TESE DE DOUTORAMENTO

FROM AGRICULTURAL CULTIVATION TO FOOD AND BIO-BASED PRODUCTS: A LIFE CYCLE ASSESSMENT PERSPECTIVE

Iana Câmara Salim

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From agricultural cultivation to food and bio-based products: A life cycle assessment perspective

Dna. Maria Teresa Moreira
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ABSTRACT

The growth of population and per capita income has led to the indiscriminate use of resources, especially those of fossil origin, causing several ecological crises. Agricultural systems have developed over time in order to comply with the population growth. However, this agricultural development is reaching a limit due to intense mechanization, widespread use of chemical fertilisers and pesticides, use of land and water. It is therefore important to find ways to make production more sustainable, while ensuring food security and human and ecosystem health, alleviating environmental impacts.

The environmental concern about the use of non-renewable sources drew attention to the use of renewable biomass for the production of biofuels and bio-based products. Examples include first-generation (1G) feedstocks, such as starch crops (e.g., maize and wheat grains), which compete with food/feed markets. Agricultural and industrial processing residues, namely second-generation (2G) feedstocks, are also of interest for use in industrial fermentation processes, although, to date, they have fewer technological advantages in relation to 1G biomass.

Bioeconomy and circular economy are key concepts to promote the development of more sustainable production processes, which promote compliance, by governments, with the commitments and initiatives of the 2030 Agenda, the United Nations SDGs and the Paris agreement, among others. In this context, significant efforts in the sustainable production of agriculture and bio-based products are essential for sustainable development. The main objective of this doctoral thesis is to assess the environmental and economic impacts of bioproducts, considering food and bio-based products, by means of the Life Cycle Assessment (LCA) methodology. This thesis comprises four sections, including I) Contextualisation, II) Agriculture and food context, III) Agriculture and bio-based context and IV) Conclusions.

Section I: Contextualisation

This section, which comprises Chapters 1 and 2, provides general information regarding circular economy and bioeconomy frameworks and gives an overview of the raw materials used for the production of food or bio-products for this thesis (Chapter 1). In addition, the methods used to develop the environmental and economic analysis of the different production alternatives proposed in this doctoral thesis (Chapter 2) are also included.

Chapter 1 is an introductory section where the importance of the circular economy and the bioeconomy is described to reduce the environmental impacts generated by conventional production processes, those based on fossil resources, and to, in turn, improve quality of life and human well-being. It highlights the need to combine these two frameworks to attain a "circular bioeconomy". A new term focused on the protection of the environment and the generation of new economic opportunities from the development of bio-based products that can replace conventional ones based on non-renewable resources. Moreover, the biorefinery concept is explained, classifying the different types of raw materials, from first generation to fourth generation feedstocks. This chapter also provides a general overview of four main agricultural crops: wheat, maize, sugar beet and potatoes. These crops are considered important agricultural commodities worldwide, due to their large volumes of production and consumption. The development of sustainable and biotechnological production processes from these crops will be the main objective of this thesis, also including waste, either for the production of food or bio-based products.

Chapter 2 presents an outline of the history of sustainability from the 19th century to the present day. In addition, this chapter identifies the methodologies available for assessing the impacts of human action on sustainability, with a focus on LCA, which is the main methodology used in this thesis, and, to a lesser extent, economic evaluation and environmental costs are also explored.

Section II: Agriculture and food context

This section aims to link the environmental impacts and economic indicators of agriculture with a view on food production. The assessment of the environmental sustainability of agricultural crops and crops processed for food production is developed in Chapters 3 and 4 while the environmental and economic profile of industrial and agricultural residues is addressed in Chapter 5.

Chapter 3 explores, from a life cycle perspective, the environmental sustainability of wheat cultivation and bread production in the Galician region, Spain. This type of bread is a combination of native Galician wheat grains and commercial Spanish wheat, in which the Galician wheat gives the aroma of bread while commercial wheat provides the right volume. This chapter attempts to evaluate the environmental impacts of an artisanal product, in which the quality of the cereal and the product are essential targets. It considered four different farming systems: 1) Galician wheat cultivated under a monoculture system; 2) Galician wheat cultivated under crop rotation system; 3) certified Galician seed production and 4) commercial Spanish wheat cultivation. Two different bread scenarios are evaluated depending on whether the bread is made from wheat grains produced in a crop rotation system or in a monoculture system.

When comparing the different agricultural systems (i.e., 1 kg of transported wheat), the figures show the lowest environmental impacts for Galician wheat grains produced in crop rotation. On the other hand, commercial wheat cultivation performs the worst in all impact categories, with exception to climate change. Galician wheat under a monoculture presented the worst case for climate change, owing to the use of nitrogen fertilisation and field operation for the application of agrochemicals.

On the other hand, the LCA results of bread production show that wheat cultivation is the main contributor to the environmental impacts, representing more than 50% in all impact categories. Galician bread that uses native wheat grains in a crop rotation system has a better environmental profile than bread using wheat grain in a monoculture system. Therefore, milling and baking producers should consider that their selection on wheat grain have a considerable impact on their environmental profile.

Food heritage products such as the Galician bread often represent traditional elements of indisputable quality, which has essential aspects of tradition and cultural identity. Although they seem insignificant on a global level, these specialty products are of great importance to local society, economy and culture. Therefore, the adaptation and modification of agricultural production systems is a key factor for the development of more sustainable production systems.

It should be mentioned that, in Chapter 3, the complex interactions of the cropping systems have not been considered, nor the effects that the predecessor crop has on the second crop.

Following this study, Chapter 4 assesses the environmental profile of potato and wheat cultivation in Galicia (Spain). The intensive production of agricultural crops has adverse environmental consequences. For this reason, the use of crop rotation appears as an alternative to boost the environmental sustainability of agricultural systems. As of wheat, potato is also an important staple food. This cultivation system is a 3-year rotation cycle, in which the first year corresponds to the cultivation of potatoes (the main crop), followed by commercial wheat in the second year and a variety of native wheat is planted in the third year. LCA method was employed using four types of functional units (FUs): in terms of productivity (kg^{-1}); land management ($ha^{-1}\cdot year^{-1}$); a financial function (euros $€^{-1}$ of income from sales) and energetic value (MJ^{-1}).

The environmental outcomes of the 3-year potato-wheat cropping system presents an impact of approximately 2431 kg CO_2 eq for climate change and 400 kg oil eq for fossil depletion per ha. If we compare the different agricultural systems, the results show that Galician native wheat has the best environmental profile per $ha^{-1}\cdot year^{-1}$, euros $€^{-1}$ of income from sales and MJ^{-1} while the potato crop has the worst profile, except for land use, due to the high yield of the potato that can be up to 10 times more than that of wheat. Potato crops use more chemical fertilisers, pesticides and field operations than wheat. On the other hand, potato cultivation has the lowest environmental impacts per kg^{-1}, again owing to its high yield compared to wheat. In addition, commercial wheat has more environmental impacts than native wheat, as it also requires more agricultural inputs than native wheat. This chapter demonstrates the relevance of using LCA to understand the environmental impacts of regional agricultural systems under a crop rotation system.

Unlike Chapters 3 and 4 above, Chapter 5 analyses the consequences of residual streams from agricultural and industrial activities. This chapter investigates the environmental and economic impacts of maize stover and sugar beet pulp as lignocellulosic raw materials with potential use as feed (e.g., as forage or fodder) or as feedstocks in industrial fermentation processes. It comprises four scenarios: beet pulp in France and the United Kingdom as well as maize stover in Italy and Belgium.

