance travel by the transports was only for the kilometres used for the ingredients and without empty transport because the transports are organised by a transport company in order to avoid this issue as much as possible
- After the sifting step, in HPF flour the destiny of the fiber part is not considered. Hence, only a mass allocation is done, 0.6 % fiber part and 0,4 % the HPF flour
- For the milling step in order to obtain the white flour the mass allocation is 0.25 for bran and germ and 0.75 for the white flour

6.4.2 Processes description

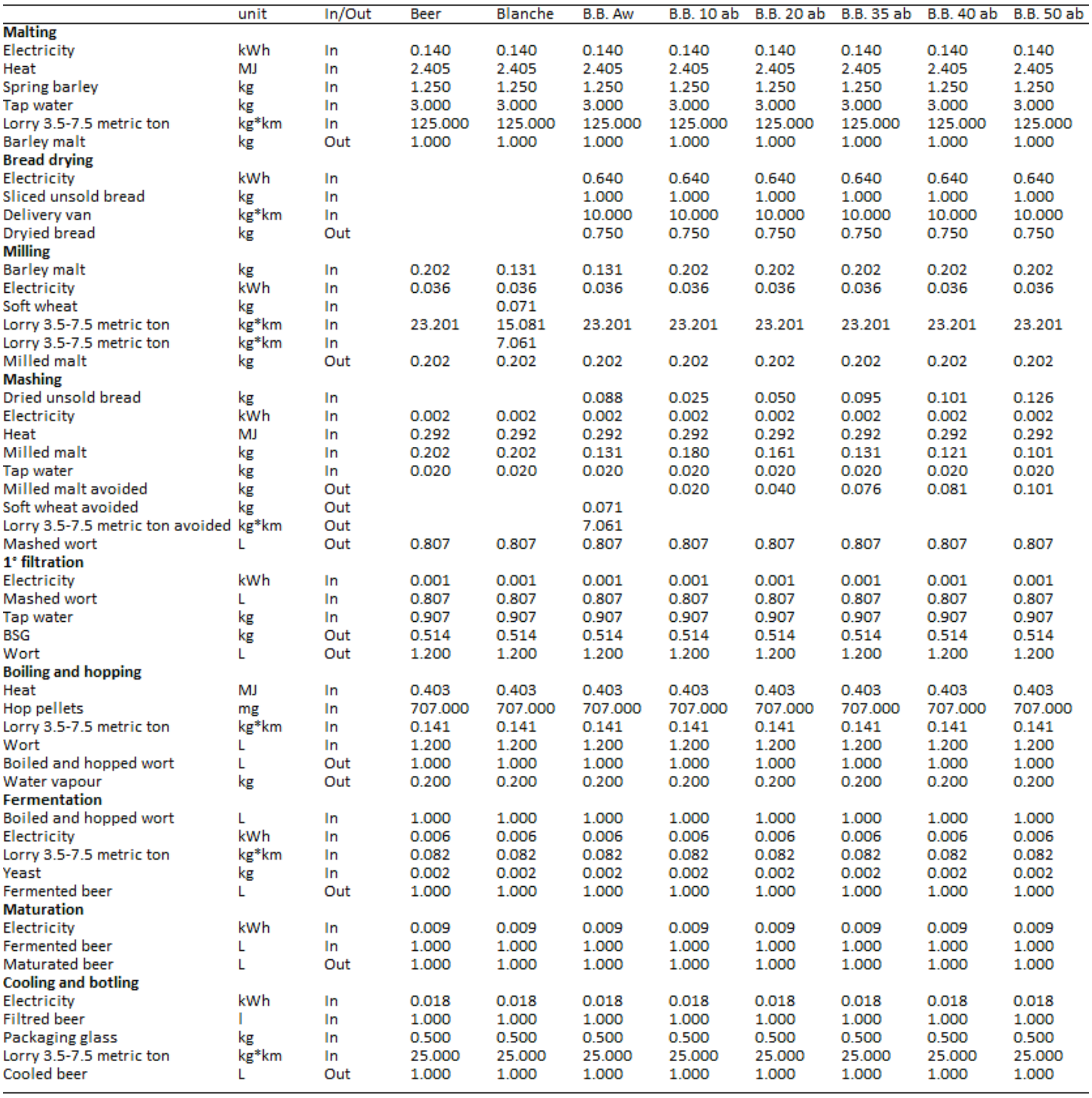
Beer

The development of microbreweries in France has been on a positive trend, today there are more than 2000 breweries. In 2019, annual production reached 22,300,000 hectolitres, making it the sixth largest producer in Europe. The pandemic has slowed this rise but it still remains an important sector for this country (The Brewers of Europe, 2021).

Cultivation: In France, one third of barley production is used for brewing, i.e., 4 million tonnes of malting barley produced per year. Wheat is also an important cereal in beer production because it is particularly involved in the production of white beer (Passion Céréales, 2021). Every year, 1.8 million tonnes of malting barley are processed in France into 1.5 million tonnes of malt. 80% of this production is exported, making France the largest malt exporter in the world (Malteurs de France, 2021). The production of hops is mainly concentrated in the north and east. In 2018, France produced 870 tonnes of hops, 70% of this production was exported while French breweries imported 85% of their hop consumption (Guillard, 2021).

Malting: an Excel questionnaire was created in order to collect all the necessary data for the analysis of the Yec'Hed Mat malthouse in Vannes and for Les Brassés in Nantes. An average of 100 kg of barley is needed to produce 75 kg of malt. The first step of the process is soaking: the grain undergoes stages of humidification and oxygenation for two to three days, which increases its moisture level. Then, germination takes place, high moisture content to allow the grain to germinate for four to six days to obtain “green malt”. Kilning involves heating the green malt to obtain the desired malt. The green malt is heated for about thirty hours at 45°C then at a higher temperature for 5 hours, temperature is function of the desired malt (generally 85°C for a blond beer malt). Finally, degermination, the last stage of malt preparation, consists of removing the non-germinated beans. Then the grain is left to age for two to three weeks before being prepared.

Brewery operations: the style that we considered is an ALE beer. The malt is crushed to be mixed with water to obtain the wort from which fermentable sugars will be formed; it takes between 50 and 80 minutes at temperatures between 64 and 69°C. Next, the must is filtered to separate the spent grain (solid part). The must is boiling for one to two hours. Hop pellets are from unknown source in OpenLCA software; yeast production, from Ecoinvent and cultivation data are collected from Agribalyse with Montemayor et al. 2022 adjustments (without negative emissions, mostly in negative HM emissions especially concerning organic productions). For high fermentation using *Saccharomyces cerevisiae* yeasts the temperature of the beer should be between 18 and 25°C (ale). After fermentation the beer is cooled (around 5°C), it must be kept at this temperature for several days (about a week). The yeast transforms the fermentable sugars in the wort into alcohol and carbon dioxide (released into the air). After a second filtration, the beer is packaged in bottles. Table 5 shows the highlights about beer products.



	unit	In/Out	Beer	Blanche	B.B. Aw	B.B. 10 ab	B.B. 20 ab	B.B. 35 ab	B.B. 40 ab	B.B. 50 ab
Malting										
Electricity	kWh	In	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140
Heat	MJ	In	2.405	2.405	2.405	2.405	2.405	2.405	2.405	2.405
Spring barley	kg	In	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.250
Tap water	kg	In	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Lorry 3.5-7.5 metric ton	kg*km	In	125.000	125.000	125.000	125.000	125.000	125.000	125.000	125.000
Barley malt	kg	Out	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Bread drying										
Electricity	kWh	In			0.640	0.640	0.640	0.640	0.640	0.640
Sliced unsold bread	kg	In			1.000	1.000	1.000	1.000	1.000	1.000
Delivery van	kg*km	In			10.000	10.000	10.000	10.000	10.000	10.000
Dryied bread	kg	Out			0.750	0.750	0.750	0.750	0.750	0.750
Milling										
Barley malt	kg	In	0.202	0.131	0.131	0.202	0.202	0.202	0.202	0.202
Electricity	kWh	In	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
Soft wheat	kg	In		0.071						
Lorry 3.5-7.5 metric ton	kg*km	In	23.201	15.081	23.201	23.201	23.201	23.201	23.201	23.201
Lorry 3.5-7.5 metric ton	kg*km	In		7.061						
Milled malt	kg	Out	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202
Mashing										
Dried unsold bread	kg	In			0.088	0.025	0.050	0.095	0.101	0.126
Electricity	kWh	In	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Heat	MJ	In	0.292	0.292	0.292	0.292	0.292	0.292	0.292	0.292
Milled malt	kg	In	0.202	0.202	0.131	0.180	0.161	0.131	0.121	0.101
Tap water	kg	In	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
Milled malt avoided	kg	Out				0.020	0.040	0.076	0.081	0.101
Soft wheat avoided	kg	Out			0.071					
Lorry 3.5-7.5 metric ton avoided	kg*km	Out			7.061					
Mashed wort	L	Out	0.807	0.807	0.807	0.807	0.807	0.807	0.807	0.807
1° filtration										
Electricity	kWh	In	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Mashed wort	L	In	0.807	0.807	0.807	0.807	0.807	0.807	0.807	0.807
Tap water	kg	In	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907
BSG	kg	Out	0.514	0.514	0.514	0.514	0.514	0.514	0.514	0.514
Wort	L	Out	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
Boiling and hopping										
Heat	MJ	In	0.403	0.403	0.403	0.403	0.403	0.403	0.403	0.403
Hop pellets	mg	In	707.000	707.000	707.000	707.000	707.000	707.000	707.000	707.000
Lorry 3.5-7.5 metric ton	kg*km	In	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141
Wort	L	In	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
Boiled and hopped wort	L	Out	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Water vapour	kg	Out	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Fermentation										
Boiled and hopped wort	L	In	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Electricity	kWh	In	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Lorry 3.5-7.5 metric ton	kg*km	In	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082
Yeast	kg	In	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Fermented beer	L	Out	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Maturation										
Electricity	kWh	In	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Fermented beer	L	In	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Maturated beer	L	Out	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Cooling and botling										
Electricity	kWh	In	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018
Filtred beer	l	In	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Packaging glass	kg	In	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
Lorry 3.5-7.5 metric ton	kg*km	In	25.000	25.000	25.000	25.000	25.000	25.000	25.000	25.000
Cooled beer	L	Out	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 5. Inventory highlights reference flow inputs and outputs for each bread product in order to obtain 1 L of bread. From the left, B.B. bread beer, ab avoided wheat, ab avoided barley malt.

Bread

The energy consuming of bakery is similar comparing with the literature (Bimpeh et al., 2006; Câmara-Salim et al., 2020; Notarnicola et al., 2017). Upstream transportation is made by "Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}| market for | Cut-off, S - Copied from Ecoinvent".

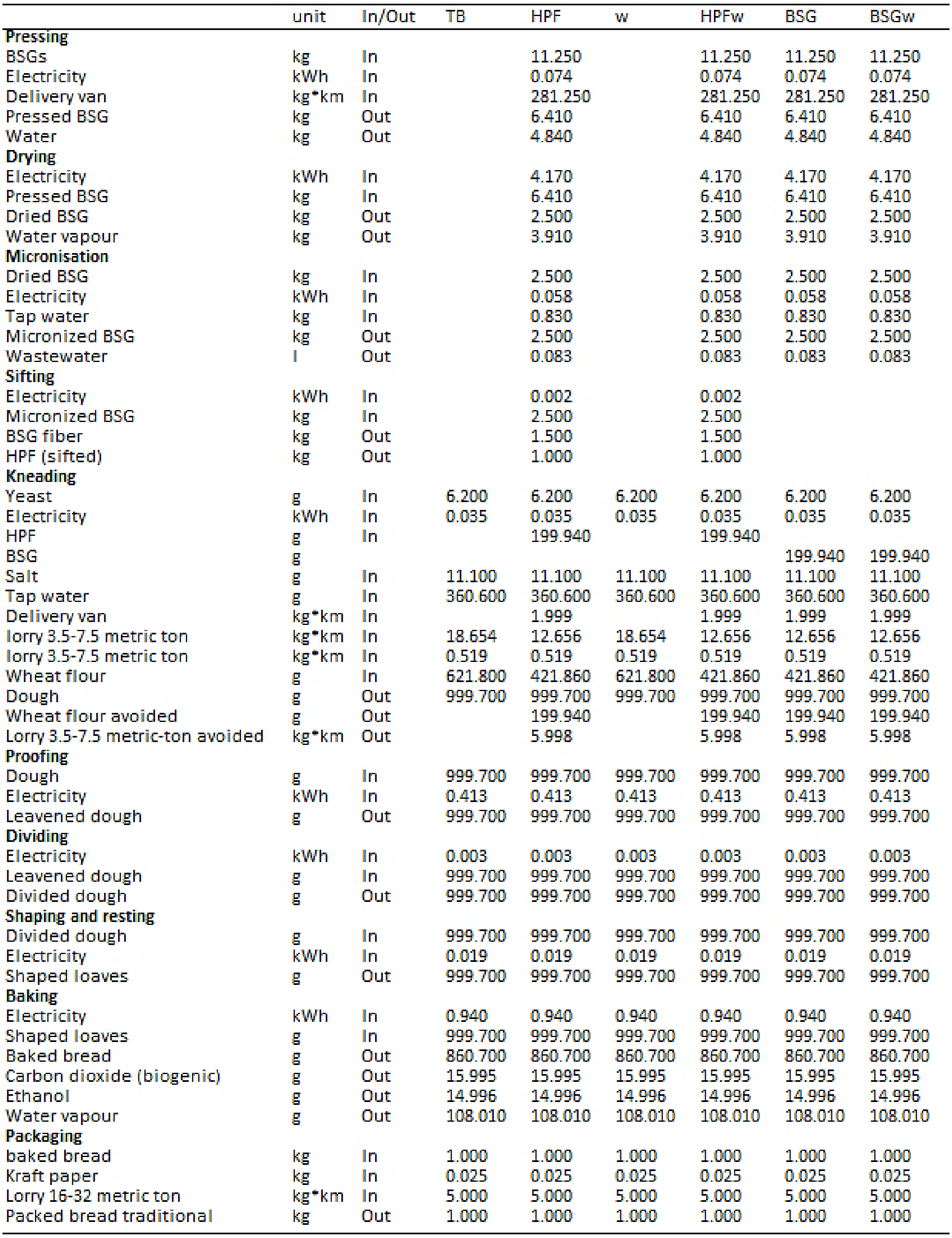
Table 6 shows the highlights about bread products and BSG stabilisation. The organic ones are not shown because of the same process and same values. The only factor that changes is the organic wheat and noticing the difference between wholemeal and white flour is necessary to analyse the milling process.

Agribalyse database is used for grain processing too according to Heshe et al., 2016 adjustments for the milling process in the comparison between wholemeal and white flour.

Soft wheat cultivation: France is the largest wheat producer in the world after China, India, Russia and USA with 36,9 millions tonnes/year (Khan et al., 2022) and almost 7 tonnes/ha and a moisture content of 15%. This wheat (soft wheat) represents the bread making quality. The distance between the farm and the milling house is assumed to be 30 km. All the ingredients (yeast, wheat and salt) are for kneading process are from the inventory of AGRIBALYSE v3.0.1, 2020. This database has been produced as part of AGRIBALYSE program lead by ADEME and INRAE since 2009. It contains agricultural and food products produced and/or consumed in France. Methodology principles follow the key international guidelines as much as possible (ISO, LEAP, PEF).

Grain milling: pre-cleaning process is carried out. Then, a 75% of the grain became white flour, in the other hand the wholemeal flour represents almost 100% of grains.

Bread making: kneading takes 8 min with low speed (50 tr/min). The dough must be at 25°C. The next step is proofing and for 1 h and 30 min. Subsequently, the division takes place, then the loaf is left to rest at room temperature for 15 min. the last 3 steps are shaping, resting (30-45 min at 27°C in proving chamber) and finally the baking (cooking) at 240°C for approximately 20 min. In table 5 is reported all the data about bread processing and its variants.



	unit	In/Out	TB	HPF	w	HPFw	BSG	BSGw
Pressing								
BSGs	kg	In		11.250		11.250	11.250	11.250
Electricity	kWh	In		0.074		0.074	0.074	0.074
Delivery van	kg*km	In		281.250		281.250	281.250	281.250
Pressed BSG	kg	Out		6.410		6.410	6.410	6.410
Water	kg	Out		4.840		4.840	4.840	4.840
Drying								
Electricity	kWh	In		4.170		4.170	4.170	4.170
Pressed BSG	kg	In		6.410		6.410	6.410	6.410
Dried BSG	kg	Out		2.500		2.500	2.500	2.500
Water vapour	kg	Out		3.910		3.910	3.910	3.910
Micronisation								
Dried BSG	kg	In		2.500		2.500	2.500	2.500
Electricity	kWh	In		0.058		0.058	0.058	0.058
Tap water	kg	In		0.830		0.830	0.830	0.830
Micronized BSG	kg	Out		2.500		2.500	2.500	2.500
Wastewater	l	Out		0.083		0.083	0.083	0.083
Sifting								
Electricity	kWh	In		0.002		0.002		
Micronized BSG	kg	In		2.500		2.500		
BSG fiber	kg	Out		1.500		1.500		
HPF (sifted)	kg	Out		1.000		1.000		
Kneading								
Yeast	g	In	6.200	6.200	6.200	6.200	6.200	6.200
Electricity	kWh	In	0.035	0.035	0.035	0.035	0.035	0.035
HPF	g	In		199.940		199.940		
BSG	g						199.940	199.940
Salt	g	In	11.100	11.100	11.100	11.100	11.100	11.100
Tap water	g	In	360.600	360.600	360.600	360.600	360.600	360.600
Delivery van	kg*km	In		1.999		1.999	1.999	1.999
lorry 3.5-7.5 metric ton	kg*km	In	18.654	12.656	18.654	12.656	12.656	12.656
lorry 3.5-7.5 metric ton	kg*km	In	0.519	0.519	0.519	0.519	0.519	0.519
Wheat flour	g	In	621.800	421.860	621.800	421.860	421.860	421.860
Dough	g	Out	999.700	999.700	999.700	999.700	999.700	999.700
Wheat flour avoided	g	Out		199.940		199.940	199.940	199.940
Lorry 3.5-7.5 metric-ton avoided	kg*km	Out		5.998		5.998	5.998	5.998
Proofing								
Dough	g	In	999.700	999.700	999.700	999.700	999.700	999.700
Electricity	kWh	In	0.413	0.413	0.413	0.413	0.413	0.413
Leavened dough	g	Out	999.700	999.700	999.700	999.700	999.700	999.700
Dividing								
Electricity	kWh	In	0.003	0.003	0.003	0.003	0.003	0.003
Leavened dough	g	In	999.700	999.700	999.700	999.700	999.700	999.700
Divided dough	g	Out	999.700	999.700	999.700	999.700	999.700	999.700
Shaping and resting								
Divided dough	g	In	999.700	999.700	999.700	999.700	999.700	999.700
Electricity	kWh	In	0.019	0.019	0.019	0.019	0.019	0.019
Shaped loaves	g	Out	999.700	999.700	999.700	999.700	999.700	999.700
Baking								
Electricity	kWh	In	0.940	0.940	0.940	0.940	0.940	0.940
Shaped loaves	g	In	999.700	999.700	999.700	999.700	999.700	999.700
Baked bread	g	Out	860.700	860.700	860.700	860.700	860.700	860.700
Carbon dioxide (biogenic)	g	Out	15.995	15.995	15.995	15.995	15.995	15.995
Ethanol	g	Out	14.996	14.996	14.996	14.996	14.996	14.996
Water vapour	g	Out	108.010	108.010	108.010	108.010	108.010	108.010
Packaging								
baked bread	kg	In	1.000	1.000	1.000	1.000	1.000	1.000
Kraft paper	kg	In	0.025	0.025	0.025	0.025	0.025	0.025
Lorry 16-32 metric ton	kg*km	In	5.000	5.000	5.000	5.000	5.000	5.000
Packed bread traditional	kg	Out	1.000	1.000	1.000	1.000	1.000	1.000

Table 6. Inventory highlights reference flow inputs and outputs for each bread product. From the left side TB: traditional baguette; w: wholemeal

Co-products stabilisation

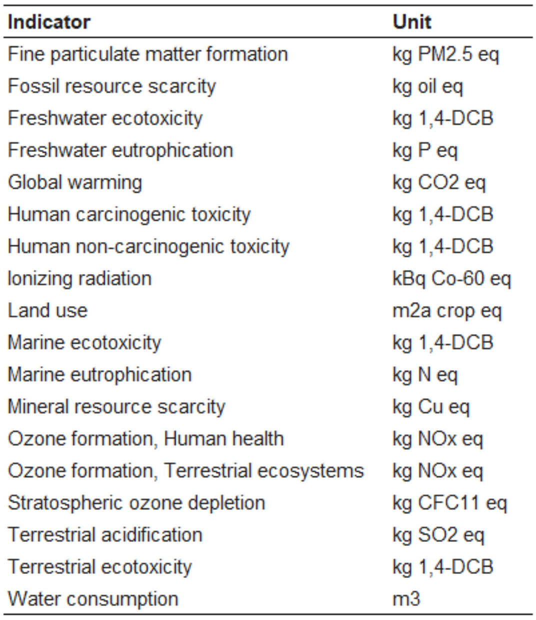
“Market for transport, freight, and light commercial vehicle” is used for BSG and unsold bread stabilization activities. It is assumed that the distance travel by the transports was only for the kilometres used for the ingredients and without empty transport because the transports are organised by a transport company in order to avoid this issue as much as possible. The percentage of unsold dried bread used for the bread beer is 50% or less (40%; 35%; 20%; 10%) as suggested by Martin-Lobera et al. 2022. The percentage use of HPF and BSG (dried) for the HPF and BSG bread is 20% as suggested by Mussatto et al. 2006 and Lynch et al. 2016. The packaging data (bottle and kraft paper) is from Ecoinvent; only one type of packaging is chosen

Unsold bread drying: collecting of unsold bread is from supermarkets and bakeries. Assuming the same dryer used for BSG stabilisation (under 10% of humidity). Table 5 shows the values in each step, before the mashing step.

BSG stabilisation: with a capacity per batch in 300 kg and duration is almost 8 hours (it is the most energy consuming). Table 6 reports the values per 1 kg of ingredient, BSG or HPF.

6.5 LCIA methods

The LCIA method is ReCiPe 2016 Midpoint (H) where 18 environmental categories are considered, table 7. A comparison between two different methods is also attempted in order to check whether there are significant differences and whether the hierarchy of products from an environmental impact point of view remains the same. CML-IA baseline method is used for this comparison (table 8). Only a few products are chosen, the most significant and the easiest to produce. Considering all assumptions (which are the most important weakness of LCA), a significance threshold of 20% is chosen in order to identify the gaps between all EICs of products. In ReCiPe 2016 Midpoint (H) includes *fine particulate matter formation (FPMF)*: indicator of the potential incidence of disease due to particulate matter formation (kg PM2.5 eq.); *fossil resource scarcity (FRS)*: indicator of depletion of natural fossil fuel resources (kg of oil eq.); *fresh water ecotoxicity (FE)*: impact on freshwater organisms of toxic substances emitted to the environment (kg 1,4 DCB); *freshwater eutrophication (FEutr)*: indicator of the freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds (kg P eq.); *global warming (GW)*: indicator of potential global warming due to emissions of the greenhouse gases to the air (Kg CO_2 eq.); *human carcinogenic toxicity and human non-carcinogenic toxicity (HTC and HNTC)*: impacts on humans of toxic substances emitted to the environment divided into non-cancer and cancer-related toxic substances (kg 1,4 DCB); *ionizing radiation (IR)*: damage to human health and ecosystems linked to the emissions of radionuclides (kBq Co-60 eq.); *land use (LU)*: measure of the changes in soil quality (biotic production, erosion resistance, mechanical filtration) (m2a crop eq); *marine ecotoxicity (ME)*: impact on marine water organisms of toxic substances emitted to the environment (kg 1,4 DCB); *marine eutrophication (MEutr)*: indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds (kg N eq); *mineral resource scarcity (MRS)*: indicator of the depletion of natural non-fossil resources (kg Cu eq.); *ozone formation, human health and terrestrial ecosystems (OF, HH and OF, TE)*: indicators of the emissions of the gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight (kg NOx eq.); *stratospheric ozone depletion (SOD)*: indicator of emissions to air that causes the destruction of the stratospheric ozone layer (kg CFC11 eq.); *terrestrial acidification (TA)*: indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides (kg SO$_2$ eq.); *terrestrial ecotoxicity (TE)*: impact on terrestrial organisms of toxic substances emitted to the environment (kg 1,4 DCB); *water consumption (WC)*: indicator of the relative amount of water used based on regionalised water scarcity factors (m^3) (openLCA.Org).

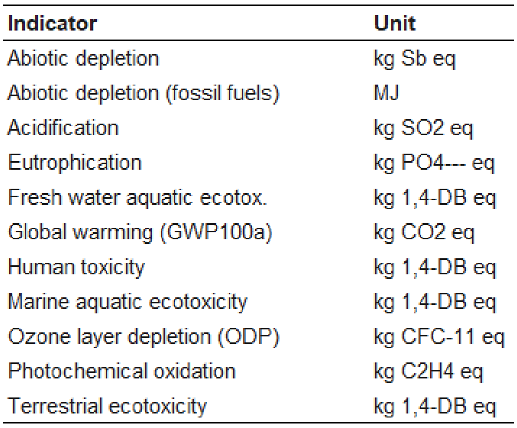


Indicator	**Unit**
Fine particulate matter formation	kg PM2.5 eq
Fossil resource scarcity	kg oil eq
Freshwater ecotoxicity	kg 1,4-DCB
Freshwater eutrophication	kg P eq
Global warming	kg CO2 eq
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Ionizing radiation	kBq Co-60 eq
Land use	m2a crop eq
Marine ecotoxicity	kg 1,4-DCB
Marine eutrophication	kg N eq
Mineral resource scarcity	kg Cu eq
Ozone formation, Human health	kg NOx eq
Ozone formation, Terrestrial ecosystems	kg NOx eq
Stratospheric ozone depletion	kg CFC11 eq
Terrestrial acidification	kg SO2 eq
Terrestrial ecotoxicity	kg 1,4-DCB
Water consumption	m3

Table 7. The environmental impact categories of ReCiPe 2016 Midpoint (H) and the respective units

On the other hand, CML-IA baseline method includes less EICs like *abiotic depletion:* indicator of the removal of abiotic resources from the earth, or the depletion of non-living natural resources (ka Sb eq.); *abiotic depletion (fossil fuels)*: it describes the reduction or the global amount of non-renewable raw materials and is determined for each extraction of minerals and fossil fuels based on the remaining reserves and rate of extraction; *acidification:*

the acidification of soils and waters occurs predominantly through the transformation of air pollutants into acids, which leads to a decrease in the pH value of rainwater and fog from 5.6 and below. Acidification potential is described as the ability of certain substances to build and release H^+ ions and is given in sulphur dioxide equivalents. indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides (kg SO_2 eq.); *eutrophication:* it is the enrichment of nutrients in a certain place. It can be aquatic or terrestrial. All emissions of N and P to air, water, and soil and of organic matter to water are aggregated into a single measure; *freshwater aquatic ecotoxicity*: impact on freshwater organisms of toxic substances emitted to the environment (kg 1,4 DB eq.); *global warming (GWP100a):* indicator of potential global warming due to emissions of the greenhouse gases to the air (Kg CO_2 eq.); *human toxicity:* impacts on humans of toxic substances emitted to the environment (kg 1,4-DB eq); *marine aquatic ecotoxicity:* impact on marine water organisms of toxic substances emitted to the environment (kg 1,4-DB eq.), *ozone layer depletion*: Ozone depletion potential represents a relative value that indicates the potential of a substance to destroy ozone gas as compared with the potential of chlorofluorocarbon-11 which is assigned a reference value of 1, resulting in an equilibrium state of total ozone reduction; *photochemical oxidation:* it is secondary air pollution, also known as summer smog. It is the formed in the troposphere caused mainly by the reaction of sunlight with emissions from fossil fuel combustion creating other chemicals (kg C_2H_4 eq.) and *terrestrial ecotoxicity:* impact on terrestrial water organisms of toxic substances emitted to the environment (kg 1,4-DB eq.)