LCA was applied considering 1 GJ of biomass as FU. In addition, economic evaluation was assessed taking into account internal (i.e., the operational costs - OPEX) and external costs (i.e., environmental costs). Moreover, uncertainty analysis was performed to evaluate the robustness of the environmental figures and sensitivity analysis was carried out for maize production considering changes in the stover removal rate from 30% to 50%.

The results of this study show that maize stover has less environmental and economic impacts. For climate change impact category, for instance, maize stover production in Italy decreased by more than 80% compared to beet pulp in United Kingdom. In the beet pulp scenarios, most of the environmental emissions come from the agricultural phase, which contributes 67% and 89% of the total CO_2 emissions in France and United Kingdom, respectively. The economic analysis ranges from 22 € per 1 GJ produced, for maize stover in Italy to 174 €, for sugar beet in the United Kingdom. Maize stover requires only an agricultural process to be produced, while beet pulp needs an additional pre-processing step. In addition, maize stover has a much higher calorific value: 16.5 $MJ \cdot kg^{-1}$ compared to sugar beet pulp (3.78 $MJ \cdot kg^{-1}$).

The results of the sensitivity analysis show a small increase, not exceeding 10%, in the impact categories when the rate of stover removal increased from 30% to 50%. In addition, the results of the uncertainty analysis show the robustness of the environmental results, with a coefficient of variation of less than 30% in all impact categories, except for freshwater eutrophication, due to the uncertainty of the background processes.

Section III: Agriculture and bio-based context

This section represents the environmental sustainability of products produced in a bio-based context, taking into consideration three different bioproducts: glucose (Chapter 6), fermentable sugars (Chapter 7), butyric acid (Chapter 8) and methionine (Chapter 9).

Chapter 6 evaluates the environmental profile of wheat cultivation and wheat-based glucose in a European context. Most LCA studies on biofuels or bio-based products evaluate the final product, such as bioethanol, and few put emphasis on upstream processes, such as glucose to be used in industrial fermentation processes. This LCA considers 1 kg of wheat grain and 1 kg of glucose as FUs, comprising 15 farming systems in 9 European countries. As the production of starch from the wet milling process delivers valuable residues, namely bran, gluten meal and gluten feed, mass and economic allocations were applied in this study.

In all the European countries analysed, on-field emissions, fertiliser application and field operations are agricultural activities that have a major contribution to the environmental impacts of wheat cultivation. Regarding the use of fertilisers, their application causes the emission of substances that adversely impact the environment, such as nitrous oxide (N_2O) and ammonia (NH_3). In addition, farming systems require considerable use of fossil fuels, such as diesel for field operations, which also involves the emission of pollutants, such as carbon dioxide (CO_2) and leads to fossil depletion. Therefore, the results show that agricultural activities play a key role in the environmental profile of glucose production. In the grain processing phase, the processes heating and electricity present a significant influence on the environmental impact categories of climate change, freshwater eutrophication and abiotic depletion. It is important to mention that the environmental results show variations depending on the country considered, mainly due to the fertilizer load, field operations and the profile of the electricity mix in each country. Regarding the allocation criteria considered, the economic allocation implies a greater impact than the mass allocation for glucose.

It is important to note that Chapters 3 and 4 also evaluated the environmental profile of wheat, with emphasis on regional farming and traditional food, considering mostly primary data from in situ interviews, whereas Chapter 6 gives an overview by country using secondary data from the literature.

Chapter 7 focuses on the environmental profile of raw material production and upstream processing under the STAR-ProBio project (grant agreement No. 727740). Maize grain, stover and sugar beet pulp are biomass rich in carbohydrates and valuable to be processed into fermentable sugars, sugars that are essential in the biotechnological production of a variety of bioproducts, namely polylactic acid (PLA) and polybutylene succinate (PBS).

The maize grain, a starch-rich crop, classified as 1G feedstock, is converted into fermentable sugar (i.e., glucose) by first carrying out milling and then enzymatic hydrolysis steps. On the other hand, maize stover and beet pulp are 2G feedstocks and rich in cellulose that can be processed into different types of fermentable sugars by first performing a pre-treatment process and then enzymatic hydrolysis.

Twenty scenarios for fermentable sugars were considered in this study. An economic allocation was performed to distribute the environmental impacts of maize grain, stover and sugar beet pulp. Subsequently, a sensitivity analysis was performed, changing the parameters to make a mass allocation and assess the robustness of the results. The environmental results related only to agriculture show that emissions in the field, chemical fertilisation, field operations and transportation are processes that have an important environmental contribution.

The environmental figures for fermentable sugars from maize grain reveal that agricultural activities are the major cause of the impacts. However, in the production of fermentable sugars from stover and mainly beet pulp, agriculture has a small contribution, if economic allocation is applied. Therefore, based on the results obtained, it is concluded that the production of fermentable sugars from beet pulp has less impact compared to its production from maize grain or stover. The environmental outcomes for maize grain sugars did not show great sensitivity to variation when changing the parameters from economic to mass allocation, as opposed to stover or beet pulp.

Chapter 8 explores the environmental profile of bio-based butyric acid as an alternative to its fossil-based. Butyric acid is a valuable chemical with many applications in the chemical, food, pharmaceutical and cosmetic sectors. However, due to technological advantages, butyric acid is currently produced industrially by chemical means. This chapter evaluates the environmental profile of butyric acid production from wheat straw, a rich lignocellulosic raw material. It considers the wheat straw produced in the Galician wheat cultivation in Chapter 4. Two product formulations were evaluated: butyric acid produced in combination with acetic acid and butyric acid with high purity. A sensitivity analysis was applied changing the current energy profile to 100% renewable energy and using alternative lignocellulosic raw materials for wheat straw, i.e., sugar beet pulp and maize stover.

The results of this evaluation show that the production of butyric acid in combination with acetic acid is the best scenario due to the lower amount of energy and inputs used. Furthermore, for both butyric acid formulations, it shows that steam production, electricity and cellulase cocktail were the main processes with the highest environmental loads. The results of the sensitivity analysis show that the switch to 100% renewable energy has considerably reduced the environmental burden of butyric acid. However, beet pulp or maize as a substitute for wheat straw has not significantly altered the global environmental impacts.

Chapter 9 assesses the environmental profile of methionine, an essential amino acid that, like butyric acid in Chapter 8, is mainly produced by chemical synthesis. However, chemically produced methionine is undesirable as it uses hazardous chemicals such as acrolein, methyl mercaptan, ammonia and cyanide which are toxic and harmful to human and ecosystem health. In addition, methionine via fermentation yields L-methionine, which is considered to be of better quality than the chemically produced D and L methionine mixture. Three formulations of methionine products were considered for benchmarking: 1) Methionine through a chemical pathway, 2) Methionine by microbial fermentation and 3) Methionine by microbial fermentation and anaerobic digestion of biowaste.

The results show that the production of methionine by microbial fermentation with anaerobic digestion has the lowest environmental impacts, while methionine via chemical synthesis is a highly polluting process. For example, CO_2 emissions linked to chemical synthesis are about 3 times higher than those associated with the microbial fermentation. Using anaerobic digestion to reuse energy and generate nitrogen as a fertiliser considerably reduced the environmental loads of microbial methionine.