Indicator	Unit
Abiotic depletion	kg Sb eq
Abiotic depletion (fossil fuels)	MJ
Acidification	kg SO2 eq
Eutrophication	kg PO4--- eq
Fresh water aquatic ecotox.	kg 1,4-DB eq
Global warming (GWP100a)	kg CO2 eq
Human toxicity	kg 1,4-DB eq
Marine aquatic ecotoxicity	kg 1,4-DB eq
Ozone layer depletion (ODP)	kg CFC-11 eq
Photochemical oxidation	kg C2H4 eq
Terrestrial ecotoxicity	kg 1,4-DB eq

Table 8. The environmental impact categories of CML-IA baseline (H) and the respective units

7. Results and discussion

Regarding the representation of hotspots choices are made. Traditional products and innovative products, which in our opinion are more representative, are chosen. In contrast, in the comparison section, all products are reviewed and, for ease of reading, in some cases products have been analysed by groups. In the table below (table 9) you can see the absolute EICs values of the. In the following sub-paragraphs there are the percentages contribution per 1 kg and 1 L of functional unit.

Indicator	TB	BSG	beer	b.b. 35 ab	Unit
Fine particulate matter formation	1.09E-03	6.64E-04	1.52E-03	1.36E-03	kg PM2.5 eq
Fossil resource scarcity	1.12E-01	9.06E-02	2.20E-01	1.98E-01	kg oil eq
Freshwater ecotoxicity	1.79E-02	1.82E-02	1.30E-02	1.18E-02	kg 1,4-DCB
Freshwater eutrophication	1.87E-04	1.29E-04	1.45E-04	1.21E-04	kg P eq
Global warming	5.60E-01	3.80E-01	7.71E-01	6.73E-01	kg CO2 eq
Human carcinogenic toxicity	1.35E-02	1.41E-02	1.71E-02	1.59E-02	kg 1,4-DCB
Human non-carcinogenic toxicity	6.01E-01	5.76E-01	5.55E-01	5.00E-01	kg 1,4-DCB
Ionizing radiation	1.06E+00	1.27E+00	9.06E-02	1.07E-01	kBq Co-60 eq
Land use	1.44E+00	5.71E-01	4.48E-01	1.45E-01	m2a crop eq
Marine ecotoxicity	2.35E-02	2.37E-02	1.89E-02	1.70E-02	kg 1,4-DCB
Marine eutrophication	1.40E-03	5.40E-04	3.58E-04	1.06E-04	kg N eq
Mineral resource scarcity	6.87E-03	3.77E-03	2.94E-03	1.77E-03	kg Cu eq
Ozone formation, Human health	1.79E-03	1.14E-03	2.37E-03	2.08E-03	kg NOx eq
Ozone formation, Terrestrial ecosystems	1.81E-03	1.17E-03	2.41E-03	2.11E-03	kg NOx eq
Stratospheric ozone depletion	7.68E-06	3.02E-06	2.12E-06	8.14E-07	kg CFC11 eq
Terrestrial acidification	5.44E-03	2.59E-03	4.58E-03	3.72E-03	kg SO2 eq
Terrestrial ecotoxicity	2.47E+00	1.78E+00	2.23E+00	1.94E+00	kg 1,4-DCB
Water consumption	1.24E-02	1.09E-02	9.05E-03	6.39E-03	m3

Table 9. Values of EICs for TB, BSG, beer, b.b. 35 ab

7.1 Traditional products spots

The starting point is to find the hotspots about both “traditional productions”. As you can see in figure 26 the major contribution is from wheat flour production (it includes cultivation, milling and grain storage) in almost every EIC. It was found the same result in Notarnicola et al.(2017). It is followed by baking and proofing because of high-energy demand. Environmental impacts of salt and yeast production are together, the contribution is very low. The other processes are not significantly impacted; this is due to the low utilisation time and the low energy demand of the equipment. An intervention in the type of cultivation and “avoided cultivation” (whether the introduction of another life-cycle process is no longer harmful) would be necessary to lower the environmental impact. For example, the organic cultivation can be a solution for the majority of the EICs.

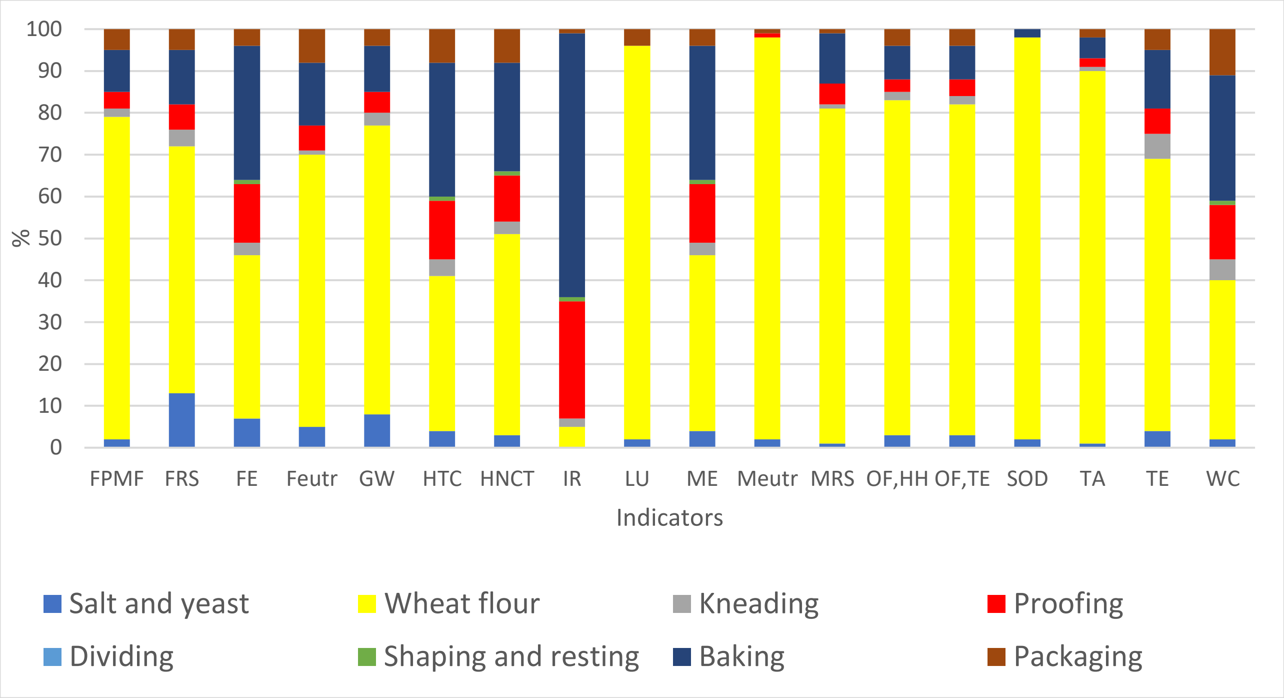


Figure 26. Stacked bar chart of tree percentage contribution of TB process for each EIC

In a typical craft brewery (100% barley malt, local production), the most important hot spot is packaging (it is included in cooling and bottling process in figure 27) because in this study the glass is not recycled. The second hot spot is barley cultivation. Therefore, similar considerations made to produce wheat flour are reiterated here as well. Another hot spot is malting step because of the high amount of energy and water consuming, and, also, in this step transportation is included which increases the impacts. In real brewing, an important factor is the boiling phase in which a lot of heat is required. All the percentage contributions are resumed in figure 27.

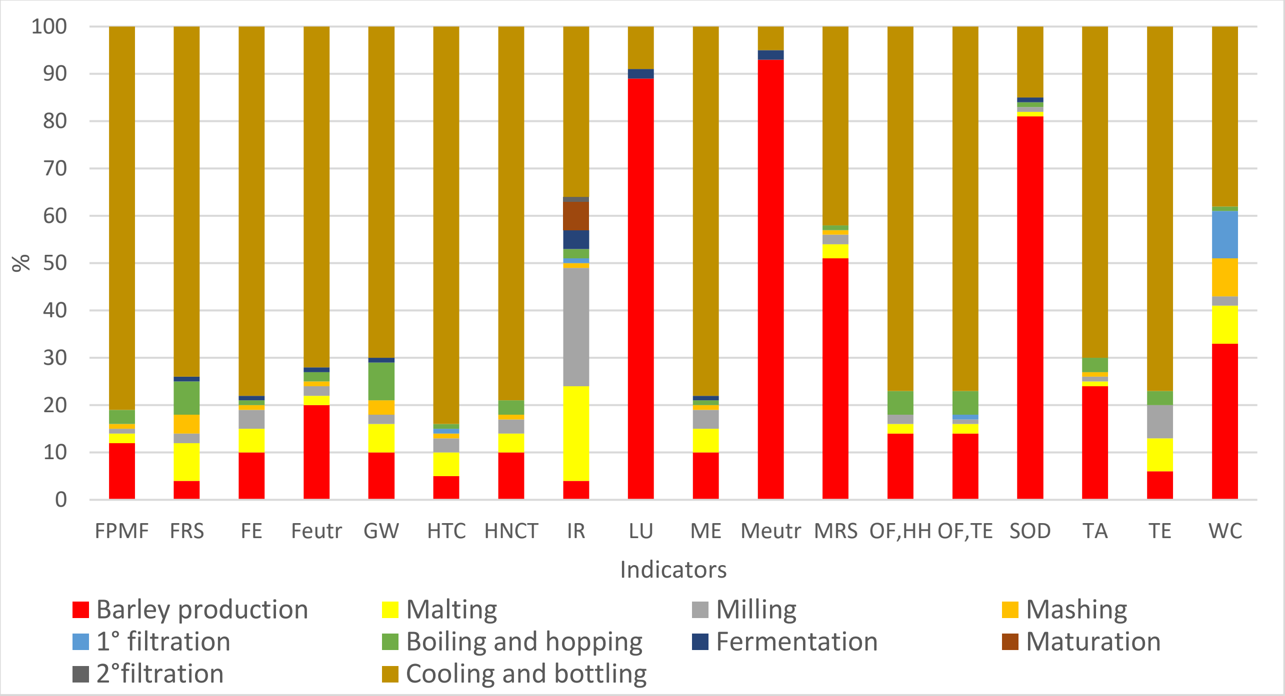


Figure 27. Stacked bar chart of tree percentage contribution of beer 100% barley production process for each EIC

7.2 Effect of adding the co-products stabilisation

In 28 is represented the tree percentage contribution in the BSG stabilisation process according to the same method. The most impactful in each EIC is the BSG collecting. In fact, according to Morgan et al. (2021) it is because of the van (light commercial vehicle) which impacts more than a normal lorry 3,5-7.5 metric ton (data form Ecoinvent). Subsequently, there is the drying process. A high energy consumption could be explained by the modelled energy mix in French, mostly nuclear production and water consumption. Applying a scaling scenario and optimizing the energy of the drying technology could be studied to minimize these potential impacts as confirmed by Petit et al. 2020. The contribution of the other processes is not significant.

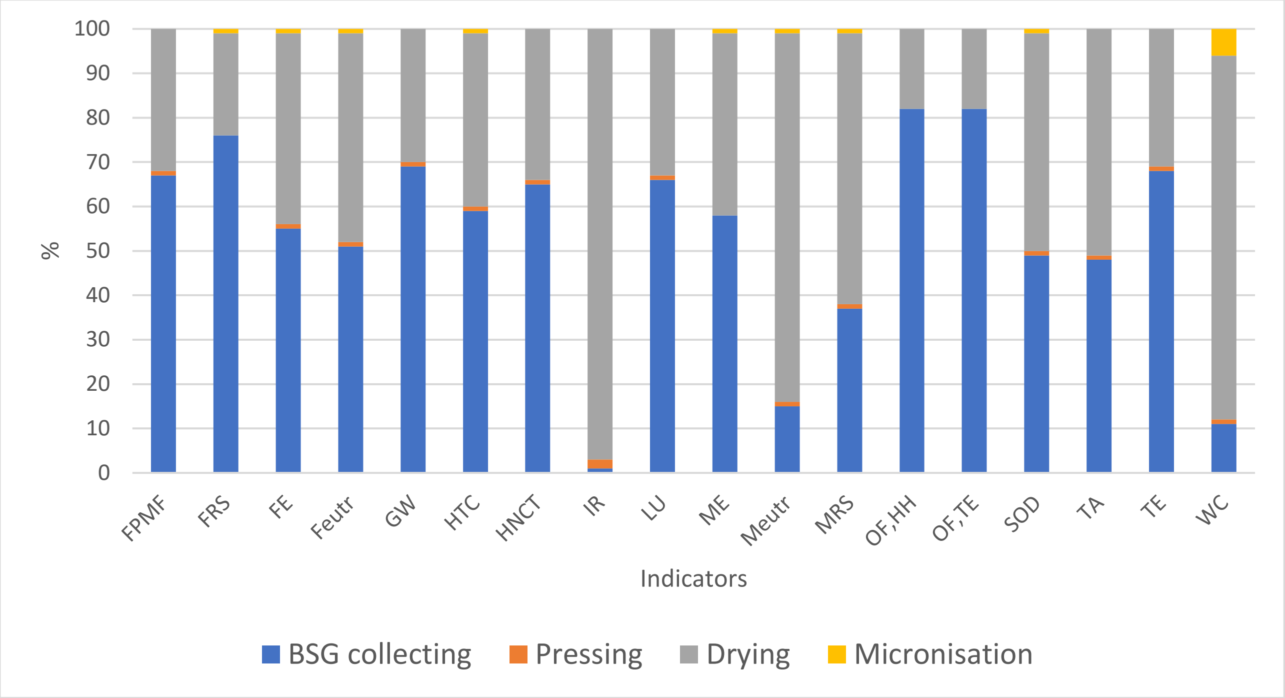


Figure 28. Stacked bar chart of tree percentage contribution of BSG stabilisation process for each EIC

An environmental analysis on an innovative product (20% BSG bread) is done. The hot spot of this product is still the wheat flour cultivation as you can see in figure 29. Bakery step is less impactful than drying step in BSG stabilisation, which is similar to proofing step. The pressing step includes BSG collecting and it has a significative impact overall production. Therefore, a solution can be organic farming (except for LU; MEutr; HCT and HNCT) and the reusing of BSG with more efficient transportation. The process can be further improved by using whole-wheat flour. However in that case fibre interference in the final loaf could be a problem (Czubaszek et al., 2022). The percentage contributions like BSG collecting, pressing, Drying and micronisation are collected in one step: BSG stabilisation in order to understand its impact on the system. The most impactful remains the wheat flour production. The BSG stabilisation does not have the biggest impact to any EIC. However, this new stage in life cycle has a significant global impact of the production. Data representation in figure 29.

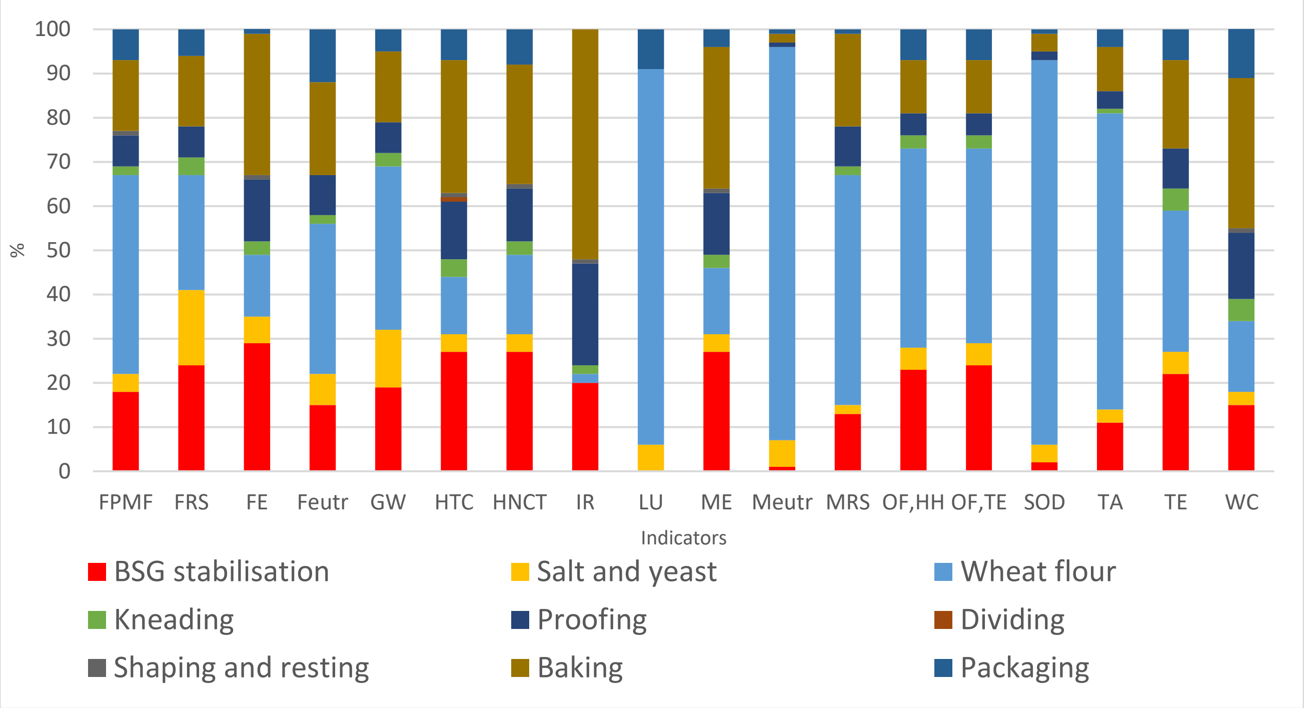


Figure 29. Stacked bar chart tree percentage contribution of BSG bread production process for each EIC

The last product percentage contribution is about innovative bread beer made form 35% of bread in mashing step. It permits to avoid around 30% of barley malt. Therefore, it includes avoided barley cultivation, malting, milling (not a significative impact) and transportation. However, an evaluation of drying unsold bread process remains to be conducted. Not considering packaging the hierarchy of impacts changes: only for LU; MEutr and SOD the barley cultivation is highest step. In addition, “boiling and hopping” and “drying bread” become important hot spots. We can deduce that avoiding part of the barley production may be a proper consideration, but only comparing different kind of products it can be precise. All the percentage contributions are shown in figure 30.

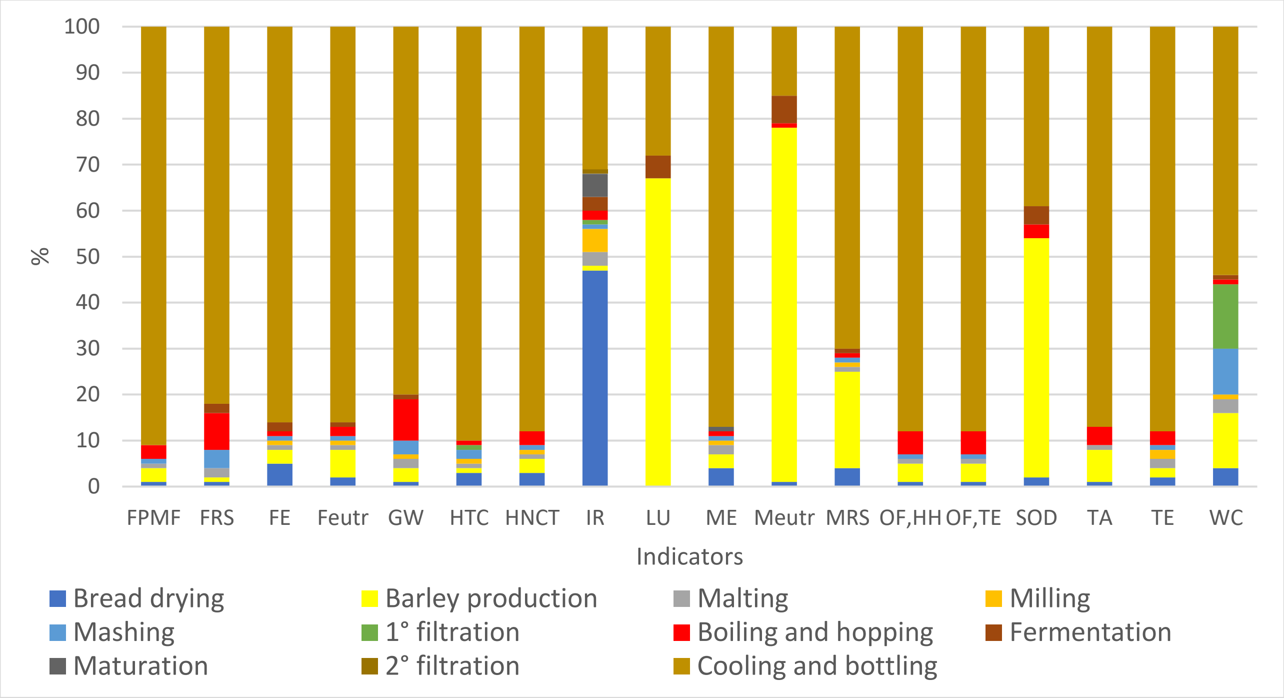


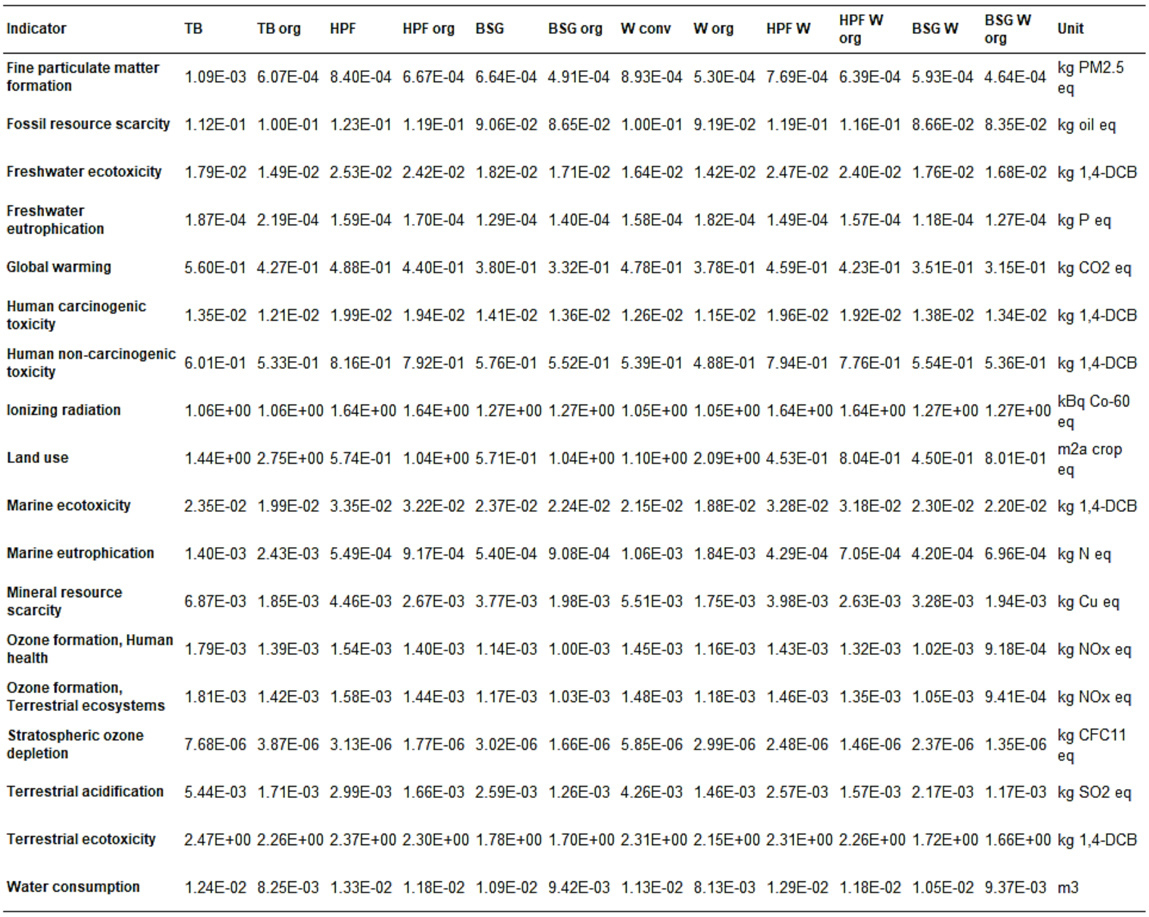
Figure 30. Stacked bar chart of tree percentage contribution of b.b. 35% (avoided barley) beer production process for each EIC

7.3 Products comparison

The difference between two different products is significant when it is up to 20% in percentage contribution. It remains the same value as in the previous chapter. It was an internal decision considered all the assumptions.

7.3.1 Bread products

Concerning most of the environmental impacts in bread production, the most impactful product is the TB and the less impactful is BSG W org because of the milling part which has less leaks and because in this case is skipping the sifting part so the fibres are part of the BSG. Hence, the total amount of BSG is using in bakery production. Also, the cultivation part, organic or non-organic, confirms these results. For example, for the global warming (one of the most important EIC) the range from TB 560 g CO_2 eq. to the BSG W org 315 g CO_2 eq (table 15). The HPF products because of the different categories of flour has the highest values (and very similar) in fossil resource scarcity, freshwater eutrophication, human carcinogenic toxicity, human non-carcinogenic toxicity, ionizing radiation, marine ecotoxicity. This is probably the cause of the increase in transports, certainly the dehydration process and the non-utilisation of fibres has engraved. TB organic production reflects the same trend as organic crops there is a considerable reduction during BSG and HPF production due to the avoided product. However, the difference between organic HPF or BSG and non-organic versions products is not the same. Marine eutrophication is reducing from 2.43E-03 kg N eq. (TB org) to 9.17E-4 kg N eq. HPF org and 7.05E-04 for HPF W org (similar values for BSG org). Even land use and freshwater eutrophication values are reduced considerably.