Section IV: Conclusions

This section provides the main findings, contributions of the thesis and recommendations. Chapter 10 gives an overview of the work built throughout this thesis, pinpointing the main conclusions identified in the different sections and chapters and delivering recommendations to enhance the sustainability of bioproducts. This work provides complete documentation through the extensive application of LCA in agricultural crops, food and bio-based products, providing a broad understanding of the sustainability profile of the products analysed in this thesis (wheat, maize, potato, maize stover, sugar beet pulp, fermentable sugars, butyric acid and methionine) as well as insights for process improvements. Environmentally harmful processes and substances were identified and measured with the aim to find solutions to reduce environmental loads.

RESUMEN

El crecimiento de la población y la renta per cápita ha provocado un incremento significativo en el consumo de recursos, especialmente en los de origen fósil, provocando varias crisis ecológicas. Los sistemas agrícolas han evolucionado y se han modernizado a lo largo de los últimos años con el objetivo de ser capaces de responder al rápido crecimiento demográfico. Sin embargo, este desarrollo agrícola llega a un límite debido a la intensa mecanización, el uso generalizado de fertilizantes químicos y pesticidas, el uso de la tierra y el agua. Por lo tanto, es importante encontrar alternativas que promuevan el desarrollo de una producción más sostenible, garantizando al mismo tiempo la seguridad alimentaria y la salud humana, al igual que la de los ecosistemas, teniéndose especialmente en cuenta los impactos ambientales asociados.

La preocupación ambiental por el uso de fuentes no renovables ha supuesto la necesidad de buscar nuevas alternativas de producción de base renovable, entre las cuales destaca el uso de la biomasa, siendo este un recurso idóneo para la producción de biocombustibles y bioproductos. De esta forma, se pueden establecer dos categorías en función del tipo de biomasa empleada: la de primera generación (1G), como cultivos de almidón (por ejemplo, granos de maíz y trigo), que compiten con los mercados de alimentos / piensos, y la de segunda generación, incluyéndose en esta categoría los residuos de procesamiento agrícola e industrial, los cuales también son de especial interés para su uso en procesos de fermentación industrial, aunque hasta la fecha tienen menos ventajas tecnológicas sobre la biomasa 1G.

La bioeconomía y la economía circular son conceptos claves para promover el desarrollo de procesos productivos más sostenibles, que fomentan el cumplimiento, por parte de los gobiernos, de los

compromisos e iniciativas de la Agenda 2030, de los ODS de las Naciones Unidas y del Acuerdo de París, entre otros. En este contexto, la valorización de los productos agrícolas y biológicos se convierte en una alternativa adecuada para promover el desarrollo sostenible. De esta forma, el objetivo principal de esta tesis doctoral es la evaluación de los impactos ambientales y económicos de los bioproductos, considerando productos alimentarios y de base biológica, utilizando la metodología de Análisis de Ciclo de Vida (ACV). El presente documento se ha dividido en cuatro apartados, siendo estos: I) Contextualización, II) Contexto agrícola y alimentario, III) Contexto agrícola y bioproductos y IV) Conclusiones.

Sección I - Contextualización

Esta sección, que comprende los capítulos 1 y 2, proporciona una descripción general de los marcos de economía circular y bioeconomía, y proporciona una descripción general de las materias primas utilizadas para la producción de alimentos o bioproductos para esta tesis (Capítulo 1). Además, también se incluyen los métodos utilizados para desarrollar el análisis ambiental y económico de las diferentes alternativas de producción propuestas en esta tesis doctoral (Capítulo 2).

El capítulo 1 se considera una sección introductoria en donde se describe la importancia de la economía circular y de la bioeconomía para reducir los impactos ambientales generados por los procesos productivos convencionales, los basados en recursos fósiles, y para, a su vez, mejorar la calidad de vida y el bienestar humano. Destaca la necesidad de combinar estos dos conceptos para lograr una "bioeconomía circular", un nuevo término enfocado en la protección del medio ambiente y la generación de nuevas oportunidades económicas a partir del desarrollo de productos de base biológica que sean capaces de substituir a aquellos convencionales basados en recursos no renovables. Por otra parte, también se introduce el concepto de biorrefinería, incluyéndose un análisis de las diferentes materias primas que pueden ser empleadas como insumos del proceso, desde las de primera generación hasta las de cuarta generación. Este capítulo también proporciona una descripción general de cuatro cultivos agrícolas principales: trigo, maíz, remolacha azucarera y patatas, considerados importantes productos agrícolas a nivel mundial debido a sus grandes volúmenes de producción y consumo. El desarrollo de procesos productivos biotecnológicos a partir de estos cultivos será el objetivo principal de esta tesis, incluyéndose también los residuos, ya sea para la producción de alimentos o productos de base biológica.

El capítulo 2 se incluye un resumen de la historia de la sostenibilidad desde el siglo XIX hasta la actualidad. Además, también se identifican las metodologías disponibles para la evaluación de los impactos generados por las actividades de la acción humana en la sostenibilidad, siendo el Análisis de Ciclo de Vida (ACV) la principal metodología utilizada en esta tesis. Además, también se han abordado, aunque en menor medida, evaluaciones económicas de las diferentes alternativas propuestas, además de cálculos de los costes ambientales asociados a los procesos biotecnológicos propuestos.

Sección II: contexto agrícola y alimentario

Esta sección tiene como objetivo vincular los impactos ambientales y los indicadores económicos de la agricultura desde la perspectiva de la producción de productos alimentarios. La evaluación de la sostenibilidad ambiental de los cultivos agrícolas y los cultivos procesados para la producción de alimentos se desarrolla en los Capítulos 3 y 4, mientras que el perfil ambiental y económico de los desechos industriales y agrícolas se aborda en el Capítulo 5.

El capítulo 3 explora, desde la perspectiva de ciclo de vida, la sostenibilidad medioambiental del cultivo de trigo y de la producción

de pan en la región gallega, ubicada en España. Este tipo de pan es una combinación de granos de trigo autóctono gallego y de trigo comercial español, en el que el trigo gallego proporciona ese aroma característico de pan, mientras que el trigo comercial aporta el volumen adecuado. Se trata, por lo tanto, de evaluar los impactos ambientales de un producto artesanal, en donde la calidad del cereal y del producto son objetivos primordiales. Dada la importancia del cultivo del cereal sobre la calidad del producto final, se han propuesto cuatro sistemas de cultivo diferentes: 1) trigo gallego cultivado bajo un sistema de monocultivo; 2) Trigo gallego cultivado en régimen de rotación de cultivos; 3) producción de semilla gallega certificada y 4) cultivo comercial de trigo español. Se han evaluado dos escenarios, el primero se centra en la elaboración de pan a partir de granos de trigo producidos en un sistema de rotación de cultivos, mientras que en el segundo escenario se ha considera una producción agrícola de monocultivo.

Al comparar los diferentes sistemas agrícolas (considerándose como unidad funcional 1 kg de trigo transportado), los valores ambientales obtenidos muestran menores impactos ambientales para el primer escenario, el que propone un sistema de producción centrado en la rotación de cultivos. Por otro lado, se ha identificado que el cultivo comercial de trigo es el que supone una mayor contribución ambiental en todas las categorías de impacto, con excepción a la de cambio climático. En lo que respecta al segundo escenario, el que consideraba la producción de trigo gallego en monocultivo, es el que presentó un mayor valor de impacto sobre la categoría de cambio climático, identificándose las actividades de fertilización nitrogenada y las operaciones requeridas para la aplicación de agroquímicos, como las principales causas que dan lugar a una elevada contribución ambiental.