Indicator	TB	TB org	HPF	HPF org	BSG	BSG org	W conv	W org	HPF W	HPF W org	BSG W	BSG W org	Unit
Fine particulate matter formation	1.09E-03	6.07E-04	8.40E-04	6.67E-04	6.64E-04	4.91E-04	8.93E-04	5.30E-04	7.69E-04	6.39E-04	5.93E-04	4.64E-04	kg PM2.5 eq
Fossil resource scarcity	1.12E-01	1.00E-01	1.23E-01	1.19E-01	9.06E-02	8.65E-02	1.00E-01	9.19E-02	1.19E-01	1.16E-01	8.66E-02	8.35E-02	kg oil eq
Freshwater ecotoxicity	1.79E-02	1.49E-02	2.53E-02	2.42E-02	1.82E-02	1.71E-02	1.64E-02	1.42E-02	2.47E-02	2.40E-02	1.76E-02	1.68E-02	kg 1,4-DCB
Freshwater eutrophication	1.87E-04	2.19E-04	1.59E-04	1.70E-04	1.29E-04	1.40E-04	1.58E-04	1.82E-04	1.49E-04	1.57E-04	1.18E-04	1.27E-04	kg P eq
Global warming	5.60E-01	4.27E-01	4.88E-01	4.40E-01	3.80E-01	3.32E-01	4.78E-01	3.78E-01	4.59E-01	4.23E-01	3.51E-01	3.15E-01	kg CO2 eq
Human carcinogenic toxicity	1.35E-02	1.21E-02	1.99E-02	1.94E-02	1.41E-02	1.36E-02	1.26E-02	1.15E-02	1.96E-02	1.92E-02	1.38E-02	1.34E-02	kg 1,4-DCB
Human non-carcinogenic toxicity	6.01E-01	5.33E-01	8.16E-01	7.92E-01	5.76E-01	5.52E-01	5.39E-01	4.88E-01	7.94E-01	7.76E-01	5.54E-01	5.36E-01	kg 1,4-DCB
Ionizing radiation	1.06E+00	1.06E+00	1.64E+00	1.64E+00	1.27E+00	1.27E+00	1.05E+00	1.05E+00	1.64E+00	1.64E+00	1.27E+00	1.27E+00	kBq Co-60 eq
Land use	1.44E+00	2.75E+00	5.74E-01	1.04E+00	5.71E-01	1.04E+00	1.10E+00	2.09E+00	4.53E-01	8.04E-01	4.50E-01	8.01E-01	m2a crop eq
Marine ecotoxicity	2.35E-02	1.99E-02	3.35E-02	3.22E-02	2.37E-02	2.24E-02	2.15E-02	1.88E-02	3.28E-02	3.18E-02	2.30E-02	2.20E-02	kg 1,4-DCB
Marine eutrophication	1.40E-03	2.43E-03	5.49E-04	9.17E-04	5.40E-04	9.08E-04	1.06E-03	1.84E-03	4.29E-04	7.05E-04	4.20E-04	6.96E-04	kg N eq
Mineral resource scarcity	6.87E-03	1.85E-03	4.46E-03	2.67E-03	3.77E-03	1.98E-03	5.51E-03	1.75E-03	3.98E-03	2.63E-03	3.28E-03	1.94E-03	kg Cu eq
Ozone formation, Human health	1.79E-03	1.39E-03	1.54E-03	1.40E-03	1.14E-03	1.00E-03	1.45E-03	1.16E-03	1.43E-03	1.32E-03	1.02E-03	9.18E-04	kg NOx eq
Ozone formation, Terrestrial ecosystems	1.81E-03	1.42E-03	1.58E-03	1.44E-03	1.17E-03	1.03E-03	1.48E-03	1.18E-03	1.46E-03	1.35E-03	1.05E-03	9.41E-04	kg NOx eq
Stratospheric ozone depletion	7.68E-06	3.87E-06	3.13E-06	1.77E-06	3.02E-06	1.66E-06	5.85E-06	2.99E-06	2.48E-06	1.46E-06	2.37E-06	1.35E-06	kg CFC11 eq
Terrestrial acidification	5.44E-03	1.71E-03	2.99E-03	1.66E-03	2.59E-03	1.26E-03	4.26E-03	1.46E-03	2.57E-03	1.57E-03	2.17E-03	1.17E-03	kg SO2 eq
Terrestrial ecotoxicity	2.47E+00	2.26E+00	2.37E+00	2.30E+00	1.78E+00	1.70E+00	2.31E+00	2.15E+00	2.31E+00	2.26E+00	1.72E+00	1.66E+00	kg 1,4-DCB
Water consumption	1.24E-02	8.25E-03	1.33E-02	1.18E-02	1.09E-02	9.42E-03	1.13E-02	8.13E-03	1.29E-02	1.18E-02	1.05E-02	9.37E-03	m3

Table 10. Bakery impact categories values

First, to avoid a confusing graphical representation because of the different scenarios, the variants of the same product are divided into groups with common characteristics. Figure 31 is the representation of the conventional bread products. The least impactful product is BSG W due to the highest use of the entire quantity of dehydrated BSG (consequently is avoiding more wheat flour in that way) and due to the use of the wholemeal (so more efficient milling process). The most significant results are FPMF ↓46% for BSG W; FRS ↓21%; FEutr ↓37%; GW ↓37%; LU ↓69; MEutr ↓70%; MRS ↓52%; OF, HH ↓43%; OF, TE ↓42%; SOD ↓69%; TA ↓60%; TE ↓30% (bar graph, figure 34). For the HPF breads is quite the same situation, no significative differences between themselves. However, comparing these products (HPF and BSG) with the conventional ones, is immediately clear that it was an impact reduction even though, the HPF bread product increases some EICs like FE ↑29%, HCT ↑32%, HNCT ↑26%, IR ↑35%, ME ↑30%. This is due to fibre mass allocation after sifting process (avoided plastic is not taken into account) Comparing HPF W with the simple W is not necessarily the case that the HPF is the less impactful probably because of the high energy consuming during the BSG drying process and fibre mass allocation. No significant difference between BSG and BSG W.

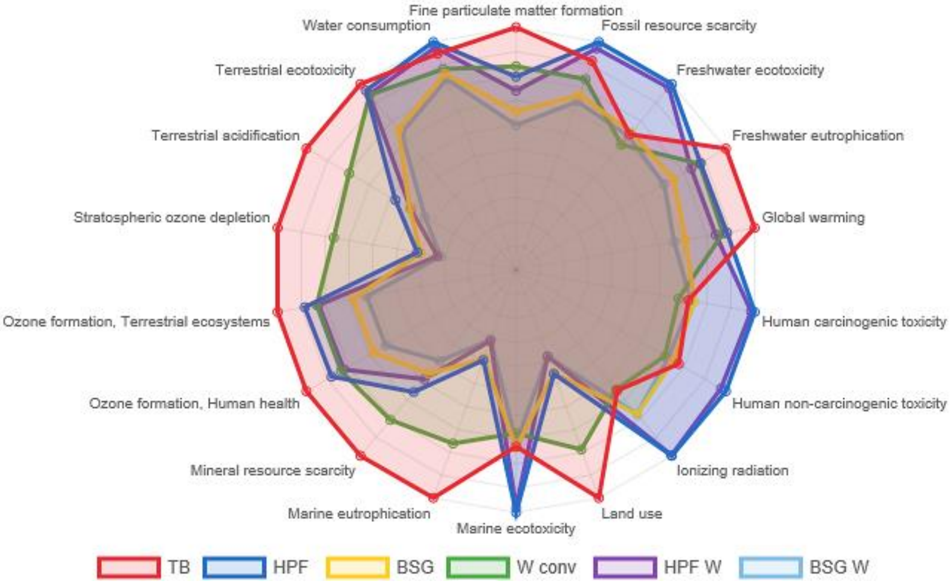


Figure 31. Radar graph of conventional breads comparing

Figure 32 shows the relative impacts of organic production. BSG org productions have positive effects in the majority of environmental impacts, especially comparing to the TB org: FE ↓36%; GW ↓22%; LU ↓62%; MEutr ↓63%; OF, HH ↓28%; OF, TE ↓28%; SOD ↓57%; TA ↓26%; TE ↓25%. Unfortunately, considering HPF org breads comparison to the TB org, there is an increase in values for the following impact categories: FE ↑38%; HCT ↑38%; HNCT ↑33%; IR ↑36%; ME ↑38%; MRS ↑31% and WC ↑30%. There is a significant decrease only in FEutr ↑22%; LU ↓62%; SOD ↓54%. It is due to the omission of avoided plastic production, because of the high-energy request during drying production and because of the transportation. On the other hand, the wholemeal org products (organic W bread and BSG W org) have positive results, the most significant are: FE ↓30; LU ↓32%; Meutr ↓62%; SOD ↓55% TA ↓20%; TE ↓23%. It is the same trend with TB org and BSG org. We can assume that the innovative products (BSG and BSG W) have more positive impacts in organic field than in conventional one, especially for LU; MEutr and SOD.

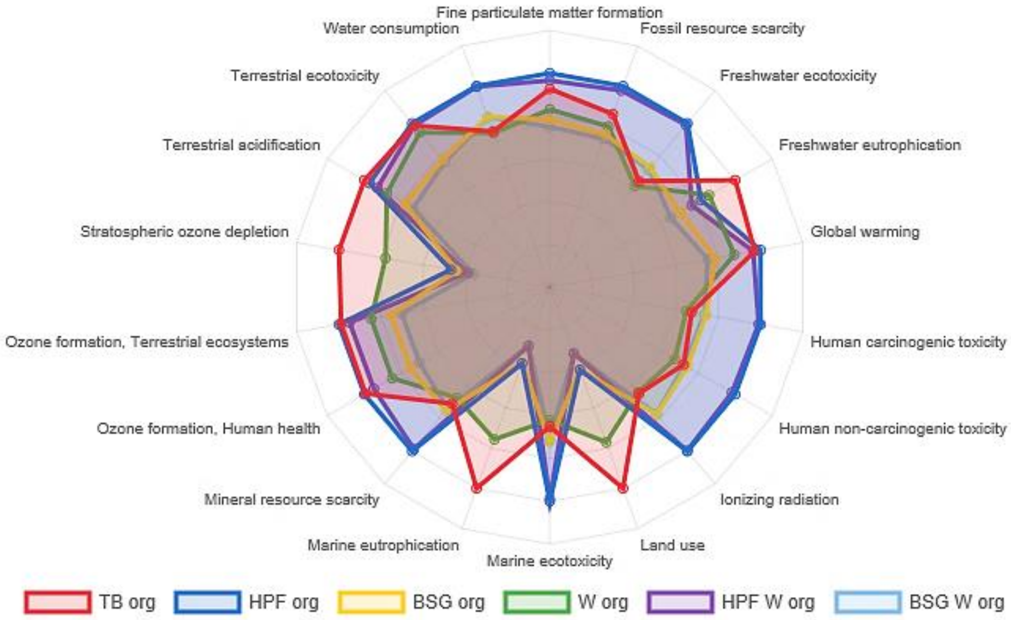


Figure 32. Radar graph of organic breads comparing

In this last comparison, you can see a big difference between TB and TB org. For example, the most important changes are the reduction of terrestrial acidification by 64%, of stratospheric ozone depletion by 49% and of mineral resource scarcity by 71% but it increases marine eutrophication, land use and fresh eutrophication. This is due to the organic agriculture discussed before. This evidence is not the same comparing HPF and HPF org. Differences gradually decreases until under the 20% significance threshold. Unless for FPME ↓21%; LU ↑45%; Meutr ↑40%; MRS ↓40%; SOD ↓33% and TA ↓45%, probably because there is less row material to compare (wheat cultivation) while the HPF stabilisation is the same. Similar assumptions are true even for BSG comparing with BSG org (figure 33).

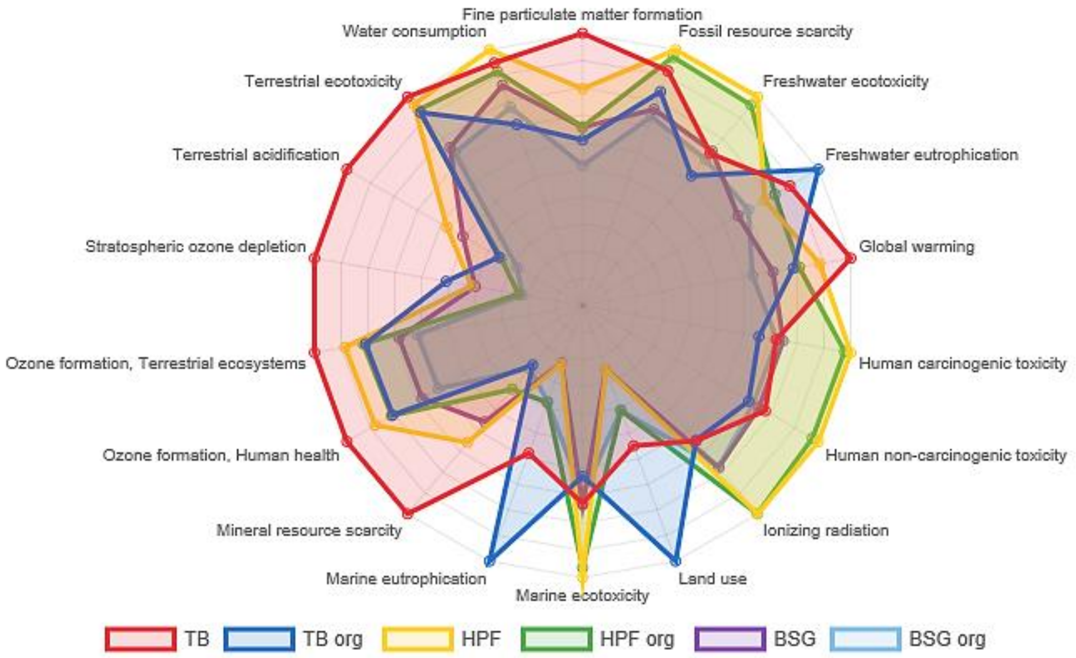
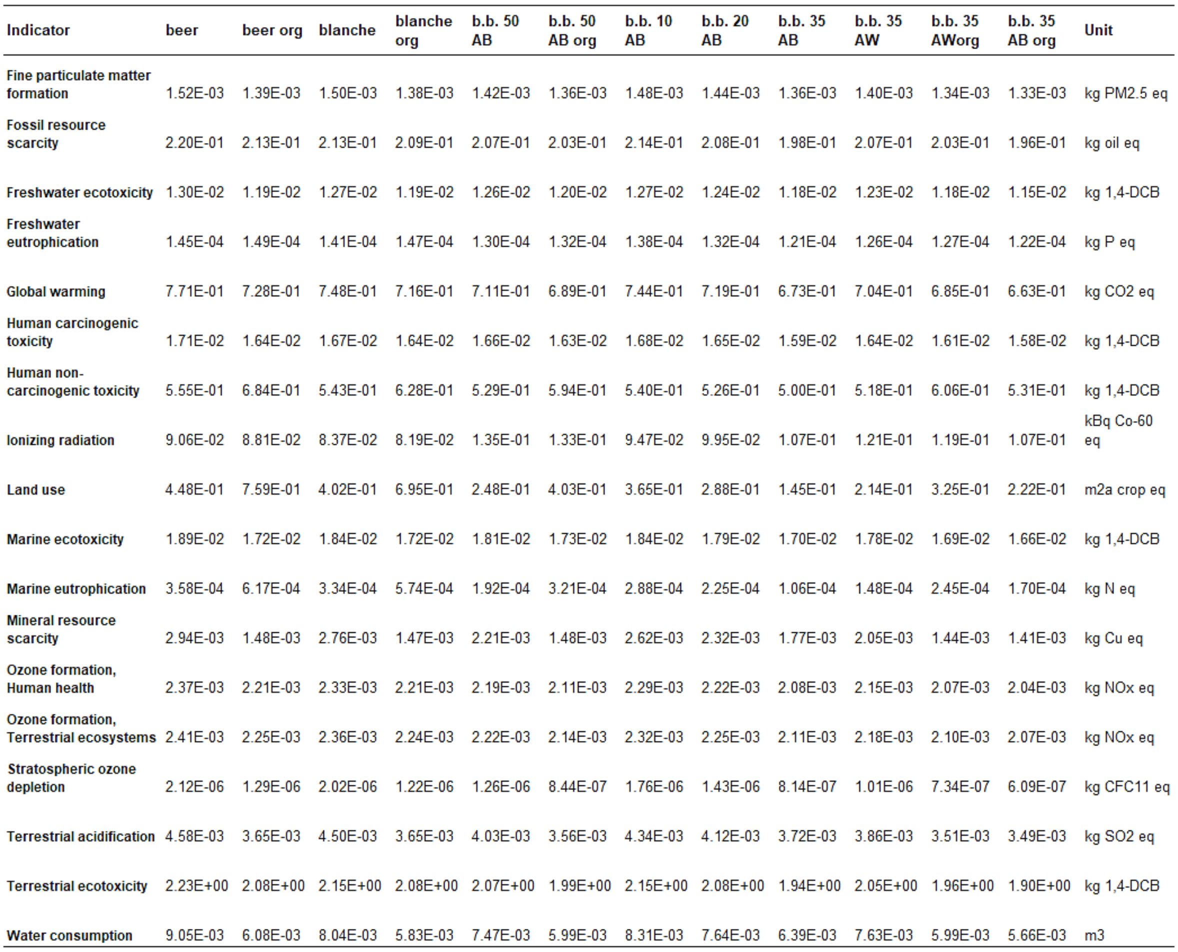


Figure 33. Radar graph of conventional and organic products.