Por otra parte, el análisis de ciclo de vida del proceso de producción de pan ha permitido concluir que el cultivo de trigo es el principal contribuyente en el perfil ambiental obtenido, representando más del

50% en todas las categorías de impacto. El pan gallego que utiliza granos de trigo autóctono en un sistema de rotación de cultivos tiene un mejor perfil ambiental que el pan que utiliza granos de trigo en un sistema de monocultivo. Por lo tanto, los productores de molienda y panificación deben considerar el desarrollo de sistemas productivos basados en la rotación de cultivos, dado a la importante contribución ambiental que supone la producción agrícola centrada únicamente en la obtención de un único cultivo de grano de trigo.

Los productos del patrimonio alimentario como el pan gallego suelen representar elementos tradicionales de indiscutible calidad, que tiene aspectos esenciales de tradición e identidad cultural. Aunque parecen insignificantes a nivel mundial, estos productos especiales son de gran importancia para la sociedad, la economía y la cultura locales, por tanto, la adaptación y modificación de los sistemas productivos agrícolas es un factor clave para el desarrollo de sistemas de producción más sostenibles.

Cabe mencionar que en el Capítulo 3, no se han considerado las complejas interacciones de los sistemas de cultivo, ni tampoco los efectos que tiene el cultivo predecesor sobre el segundo cultivo.

Tras este estudio, el Capítulo 4 evalúa el perfil medioambiental del cultivo de patata y trigo en Galicia (España). La producción intensiva de cultivos agrícolas tiene importantes consecuencias ambientales, por ello, el uso de un sistema productivo basado en la rotación de cultivos se considera como una alternativa adecuada para impulsar la sostenibilidad ambiental de los sistemas agrícolas. Al igual que el trigo, la papa también es un alimento básico importante. Este sistema de cultivo se basa en una rotación cada 3 años: el primer año corresponde al cultivo de patata (cultivo principal), seguido del trigo comercial en el segundo año y de una variedad de trigo nativo en el tercero. Para desarrollar los estudios de impacto ambiental se ha empleado la

metodología de ACV, considerándose cuatro tipos de unidades funcionales (UF): en términos de productividad (kg^{-1}); de superficie de cultivo (ha^{-1}·$año^{-1}$); en términos económicos (euros $€^{-1}$ de ingresos por ventas) y en valor energético (MJ^{-1}).

Los resultados ambientales del sistema de cultivo de patata-trigo de 3 años presentan un impacto de aproximadamente 2431 kg_{eq} de CO_2 para el cambio climático y 400 kg eq de petróleo para el agotamiento fósil por ha. Si comparamos los diferentes sistemas agrícolas, los resultados muestran que el trigo autóctono gallego tiene el mejor perfil medioambiental por ha^{-1}·$año^{-1}$, euros $€^{-1}$ de ingresos por ventas y MJ^{-1}, mientras que el cultivo de patata tiene el peor perfil, excepto en el uso de la tierra, debido a que el rendimiento productivo de la patata puede llegar a ser hasta 10 veces mayor que el del trigo. Los cultivos de patata utilizan más fertilizantes químicos, pesticidas y operaciones de campo que el trigo. Por otro lado, el cultivo de patata tiene los impactos ambientales más bajos por kg^{-1}, nuevamente debido a su alto rendimiento en comparación con el trigo. Además, el trigo comercial tiene más impactos ambientales que el trigo nativo, ya que también requiere más insumos agrícolas que el trigo nativo. Este capítulo demuestra la relevancia de utilizar la metodología de ACV para comprender y evaluar los impactos ambientales de los sistemas agrícolas regionales bajo un sistema de rotación de cultivos.

A diferencia de los capítulos 3 y 4 anteriores, el capítulo 5 analiza las consecuencias de los flujos residuales de las actividades agrícolas e industriales. Este capítulo investiga los impactos ambientales y económicos del rastrojo de maíz y la pulpa de remolacha azucarera como materia prima lignocelulósica con uso potencial como alimento (por ejemplo, como forraje o forraje) o como materia prima en procesos de fermentación industrial. Comprende cuatro escenarios: pulpa de remolacha en Francia (escenario 1) y Reino Unido (escenario 2), así como rastrojo de maíz en Italia (escenario 3) y Bélgica (escenario 4).

Una vez identificados los escenarios, se aplicó la metodología de ACV, considerando 1 GJ de biomasa como FU. Además, este capítulo también incluye un análisis desde el punto de vista económico, teniendo en cuenta los costes internos (es decir, los costes operativos - OPEX) y los costes externos (es decir, los costes ambientales). Además, también se ha desarrollado un análisis de incertidumbre para evaluar la robustez de las cifras ambientales y un análisis de sensibilidad para la producción de maíz, considerando cambios en la tasa de eliminación de rastrojo de 30% a 50%.

Los resultados de este estudio muestran que el rastrojo de maíz es el que da lugar a un menor impacto, tanto desde el punto de vista ambiental como económico. Para la categoría de impacto del cambio climático, por ejemplo, la producción de rastrojo de maíz en Italia es un 80% más baja en comparación con la pulpa de remolacha en el Reino Unido. En los escenarios de pulpa de remolacha, la mayoría de las emisiones ambientales provienen de la fase agrícola, que aporta el 67% y el 89% de las emisiones totales de CO_2 en Francia y Reino Unido, respectivamente. El análisis económico oscila entre los 22 € por 1 GJ producido, para el rastrojo de maíz en Italia, hasta los 174 €, para la remolacha azucarera en el Reino Unido. El rastrojo de maíz solo requiere un proceso agrícola para producirse, mientras que la pulpa de remolacha necesita un paso adicional de preprocesamiento. Además, el rastrojo de maíz tiene un poder calorífico mucho más alto: 16,5 $MJ{\cdot}kg^{-1}$ en comparación con la pulpa de remolacha azucarera (3,78 $MJ{\cdot}kg^{-1}$).

En lo que respecta a los resultados de análisis de sensibilidad, muestran un pequeño aumento, que no supera el 10%, en las categorías de impacto cuando la tasa de eliminación de los rastrojos aumentó del 30% al 50%. Además, los resultados del análisis de incertidumbre señalan la robustez de los resultados ambientales, con un coeficiente de variación inferior al 30% en todas las categorías de impacto, excepto en la

eutrofización de agua dulce, debido a la incertidumbre de los procesos de fondo.

Sección III: Contexto agrícola y bioproductos

Esta sección representa la sostenibilidad ambiental de los productos producidos en un contexto de base biológica, teniendo en cuenta varios bioproductos: glucosa (Capítulo 6), azúcares fermentables (Capítulo 7), ácido butírico (Capítulo 8) y metionina (Capítulo 9).

El Capítulo 6 evalúa el perfil ambiental de la producción de glucosa a partir de trigo en un contexto europeo. La mayoría de los estudios de ACV sobre biocombustibles o bioproductos evalúan el producto final, como el bioetanol, y pocos ponen énfasis en los procesos upstream, como es el caso de la obtención de glucosa, la cual puede ser empleada como fuente de azúcares en los medios de cultivo requeridos para los procesos industriales basados en sistemas de fermentación. Este ACV considera 1 kg de grano de trigo y 1 kg de glucosa como UF, que comprende 15 sistemas agrícolas en 9 países europeos. Dado que la producción de almidón a partir del proceso de molienda en húmedo produce residuos valiosos, como el salvado, harina y pienso, en este estudio se aplicaron asignaciones másicas y económicas.

En todos los países europeos analizados, las emisiones asociadas a las actividades agrícolas, la aplicación de fertilizantes y las operaciones de campo, son aquellas que han supuesto una contribución importante sobre el perfil ambiental del cultivo de trigo. En lo que respecta al uso de fertilizantes, su aplicación conduce a la emisión de sustancias que tienen un impacto negativo sobre el medio ambiente, como el óxido nitroso (N_2O) y el amoníaco (NH_3). Además, los sistemas agrícolas requieren un uso considerable de combustibles fósiles, como el diésel, para las operaciones de campo, lo cual también supone la emisión de sustancias contaminantes, como el dióxido de carbono (CO_2). Por tanto, los resultados muestran que las actividades agrícolas tienen un papel clave en el perfil ambiental de la producción de glucosa. En la fase de procesamiento de los granos, los procesos de calentamiento y electricidad presentan una influencia significativa en las categorías de impacto ambiental de cambio climático, eutrofización de agua dulce y agotamiento abiótico. Por otra parte, es importante mencionar que los resultados ambientales presentan variaciones en función del país considerado, principalmente debido a la carga de fertilizantes, las operaciones de campo y el perfil de la combinación de electricidad en cada país. En lo que respecta a los criterios de asignación considerados, la asignación económica implica un impacto mayor que la asignación másica de glucosa.

Es importante señalar que los Capítulos 3 y 4 también evaluaron el perfil ambiental del trigo, con énfasis en la agricultura regional y la comida tradicional, considerando principalmente datos primarios de entrevistas in situ, mientras que el Capítulo 6 ofrece una descripción general por país utilizando datos secundarios de la literatura.

El capítulo 7 se centra en el perfil medioambiental de la producción de materias primas y de su procesamiento, en el marco del proyecto STAR-ProBio (acuerdo de subvención núm. 727740). El grano de maíz, el rastrojo y la pulpa de remolacha azucarera son biomasas ricas en carbohidratos, lo cual las convierte en recursos valiosos para ser procesados para la obtención de azúcares fermentables, los cuales son esenciales en la producción biotecnológica de una variedad de bioproductos, como por ejemplo el ácido poliláctico (PLA) y el succinato de polibutileno (PBS).

El grano de maíz, un cultivo rico en almidón, clasificado como materia prima 1G, se convierte en azúcar fermentable (es decir, glucosa) a través de un primer pretratamiento de reducción de tamaño (molienda), seguido de una hidrólisis enzimática. En lo que respecta al rastrojo de maíz y a la pulpa de remolacha, son materias primas 2G y ricas en celulosa, que pueden procesarse para dar lugar a diferentes tipos de azúcares fermentables, a través de un primer proceso de pretratamiento para continuar con una hidrólisis enzimática.

En este estudio se consideraron veinte escenarios para azúcares fermentables. Se realizó una asignación económica para distribuir los impactos ambientales del maíz en grano, rastrojo y pulpa de remolacha azucarera. Posteriormente, se desarrolló un análisis de sensibilidad, modificando los parámetros necesarios con el objetivo de plantear, en este caso, una asignación másica, permitiéndose así evaluar la robustez de los resultados. Los resultados ambientales relacionados únicamente con la agricultura muestran que las emisiones derivadas de la producción agrícola, la fertilización química, las operaciones de campo y el transporte, son aquellos que muestran una mayor contribución sobre el perfil ambiental obtenido.

En la producción de azúcares fermentables a partir de rastrojos y principalmente pulpa de remolacha, las actividades agrícolas presentan una pequeña contribución, si se aplica la asignación económica. Por tanto, en base a los resultados obtenidos se concluye que la producción de azúcares fermentables a partir de pulpa de remolacha tiene menos impacto en comparación con su producción a partir de maíz en grano o rastrojo. Por otra parte, los resultados ambientales de los azúcares de grano de maíz no mostraron una gran sensibilidad a la variación al cambiar los parámetros de la asignación económica a la másica, en contraposición con lo que se observó para la pulpa de remolacha o el rastrojo de maíz.

El capítulo 8 explora el perfil medioambiental del ácido butírico de origen biológico como alternativa al de origen fósil. El ácido butírico es una sustancia química de alto valor añadido, con infinidad de aplicaciones en los sectores químico, alimentario, farmacéutico y cosmético. Sin embargo, debido a las ventajas tecnológicas, actualmente el ácido butírico se produce industrialmente por medios químicos. Este capítulo evalúa el perfil ambiental de la producción de ácido butírico a partir de la paja de trigo, concretamente la variedad de trigo gallego introducida en el Capítulo 4 de esta tesis, una materia prima lignocelulósica. Se evaluaron dos formulaciones de producto: ácido butírico producido en combinación con ácido acético y ácido butírico de alta pureza. Una vez obtenidos los perfiles ambientales de las alternativas de producción propuestas, se aplicaron dos análisis de sensibilidad, el primero de ellos basado en la substitución del perfil energético convencional a energía 100% renovable, y el segundo considerando el empleo de materias primas lignocelulósicas alternativas, como la pulpa de remolacha azucarera y rastrojo de maíz.

Los resultados de esta evaluación muestran que la producción de ácido butírico en combinación con ácido acético es el mejor escenario, debido a la menor cantidad de energía e insumos utilizados. Además, para ambas formulaciones de ácido butírico, muestra que la producción de vapor, la electricidad y el cóctel enzimático de celulasa, se identifican como los principales contribuyentes sobre los perfiles ambientales obtenidos. En lo que respecta a los resultados obtenidos de los análisis de sensibilidad, el uso de energía 100% renovable ha reducido considerablemente la carga ambiental del ácido butírico. Sin embargo, la pulpa de remolacha o el maíz como sustituto de la paja de trigo no ha alterado significativamente los impactos ambientales globales.

El Capítulo 9 evalúa el perfil ambiental de la metionina, un aminoácido esencial que, como el ácido butírico en el Capítulo 8, puede producirse por síntesis química. Sin embargo, la metionina producida químicamente es indeseable utiliza sustancias químicas peligrosas como acroleína, metilmercaptano, amoníaco y cianuro, que son tóxicas y nocivas para la salud humana y para el ecosistema. Además, la metionina por fermentación produce L-metionina, que se considera de mejor calidad que la mezcla de D y L metionina producida químicamente. Para el desarrollo del estudio ambiental, se han considerado tres escenarios de producción de metionina: 1) Metionina a través de una vía química, 2) Metionina por fermentación microbiana y 3) Metionina por fermentación microbiana y digestión anaeróbica de residuos biológicos.

Los resultados muestran que la producción de metionina por fermentación microbiana con digestión anaeróbica tiene los impactos ambientales más bajos, mientras que la metionina a través de síntesis química es un proceso altamente contaminante. Por ejemplo, las emisiones de CO_2 relacionadas con la síntesis química son aproximadamente 3 veces más altas que las asociadas con la fermentación microbiana. El uso de la digestión anaeróbica para revalorización energética y generación de nitrógeno para su empleo como fertilizante, redujo considerablemente las cargas ambientales de metionina microbiana.

Sección IV: Conclusiones

Esta sección proporciona los principales hallazgos, contribuciones de la tesis y recomendaciones. El Capítulo 10 ofrece una visión general del trabajo desarrollado a lo largo de esta tesis, señalando las principales conclusiones identificadas en las diferentes secciones y capítulos, incluyéndose una serie de recomendaciones para mejorar la sostenibilidad de los bioproductos. Este trabajo proporciona una documentación completa a través de la aplicación extensiva de la metodología de ACV en cultivos agrícolas, alimentos y productos biológicos, facilitándose así una comprensión amplia del perfil de sostenibilidad de los productos analizados en esta tesis (trigo, maíz, papa, rastrojo de maíz, pulpa de remolacha azucarera, azúcares fermentables, ácido butírico y metionina), así como aquellos aspectos que deben tenerse en cuenta para mejorar los procesos. Para ello, se

identificaron y evaluaron aquellos procesos y aquellas sustancias que suponían una mayor contribución ambiental, con el fin de encontrar soluciones para reducir las cargas ambientales.