7.3.2 Beer products

Environmental values per L of beer varied considerably across the variants of beer products. The less three impactful among all the beer products are b.b. 35 ab org; b.b. 35 ab and b.b. 40 ab. Referring to the table 11, for example, global warming potential ranged from 663 g CO_2 eq. (b.b. 35 ab org) to 771 g CO_2 eq. (beer) per L. For the fossil resource scarcity, it is ranging from 196 g oil eq. to 220 g oil eq. per L. Comparing b.b. 35 ab to the conventional beer the EIC stratospheric ozone depletion is reduced by 62%, land use by 40% and water consumption by 29% (the most important differences in EIC). The only EIC that is higher is ionizing radiation (13%). Concerning organic productions (beer organic and b.b. 35% org) the benefits of adding unsold bread during mashing are especially in land use and in marine eutrophication. The blanche and the beer 100% barley have almost the same EIC values, few % points less for the blanche because there is no malting process for wheat grains in this style of beer. Same consideration for the organic variants. 35 b.b. aw organic decrease considerably in marine eutrophication (↓43%) and land use (↓49%) but it increases ionization radiation (↑28%) comparing to organic blanche. Considering the conventional blanche and the 35 b.b. aw the hotspots are stratospheric ozone depletion (↓47%), marine eutrophication (↓30%) and land use (↓25%) and ionizing radiation (↑28%).



Indicator	beer	beer org	blanche	blanche org	b.b. 50 AB	b.b. 50 AB org	b.b. 10 AB	b.b. 20 AB	b.b. 35 AB	b.b. 35 AW	b.b. 35 AWorg	b.b. 35 AB org	Unit
Fine particulate matter formation	1.52E-03	1.39E-03	1.50E-03	1.38E-03	1.42E-03	1.36E-03	1.48E-03	1.44E-03	1.36E-03	1.40E-03	1.34E-03	1.33E-03	kg PM2.5 eq
Fossil resource scarcity	2.20E-01	2.13E-01	2.13E-01	2.09E-01	2.07E-01	2.03E-01	2.14E-01	2.08E-01	1.98E-01	2.07E-01	2.03E-01	1.96E-01	kg oil eq
Freshwater ecotoxicity	1.30E-02	1.19E-02	1.27E-02	1.19E-02	1.26E-02	1.20E-02	1.27E-02	1.24E-02	1.18E-02	1.23E-02	1.18E-02	1.15E-02	kg 1,4-DCB
Freshwater eutrophication	1.45E-04	1.49E-04	1.41E-04	1.47E-04	1.30E-04	1.32E-04	1.38E-04	1.32E-04	1.21E-04	1.26E-04	1.27E-04	1.22E-04	kg P eq
Global warming	7.71E-01	7.28E-01	7.48E-01	7.16E-01	7.11E-01	6.89E-01	7.44E-01	7.19E-01	6.73E-01	7.04E-01	6.85E-01	6.63E-01	kg CO2 eq
Human carcinogenic toxicity	1.71E-02	1.64E-02	1.67E-02	1.64E-02	1.66E-02	1.63E-02	1.68E-02	1.65E-02	1.59E-02	1.64E-02	1.61E-02	1.58E-02	kg 1,4-DCB
Human non-carcinogenic toxicity	5.55E-01	6.84E-01	5.43E-01	6.28E-01	5.29E-01	5.94E-01	5.40E-01	5.26E-01	5.00E-01	5.18E-01	6.06E-01	5.31E-01	kg 1,4-DCB
Ionizing radiation	9.06E-02	8.81E-02	8.37E-02	8.19E-02	1.35E-01	1.33E-01	9.47E-02	9.95E-02	1.07E-01	1.21E-01	1.19E-01	1.07E-01	kBq Co-60 eq
Land use	4.48E-01	7.59E-01	4.02E-01	6.95E-01	2.48E-01	4.03E-01	3.65E-01	2.88E-01	1.45E-01	2.14E-01	3.25E-01	2.22E-01	m2a crop eq
Marine ecotoxicity	1.89E-02	1.72E-02	1.84E-02	1.72E-02	1.81E-02	1.73E-02	1.84E-02	1.79E-02	1.70E-02	1.78E-02	1.69E-02	1.66E-02	kg 1,4-DCB
Marine eutrophication	3.58E-04	6.17E-04	3.34E-04	5.74E-04	1.92E-04	3.21E-04	2.88E-04	2.25E-04	1.06E-04	1.48E-04	2.45E-04	1.70E-04	kg N eq
Mineral resource scarcity	2.94E-03	1.48E-03	2.76E-03	1.47E-03	2.21E-03	1.48E-03	2.62E-03	2.32E-03	1.77E-03	2.05E-03	1.44E-03	1.41E-03	kg Cu eq
Ozone formation, Human health	2.37E-03	2.21E-03	2.33E-03	2.21E-03	2.19E-03	2.11E-03	2.29E-03	2.22E-03	2.08E-03	2.15E-03	2.07E-03	2.04E-03	kg NOx eq
Ozone formation, Terrestrial ecosystems	2.41E-03	2.25E-03	2.36E-03	2.24E-03	2.22E-03	2.14E-03	2.32E-03	2.25E-03	2.11E-03	2.18E-03	2.10E-03	2.07E-03	kg NOx eq
Stratospheric ozone depletion	2.12E-06	1.29E-06	2.02E-06	1.22E-06	1.26E-06	8.44E-07	1.76E-06	1.43E-06	8.14E-07	1.01E-06	7.34E-07	6.09E-07	kg CFC11 eq
Terrestrial acidification	4.58E-03	3.65E-03	4.50E-03	3.65E-03	4.03E-03	3.56E-03	4.34E-03	4.12E-03	3.72E-03	3.86E-03	3.51E-03	3.49E-03	kg SO2 eq
Terrestrial ecotoxicity	2.23E+00	2.08E+00	2.15E+00	2.08E+00	2.07E+00	1.99E+00	2.15E+00	2.08E+00	1.94E+00	2.05E+00	1.96E+00	1.90E+00	kg 1,4-DCB
Water consumption	9.05E-03	6.08E-03	8.04E-03	5.83E-03	7.47E-03	5.99E-03	8.31E-03	7.64E-03	6.39E-03	7.63E-03	5.99E-03	5.66E-03	m3

Table 11. Brewery impact categories values

Initially, a comparison is made with conventional beer with a gradual increase in the use of dehydrated bread. The following chart (figure 34) shows the relative indicator results of the respective project variants. For each indicator, the maximum result is set to 100% and the results of the other variants are displayed in relation to this result. It shows that the increasing of dehydrated breads is not linear and proportional with the environmental impact categories reducing. The most impactful is the conventional beer but the lowest one is beer made by 35% and 40% (same values) of dehydrated bread and not the one with 50%. Probably it is due to the dehydration step, it requires more energy to dry a higher amount of row material. It is the the step with the most energy consuming, in fact, drying step has a significant impact according to figure 36. A comparison between beer and b.b. 35 ab is made to figure out the differences form an environmental point of view. The EIC that are affected are LU ↓68%; MEutr ↓70%; MRS ↓40%; SOD ↓62%; WC ↓29%. It is due to the energy consuming and because of the transport of unsold bread meanwhile, the positive effects are due to the avoided malt.

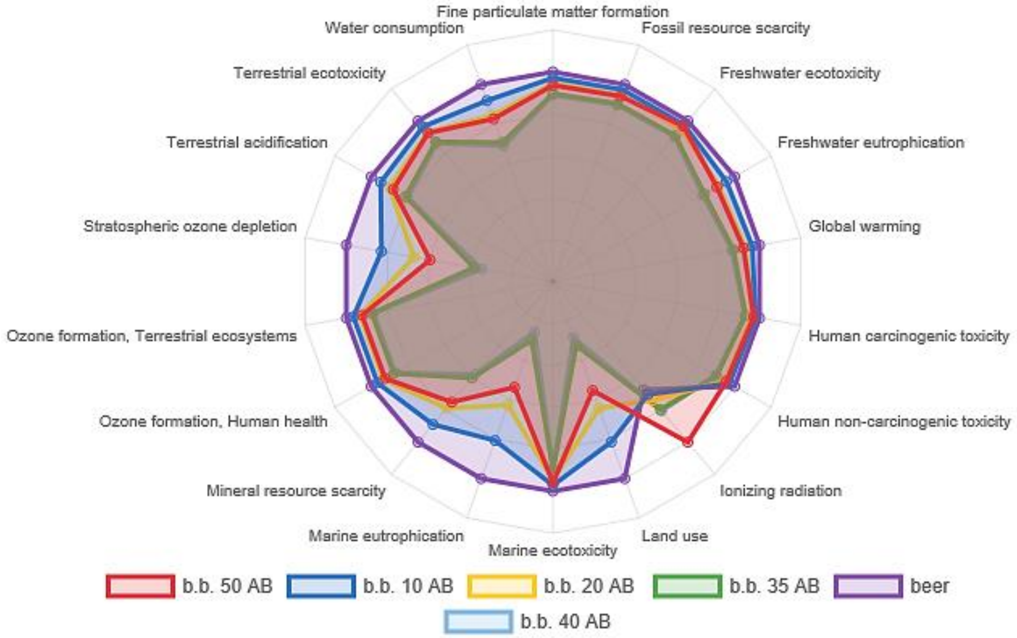


Figure 34. Radar graph of conventional beer comparing to different percentages of dehydrated bread

The second comparison (figure 35) is between conventional beer and blanche with the same amount replaced by unsold bread. No significant difference between blanche and beer 100% barley even though the unmalted wheat prevents a part of barley malt. Comparing blanche with b.b. 35 aw some EICs are affected like: IR ↑31% (and this one is significative unlike the beer with b.b. 35 ab); LU ↓47%; MEutr ↓56%; MRS ↓26% and SOD ↓50% (unlike the previous comparison where the WC was a significant EIC). Finally comparing b.b. 35 AB with b.b. 35 aw the significative differences are only in three EICs: LU ↓32% for b.b. 35 AB; MEutr ↓28% and SOD ↓20%. It is probably because of the avoiding barley, when you avoid barley malt there is a bigger gap in EICs because it is taken in account even the malting process and the transportation instead of avoided unmalted wheat.

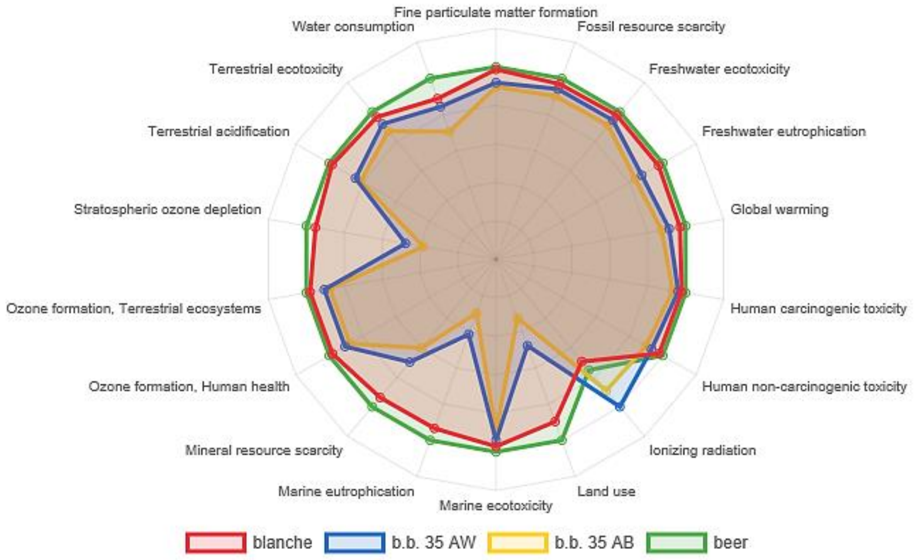


Figure 35. Radar graph of conventional beer with Blanche and the respective bread beer products

Is interesting to compare the the two innovative products: b.b. 35 AB and b.b. 35 AB org, the difference is only for few EICs like LU and MEutr, respectively ↓34% and ↓37% in favour of the non-organic one. They are reflected from the 100% barley beers, which have almost, the same trends. A comparison among organic products is necessary, the most significant EICs are: HNCT ↓22% (organic product); LU ↓71%; MEutr ↓72% (they are improving a lot) and SOD ↓53%. This is due to avoided product but not for all the EICs, sometimes it can be higher because of the drying process. Figure 46 shows all the relative results.