RESUMO

O crecemento da poboación e da renda per cápita xerou un incremento significativo no consumo de recursos, especialmente nos de orixe fósil, provocando varias crises ecolóxicas. Os sistemas agrícolas evolucionaron e modernizáronse nos últimos anos para poder responder ao rápido crecemento da poboación. Non obstante, este desenvolvemento agrícola alcanza un límite debido á intensa mecanización, ao uso xeneralizado de fertilizantes químicos e pesticidas, ao uso da terra e da auga. Por iso, é importante atopar alternativas que promovan o desenvolvemento dunha produción máis sostible, á vez que se garanta a seguridade alimentaria e a saúde humana, así como a dos ecosistemas, tendo en conta os impactos ambientais asociados.

A preocupación ambiental polo uso de fontes non renovables deu lugar á necesidade de buscar novas alternativas de produción baseadas en materias primas renovables, entre as que destaca o uso de biomasa, sendo este un recurso idóneo para a produción de biocombustibles e bioprodutos. Deste xeito, pódense establecer dúas categorías dependendo do tipo de biomasa empregada: a primeira xeración (1G), como os cultivos de almidón (por exemplo, millo e grans de trigo), que compiten cos mercados de alimentos/pensos. E segunda xeración, incluíndo nesta categoría residuos de transformación agrícola e industrial, que tamén son de especial interese para o seu uso en procesos de fermentación industrial, aínda que ata a data teñen menos vantaxes tecnolóxicas respecto á biomasa 1G.

A bioeconomía e a economía circular son conceptos clave para promover o desenvolvemento de procesos de produción máis sostibles, que promovan o cumprimento, por parte dos gobernos, dos compromisos e iniciativas da Axenda 2030, os ODS das Nacións Unidas e o Acordo de París, entre outros. Neste contexto, a valorización

de produtos agrícolas e biolóxicos convértese nunha alternativa adecuada para promover un desenvolvemento sostible. Deste xeito, o principal obxectivo desta tese de doutoramento é a avaliación dos impactos ambientais e económicos dos bioprodutos, considerando os produtos alimenticios e biolóxicos, utilizando a metodoloxía de Análise do Ciclo de Vida (ACV). Este documento dividiuse en catro seccións: I) Contextualización, II) Contexto agrícola e alimentario, III) Contexto agrícola e bioprodutos e IV) Conclusións.

Sección I - Contextualización

Esta sección, que comprende os capítulos 1 e 2, ofrece unha visión xeral dos marcos de economía circular e bioeconomía e das materias primas empregadas para a produción de alimentos ou bioprodutos para esta tese (capítulo 1). Ademais, tamén se inclúen os métodos empregados para desenvolver a análise ambiental e económica das diferentes alternativas de produción propostas nesta tese de doutoramento (capítulo 2).

O capítulo 1 considérase unha sección introdutoria onde se describe a importancia da economía circular e da bioeconomía para reducir os impactos ambientais xerados polos procesos de produción convencionais, os baseados en recursos fósiles e, á súa vez, mellorar a calidade de vida e o benestar humano. Destaca a necesidade de combinar estes dous conceptos para lograr unha "bioeconomía circular", un novo termo centrado na protección do medio ambiente e na xeración de novas oportunidades económicas a partir do desenvolvemento de produtos de base biolóxica capaces de substituír os convencionais, baseados en recursos non renovables. Por outra banda, tamén se introduce o concepto de biorrefinería, que inclúe unha análise das diferentes materias primas que se poden empregar como insumos para o proceso, dende a primeira xeración ata a cuarta xeración. Este capítulo tamén ofrece unha visión xeral de catro principais cultivos agrícolas: trigo, millo, remolacha azucreira e patacas, considerados produtos agrícolas importantes en todo o mundo debido aos seus grandes volumes de produción e consumo. O desenvolvemento dos procesos de produción biotecnolóxica a partir destes cultivos será o principal obxectivo desta tese, incluíndo tamén os residuos, xa sexa para a produción de alimentos ou de produtos biolóxicos.

O capítulo 2 inclúe un resumo da historia da sustentabilidade dende o século XIX ata a actualidade. Ademais, tamén se identifican as metodoloxías dispoñibles para a avaliación dos impactos xerados polas actividades de acción humana sobre a sustentabilidade, sendo a Análise do Ciclo de Vida (ACV) a principal metodoloxía empregada nesta tese. Ademais, tamén se abordaron as avaliacións económicas das diferentes alternativas propostas, aínda que en menor medida, incluíndose cálculos dos custos ambientais asociados aos procesos biotecnolóxicos propostos.

Sección II: contexto agrícola e alimentario

Esta sección ten como obxectivo vincular os impactos ambientais e os indicadores económicos da agricultura desde a perspectiva da produción de produtos alimentarios. A avaliación da sustentabilidade ambiental dos cultivos agrícolas e dos cultivos procesados para a produción de alimentos desenvólvese nos capítulos 3 e 4, mentres que o perfil ambiental e económico dos residuos industriais e agrícolas se aborda no capítulo 5.

O capítulo 3 explora, desde a perspectiva do ciclo de vida, a sustentabilidade ambiental do cultivo de trigo e da produción de pan na rexión galega, situada en España. Este tipo de pan é unha combinación de grans de trigo autóctonos de Galicia e trigo comercial español, no que o trigo galego proporciona ese aroma característico do pan, mentres que o trigo comercial proporciona o volume adecuado. Trátase, por

tanto, de avaliar os impactos ambientais dun produto artesán, onde a calidade do cereal e do produto son obxectivos primordiais. Dada a importancia do cultivo de cereais sobre a calidade do produto final, propuxéronse catro sistemas de cultivo diferentes: 1) trigo galego cultivado baixo un sistema de monocultivo; 2) Trigo galego cultivado baixo un réxime de rotación de cultivos; 3) produción de semente galega certificada e 4) cultivo comercial de trigo español. Avaliáronse dous escenarios, o primeiro céntrase en facer pan a partir de grans de trigo producidos nun sistema de rotación de cultivos, mentres que o segundo escenario considera a produción agrícola monocultiva.

Ao comparar os diferentes sistemas agrícolas (considerando 1 kg de trigo transportado como unidade funcional), os valores ambientais obtidos mostran menores impactos ambientais para o primeiro escenario, que propón un sistema de produción centrado na rotación de cultivos. Por outra banda, identificouse que o cultivo comercial de trigo é o que da lugar a unha maior contribución ambiental en todas as categorías de impacto, a excepción do cambio climático. En canto ao segundo escenario, o que considerou a produción de trigo galego no monocultivo, é o que presentou un maior valor de impacto na categoría de cambio climático, identificando as actividades de fertilización con nitróxeno e as operacións necesarias para a aplicación de agroquímicos, como as principais causas que orixinan unha elevada achega ambiental.