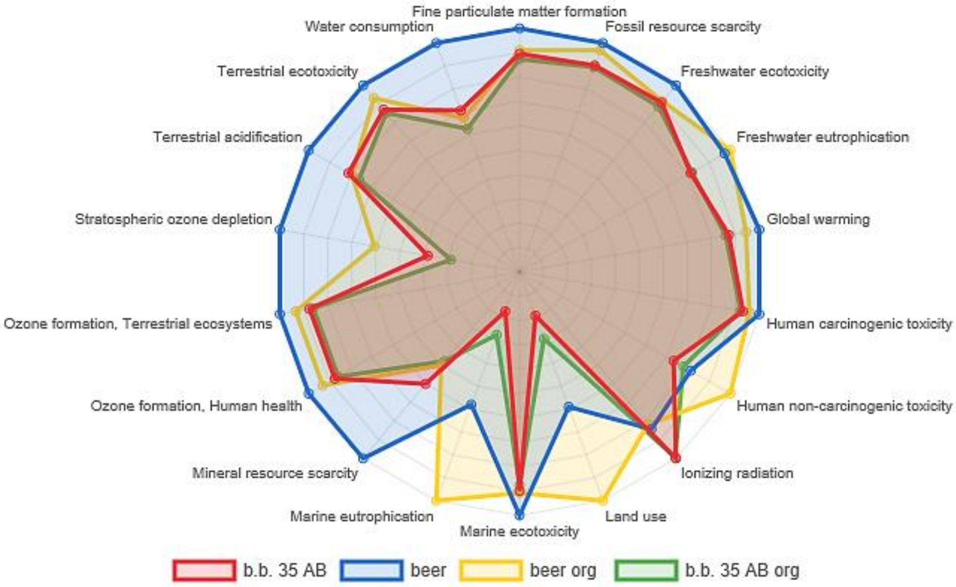


Figure 36. Radar EICs graph of conventional beer and b.b. 35% ABs and the respective organic production

The last group comparison is among organic production. You can notice in the radar diagram (figure 37) the EICs are not decreasing linearly as the increasing of the unsold bread percentage. In fact, the best product (at least in IR; LU; MEutr and SOD) like in conventional production.

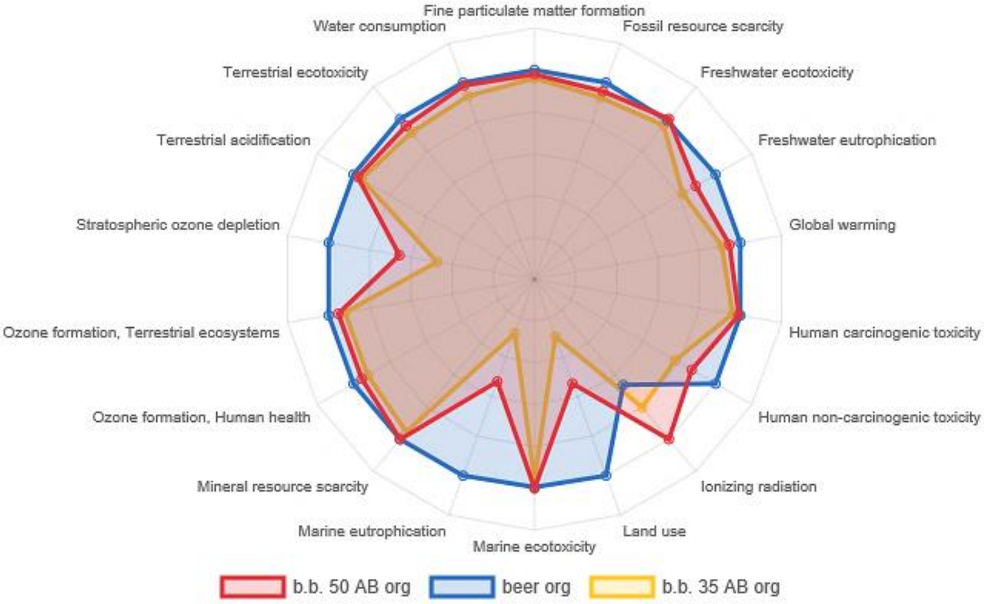


Figure 37. Radar EICs graph of organic beer and its innovative product

7.3.3 Focus on cultivation

In both productions, the conventional cultivation results worse than the organic one (for 1 kg of grain at the farm gate) unless for the LU, HNCT (only for barley), FEutr and Meutr. For example, a process with organic wheat flour production contributions: FPMF: 59.43%; FRS: 53.77%; FE: 27.48%; FEutr: 59.61%; GW: 29.48%; HTC: 41.94%; IR: 4.62%; LU: 96.42%; ME: 31.43%; MEutr: 97.79% MRS: 27.60%; OF, HH: 73.62%; OF, TE: 73.44%; SOD: 91.37%; TA: 64.53%; TE: 61.71%; WC: 8.01%. It is less in almost every EIC comparing with the non-organic one which is the most impactful. Figure 38 shows the difference between wheat, organic wheat, barley and organic barley cultivation.

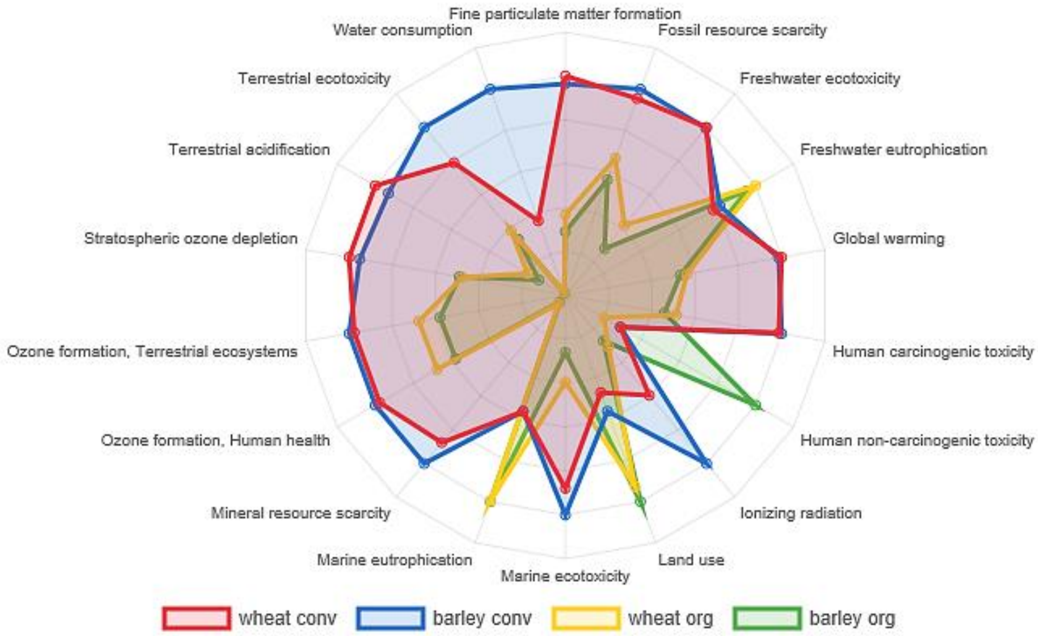


Figure 38. Radar graph of cultivation environmental impact between organic and conventional cultivation

7.4 Methods comparison

A comparison between two different LCA methods is done in order to evaluate if the hierarchy of products is maintained. The methods are: the main one, ReCiPe 2016 Midpoint (H) and CML-IA baseline, which has less EICs. Only a few products are chosen for the test. The results are similar but it is difficult to compare different methods because the EICs are not exactly the same, there are some analogies. However, it seems that the hierarchy is almost the same for both productions. It shows many highlights. Therefore, the CML-IA baseline seems suitable as well as ReCiPe 2016 Midpoint (H) for this study. In the figures 39 you can see a comparison between the two methods and also the maintenance of the EIC products' hierarchy.

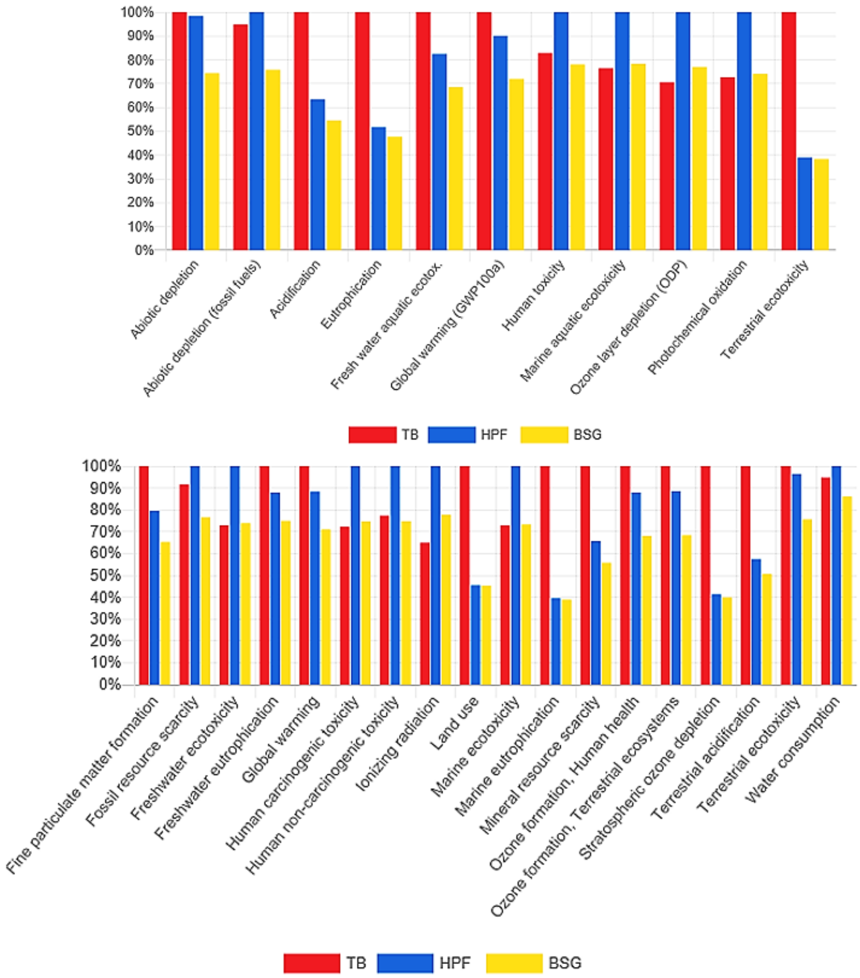


Figure 39. Bar chart comparison between two different LCA methods in bakery: CML-IA baseline (above) ReCiPe 2016 Midpoint (H) (below)

7.5 System comparison

The last step is to compare the whole system to the conventional one in order to express the feasibility of the circular economy, if it is better than a traditional one from an environmental point of view. This is the most important question concerning this type of project. The BSG and b.b. 35% ab variants are chosen because they are considered more representative and more easily reproducible by the manufacturers. The most difficult limitation about OpenLCA is to obtain the EIC values of the entire circular economy system and to compare it to the EIC values of the entire non-circular economy system. Therefore, to achieve this goal the strategy adopted is to sum the EIC values of bakery process with the ones of the brewery process. Everything was configured in excel. It is not easy to compare two conventional systems together with one innovative production because there is a limitation of the model to create a logic and comparable link among the productions and clarify the strategy about environmental charging is also a focus point. For that reason, two different strategies are carried out. First: adding the two productions separately, without co-products environmental charging. Second: make only one production with the link between 1° filtration and BSG pressing and finally, adding the remaining brewing steps without previous steps environmental charging. For a clearer interpretation please refer to the flowcharts in figure 40, 41 and 42. Figure 40 represents the sum of traditional products impact; figure 41 represents the innovative system flowchart illustration, first strategy (with environmental charging on the BSG that includes unsold bread); figure 42 represents innovative system flowchart illustration, second strategy (without environmental charging on BSG and unsold bread), it is a sum of impacts considering BSG and unsold bread ex novo intermediate products.