Por outra banda, a análise do ciclo de vida do proceso de produción de pan permitiu concluír que o cultivo de trigo é o principal contribuínte ao perfil ambiental obtido, representando máis do 50% en todas as categorías de impacto. O pan galego que usa grans de trigo autóctonos nun sistema de rotación de cultivos ten un mellor perfil ambiental que o pan que usa grans de trigo nun sistema de monocultivo. Polo tanto, os produtores de moenda e panadaría deberían considerar o desenvolvemento de sistemas de produción baseados na rotación de cultivos, dada a importante contribución ambiental que a produción

agrícola implica unicamente centrada na obtención dun único cultivo de grans de trigo.

Os produtos patrimoniais alimentarios como o pan galego adoitan representar elementos tradicionais de calidade indiscutible, que teñen aspectos esenciais da tradición e da identidade cultural. Aínda que parecen insignificantes a nivel mundial, estes produtos son de gran importancia para a sociedade, a economía e a cultura locais, polo tanto, a adaptación e modificación dos sistemas de produción agrícola é un factor clave para o desenvolvemento de sistemas de produción máis sostibles.

Cabe mencionar que no capítulo 3 non se consideraron as complexas interaccións dos sistemas de cultivo nin os efectos que o cultivo predecesor ten sobre o segundo cultivo.

Tras este estudo, o capítulo 4 avalía o perfil ambiental do cultivo de pataca e trigo en Galicia (España). A produción intensiva de cultivos agrícolas ten importantes consecuencias ambientais, polo tanto, o uso dun sistema de produción baseado na rotación de cultivos considérase unha alternativa adecuada para promover a sustentabilidade ambiental dos sistemas agrícolas. Este sistema de cultivo baséase nunha rotación cada 3 anos: o primeiro ano corresponde ao cultivo de pataca (cultivo principal), seguido do trigo comercial no segundo ano e unha variedade de trigo autóctono no terceiro. Para desenvolver os estudos de impacto ambiental, empregouse a metodoloxía LCA, considerando catro tipos de unidades funcionais (FU): en termos de produtividade (kg^{-1}); área de cultivo ($ha^{-1} \cdot ano^{-1}$); en termos económicos ($€^{-1}$ de ingresos por vendas) e en valor enerxético (MJ^{-1}).

Os resultados ambientais do sistema de cultivo de pataca e trigo de 3 anos amosan un impacto de aproximadamente 2431 kg eq de CO_2 para o cambio climático e 400 kg eq de petróleo para o esgotamento de fósiles por ha. Se comparamos os diferentes sistemas agrícolas, os resultados mostran que o trigo autóctono galego ten o mellor perfil ambiental por ha^{-1} · ano^{-1}, € $^{-1}$ de ingresos por vendas e MJ^{-1}, mentres que o cultivo de pataca ten o peor perfil, agás no uso da terra, porque o rendemento produtivo das patacas pode ser ata 10 veces maior que o do trigo. Os cultivos de pataca usan máis fertilizantes químicos, pesticidas e operacións de campo que o trigo. Por outra banda, o cultivo de pataca ten os impactos ambientais máis baixos por kg^{-1}, de novo, debido ao seu alto rendemento en comparación co trigo. Ademais, o trigo comercial ten máis impactos ambientais que o trigo nativo, xa que tamén require máis insumos agrícolas que o trigo nativo. Este capítulo demostra a relevancia do uso da metodoloxía LCA para comprender e avaliar os impactos ambientais dos sistemas agrícolas rexionais baixo un sistema de rotación de cultivos.

A diferenza dos capítulos 3 e 4 anteriores, o capítulo 5 analiza as consecuencias dos fluxos residuais das actividades agrícolas e industriais. Este capítulo investiga os impactos ambientais e económicos dos restos de millo e da pasta de remolacha azucreira como materia prima lignocelulósica cun potencial uso como alimento (por exemplo, forraxe) ou como materia prima nos procesos de fermentación industrial. Comprende catro escenarios: pasta de remolacha en Francia (escenario 1) e Reino Unido (escenario 2), así como restos de millo en Italia (escenario 3) e Bélxica (escenario 4). Unha vez identificados os escenarios, aplicouse a metodoloxía LCA, considerando 1 GJ de biomasa como FU. Ademais, este capítulo tamén inclúe unha análise desde o punto de vista económico, tendo en conta os custos internos (é dicir, os custos operativos - OPEX) e os custos externos (é dicir, os custos ambientais). Ademais, tamén se desenvolveu unha análise de incerteza para avaliar a solidez das cifras ambientais e unha análise de sensibilidade para a produción de millo, considerando cambios na taxa de eliminación de restos do 30% ao 50%.

Os resultados deste estudo mostran que a restra de millo ten o menor impacto, tanto desde o punto de vista ambiental como económico. Para a categoría de impacto do cambio climático, por exemplo, a produción de restos de millo en Italia é un 80% menor en comparación coa pasta de remolacha do Reino Unido. Nos escenarios de pasta de remolacha, a maioría das emisións ambientais proceden da fase agrícola, que achega o 67% e o 89% das emisións totais de CO_2 en Francia e o Reino Unido, respectivamente. A análise económica oscila entre os 22 € por 1 GJ producido, para os restos de millo en Italia, ata os 174 € da remolacha azucarera no Reino Unido. Os restos de millo só requiren un proceso agrícola para producirse, mentres que a pasta de remolacha precisa un paso adicional de pre-procesado. Ademais, os restos de millo teñen un poder calorífico moito maior: 16,5 $MJ \cdot kg^{-1}$ en comparación coa pasta de remolacha azucarera (3,78 $MJ \cdot kg^{-1}$).

En canto aos resultados da análise de sensibilidade, mostran un pequeno aumento, non superior ao 10%, nas categorías de impacto cando a taxa de eliminación de restos aumentou do 30% ao 50%. Ademais, os resultados da análise de incerteza indican a solidez dos resultados ambientais, cun coeficiente de variación inferior ao 30% en todas as categorías de impacto, agás na eutrofización de auga doce, debido á incerteza dos procesos de fondo.

Sección III: Contexto agrícola e bioprodutos

Esta sección representa a sustentabilidade ambiental dos produtos producidos nun contexto de base biolóxica, tendo en conta varios subprodutos: glicosa (capítulo 6), azucres fermentables (capítulo 7), ácido butírico (capítulo 8) e metionina (capítulo 9).

O capítulo 6 avalía o perfil ambiental da produción de glicosa a partir do trigo nun contexto europeo. A maioría dos estudos de ACV sobre biocombustibles ou bioprodutos avalían o produto final, como o bioetanol, e poucos fan énfase nos procesos de upstream, como é o caso da obtención de glicosa, que pode usarse como fonte de azucres nos medios de cultivo necesarios para procesos industriais baseados sobre sistemas de fermentación. Este ACV considera 1 kg de gran de trigo e 1 kg de glicosa como UF, que comprende 15 sistemas agrícolas en 9 países europeos. Dado que a produción de almidón a partir do proceso de moenda en húmido produce residuos valiosos, como farelo, fariña e penso, neste estudo aplicáronse asignacións económicas e de masa.

En tódolos países europeos analizados, as emisións asociadas ás actividades agrícolas, a aplicación de fertilizantes e as operacións de campo son as que contribuíron de xeito importante ao perfil ambiental do cultivo de trigo. En canto ao uso de fertilizantes, a súa aplicación leva á emisión de substancias que teñen un impacto negativo sobre o medio ambiente, como o óxido nitroso (N_2O) e o amoníaco (NH_3). Ademais, os sistemas agrícolas requiren un uso considerable de combustibles fósiles, como o diésel, para operacións de campo, o que tamén implica a emisión de contaminantes, como o dióxido de carbono (CO_2). Polo tanto, os resultados amosan que as actividades agrícolas xogan un papel clave no perfil ambiental da produción de glicosa. Na fase de procesamento de grans, os procesos de intercambio calorífico e electricidade inflúen de forma significativa nas categorías de impacto ambiental do cambio climático, a eutrofización da auga doce e o esgotamento abiótico. Por outra banda, é importante mencionar que os resultados ambientais mostran variacións dependendo do país considerado, principalmente debido á carga de fertilizante, ás operacións de campo e ao perfil do mix eléctrico en cada país. En canto aos criterios de asignación considerados, a asignación económica implica un maior impacto que a asignación másica de glicosa.