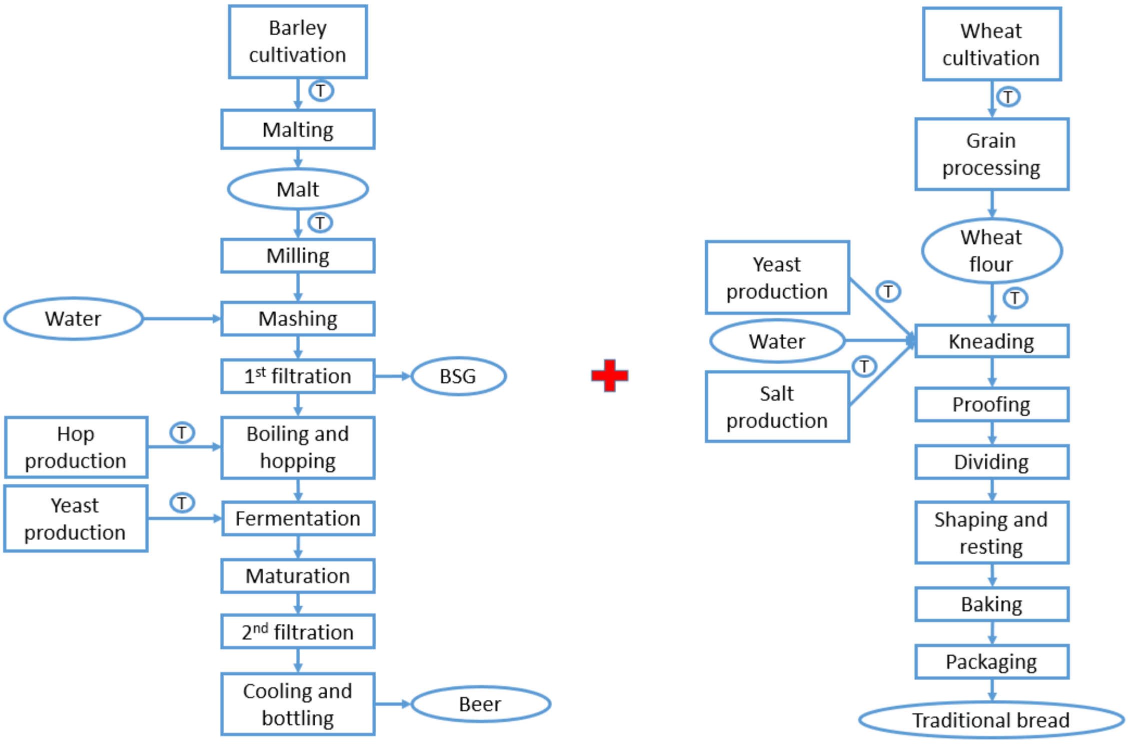


Figure 40. Traditional system flowchart illustration

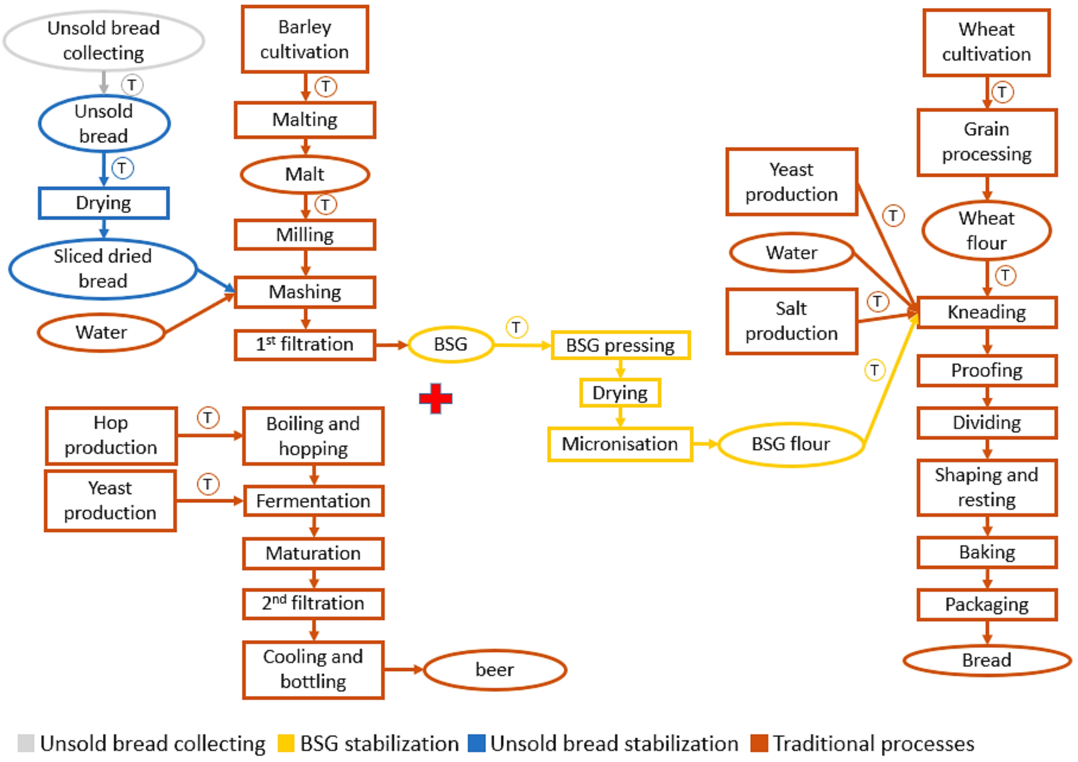


Figure 41. Innovative system flowchart illustration, first strategy (with environmental charging)

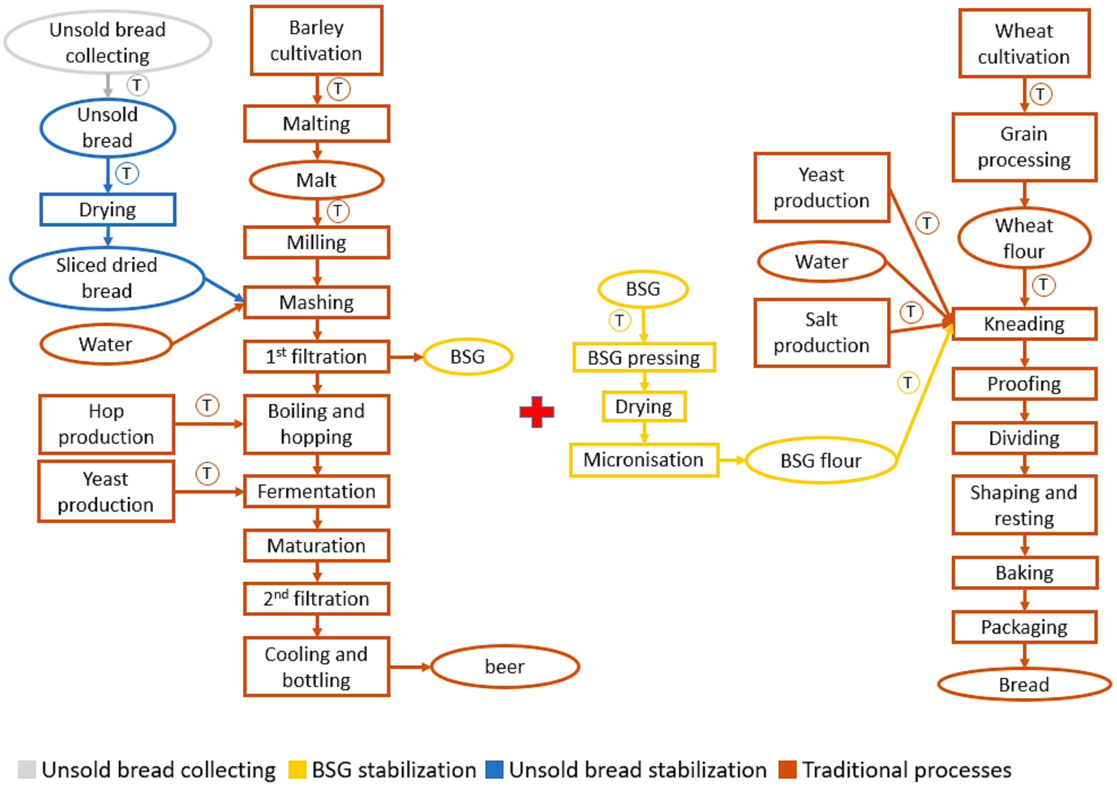


Figure 42. Innovative system flowchart illustration, second strategy, (without environmental charging)

In table 12 there are the EIC's values about all the systems and the corresponding percentages considering the highest value per EIC 100%. Consequentially, each values under that value is considered relative to the highest value (100%). For a graphical percentage view, you can consider figure 43. The various acronyms represent the system strategy considered in that specific analysis. TS = traditional system: the EICs sum of traditional productions; ECCS = environmental charging circular system: it is the EICs sum of the brewery passing through the filtration part until the bread product (BSG has the environmental charging of the steps before) and the rest of the brewery production, after the filtration step until the beer product; WECCS = without environmental charging circular system: it is a sum o EICs divided in two processes, in that way the BSG has not an environmentally charged with the processes before. Usually in figure 43 there are in the middle for each EIC the traditional approaches which represent the 100%.

indicators/system names	**TS**	**ECCS**	**WECCS**	**Unit**	**ECCS (%)**	**TS - ECCS (%)**	**TS - WECCS (%)**	**WECCS (%)**
FPMF	0.003	0.002	0.002	kg PM2.5 eq	81	100	100	78
FRS	0.331	0.307	0.289	kg oil eq	93	100	100	87
FE	0.031	0.031	0.030	kg 1,4-DCB	100	99	100	97
Feutr	0.000	0.000	0.000	kg P eq	79	100	100	75
GW	1.331	1.119	1.053	kg CO2 eq	84	100	100	79
HCT	0.031	0.031	0.030	kg 1,4-DCB	100	98	100	98
HNCT	1.156	1.121	1.076	kg 1,4-DCB	97	100	100	93
IR	1.150	1.444	1.379	kBq Co-60 eq	100	80	83	100
LU	1.890	0.818	0.717	m2a crop eq	43	100	100	38
ME	0.042	0.043	0.041	kg 1,4-DCB	100	100	100	96
Meutr	0.002	0.001	0.001	kg N eq	42	100	100	37
MRS	0.010	0.006	0.006	kg Cu eq	62	100	100	56
OF, HH	0.004	0.003	0.003	kg NOx eq	81	100	100	77
OF, TE	0.004	0.003	0.003	kg NOx eq	81	100	100	78
SOD	0.000	0.000	0.000	kg CFC11 eq	44	100	100	39
TA	0.010	0.007	0.006	kg SO2 eq	66	100	100	63
TE	4.705	3.880	3.720	kg 1,4-DCB	82	100	100	79
WC	0.021	0.020	0.017	m3	94	100	100	81

Table 12. EIC's values for each system and respective percentages

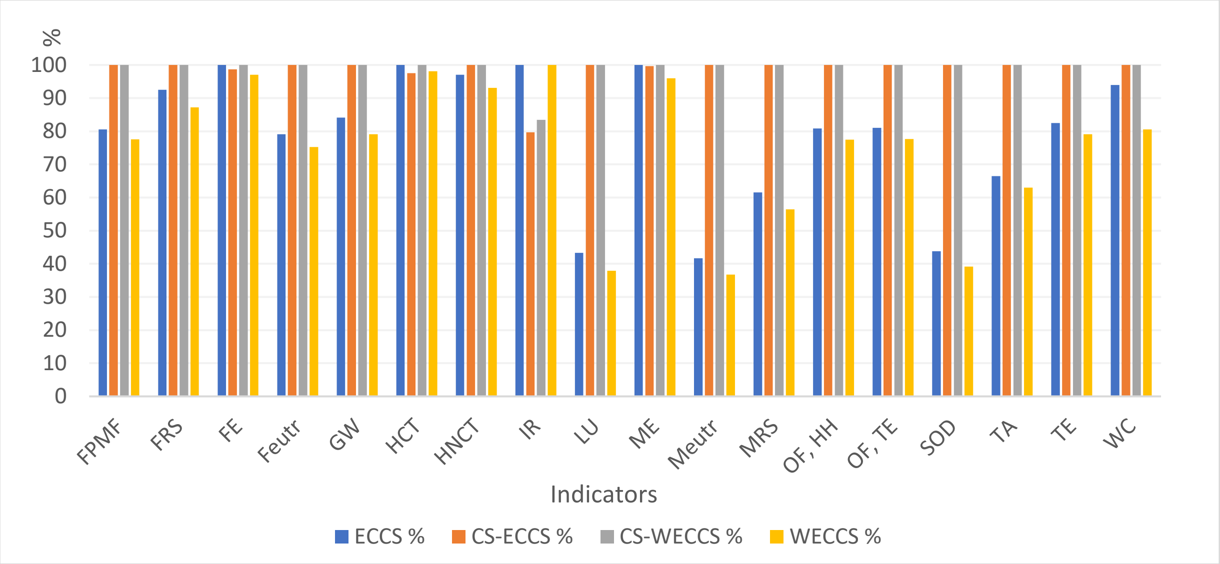


Figure 43. Percentage bar chart about systems comparison

The results underlined in green are the significative values percentage comparing to the 100% which is always the conventional system unless for the IR. The first strategy (ECCS) underlines FE, LU, MEutr, MRS, SOD and TA. IR of the ECCE (% in red) is the only EIC that is significantly higher than the IR in traditional system. There are no significative differences between WECCS and ECCE but the WECCS relies more significative EICs than the ECCS, the gap is higher comparing to the traditional system, for example: FPMF; GW; OF, HH; OF, TE and TE, without having a significant negative impact (no red boxes in WECCS)

8. Conclusion

This study was about comparative environmental evaluation in the brewing and bakery sectors focused on hot spots in single productions and on different product environmental comparison. The major hot spot in bread making is wheat flour production. Therefore, the strategy is to avoid part of this product. Similar deduction can be made about brewery sector regarding barley: if the non-recycling bottle step is not considered we can assume that the barley production is an important hot spot. However, the impact of introducing a new stage in the life cycle of the spent grain is significant on the global environmental impact of the product. Taking in account all the assumptions, the BSG bread (especially the wholemeal variant) resulted the best option between conventional cultivation. The organic version is a valid option, but it is necessary to evaluate each significant EIC because there are some with high impact like LU and MEutr. On the other hand, in brewery, the non-linearity with the increasing of the percentage of unsold bread is a very interesting point. In fact, the 50% is more impactful than the 35% or 40%. So, it is necessary to find the optimum value to be efficient form an environmental point of view. There are no significant differences between blanche and typical beer. The most important thing is that the innovative process seems to decrease some EIC especially for organic products (mostly for the organic critical EIC). The CML-IA baseline seems to give similar results especially for bread production.

Finally, in sistem comparison it is not easy to precisely compare a circular economy process with a conventional one because in this case there are 2 different functional units. For example, in innovative processes, the software does not consider the unit operations following the recovery of BSG (boiling and hopping, 2° filtration ecc.), whereas conventional systems consider the entire production process. Finally, a sum on Excel file was implemented. Consequently, it can be assumed that the circular economy system impacts less for more than half of the EICs especially in WECCS strategy and has no high values for any EICs.

In conclusion, a study with less assumptions, more complete with more primary data, an economic evaluation by Life Cycle Costing (LCC) and a social evaluation by Social Life Cycle Assessment (S-LCA), should be carried out. Further studies are necessary in order to amplify the circular economy view because in this study is missing the consumption phase. Are also necessary chemical analysis, physical analysis and sensory analysis in order to understand if the innovative products respect the standards and the market competitivity. The study is still useful for the scientific community and for the manufacturers to improve their organization and their technical skills.

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