É importante ter en conta que os capítulos 3 e 4 tamén avaliaron o perfil ambiental do trigo, con énfase na agricultura rexional e na comida tradicional, considerando principalmente os datos primarios das entrevistas in situ, mentres que o capítulo 6 ofrece unha visión xeral por país empregando datos secundarios.

O capítulo 7 céntrase no perfil ambiental da produción e procesamento de materias primas no marco do proxecto STAR-ProBio (acordo de subvención no 727740). O gran de millo, o restrollo e a pasta de remolacha azucreira son biomasas ricas en hidratos de carbono, o que as converten en valiosos recursos para procesar e para obter azucres fermentables, que son esenciais na produción biotecnolóxica dunha variedade de bioprodutos, como o ácido poliláctico (PLA) e o succinato de polibutileno (PBS).

O gran de millo, un cultivo rico en almidón, clasificado como materia prima 1G, convértese en azucre fermentable (é dicir, glicosa) mediante un primeiro tratamento de redución de tamaño (moenda), seguido de hidrólise encimática. En canto a restos de millo e pasta de remolacha, son materias primas 2G e ricas en celulosa, que se poden procesar para dar lugar a diferentes tipos de azucres fermentables, mediante un primeiro proceso de pretratamento para continuar cunha hidrólise encimática.

Neste estudo consideráronse vinte escenarios para os azucres fermentables. Fíxose unha asignación económica para distribuír os impactos ambientais dos grans de millo, restos e polpa de remolacha azucreira. Posteriormente, desenvolveuse unha análise de sensibilidade, modificando os parámetros necesarios para propoñer, neste caso, unha asignación másica, permitindo así avaliar a solidez dos resultados. Os resultados ambientais relacionados só coa agricultura mostran que as emisións derivadas da produción agrícola, a fertilización química, as operacións de campo e o transporte son as que amosan unha maior contribución ao perfil ambiental obtido, concluíndo así que as actividades agrícolas son a principal causa dos impactos xerados. Non obstante, na produción de azucres fermentables a partir de restos e, principalmente de pasta de remolacha, as actividades agrícolas presentan unha pequena contribución, se se aplica a asignación económica. Polo tanto, baseándose nos resultados obtidos, conclúese que a produción de azucres fermentables a partir de pasta de remolacha ten menos impacto en comparación coa súa produción a partires de millo en grans ou restos. Por outra banda, os resultados ambientais dos azucres dos grans de millo non mostraron gran sensibilidade á variación dos parámetros da asignación económica a másica, en contraste co que se observou para a pasta de remolacha ou o restrollos do millo.

O capítulo 8 explora o perfil ambiental do ácido butírico de orixe biolóxica como alternativa ao de orixe fósil. O ácido butírico é unha substancia química de alto valor engadido, con infinidade de aplicacións nos sectores químico, alimentario, farmacéutico e cosmético. Non obstante, debido ás vantaxes tecnolóxicas, o ácido butírico prodúcese actualmente industrialmente por medios químicos. Este capítulo avalía o perfil ambiental da produción de ácido butírico a partir de palla de trigo, concretamente a variedade de trigo galega introducida no capítulo 4 desta tese, unha materia prima lignocelulósica. Avaliáronse dúas formulacións de produtos: o ácido butírico producido en combinación con ácido acético e o ácido butírico de alta pureza. Unha vez obtidos os perfís ambientais das alternativas de produción propostas, aplicáronse dúas análises de sensibilidade, a primeira baseada na substitución do perfil enerxético convencional por 100% de enerxía renovable e a segunda considerando o uso de materias primas lignocelulósicas alternativas, como a pasta de remolacha e restrollos de millo. Os resultados desta avaliación mostran que a produción de ácido butírico en combinación con ácido acético é o mellor escenario, debido á menor cantidade de enerxía e insumos empregados. Ademais, para ambas formulacións de ácido butírico, a produción de vapor, electricidade e o cóctel encimático de celulasas identifícanse como os principais contribuíntes aos perfís ambientais obtidos. En canto aos resultados obtidos das análises de sensibilidade, o uso de enerxía 100% renovable reduciu considerablemente a carga ambiental de ácido butírico. Non obstante, a pasta de remolacha ou o millo como substitutos da palla de trigo non alteraron significativamente os impactos ambientais globais.

O capítulo 9 avalía o perfil ambiental da metionina, un aminoácido esencial que, como o ácido butírico, pode producirse por síntese química. Non obstante, a metionina producida químicamente emprega produtos químicos perigosos como a acroleína, o metil mercaptano, o amoníaco e o cianuro, que son tóxicos e prexudiciais para a saúde humana e o ecosistema. Ademais, a metionina por fermentación produce L-metionina, que se considera de mellor calidade que a mestura producida químicamente de D e L metionina. Para o desenvolvemento do estudo ambiental, consideráronse tres escenarios de produción de metionina: 1) Metionina a través dunha vía química, 2) Metionina por fermentación microbiana e 3) Metionina por fermentación microbiana e dixestión anaerobia de residuos biolóxicos.

Os resultados mostran que a produción de metionina mediante fermentación microbiana con dixestión anaerobia ten os impactos ambientais máis baixos, mentres que a metionina a través da síntese química é un proceso altamente contaminante. Por exemplo, as emisións de CO_2 relacionadas coa síntese química son aproximadamente 3 veces superiores ás asociadas á fermentación microbiana. O uso da dixestión anaerobia para a revalorización da enerxía e a xeración de nitróxeno para o seu uso como fertilizante, reduciu considerablemente as cargas ambientais de metionina microbiana.

Sección IV: Conclusións

Esta sección ofrece os principais descubrimentos, contribucións da tese e recomendacións. O capítulo 10 ofrece unha visión xeral do traballo

desenvolvido ao longo desta tese, sinalando as principais conclusións identificadas nas diferentes seccións e capítulos, incluíndo unha serie de recomendacións para mellorar a sustentabilidade dos bioprodutos. Este traballo proporciona unha documentación completa a través da aplicación extensa da metodoloxía ACV en cultivos agrícolas, alimentos e produtos biolóxicos, facilitando así unha comprensión ampla do perfil de sustentabilidade dos produtos analizados nesta tese (trigo, millo, pataca, millo de restos, azucre polpa de remolacha, azucres fermentables, ácido butírico e metionina), así como aqueles aspectos que se deben ter en conta para mellorar os procesos. Para iso, identificáronse e avaliáronse aqueles procesos e substancias que deron lugar a unha maior contribución ambiental, co fin de atopar solucións para reducir as cargas ambientais.


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SECTION I

CONTEXTUALIZATION


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CHAPTER 1: GENERAL INTRODUCTION

SUMMARY

Population and income growth have led to the excessive use of resources, especially those of fossil origin, putting great pressure on the environment. Food and agricultural systems have developed over time to meet this growing demand from the population. However, this growth, which is accompanied by intense mechanization, increased use of agrochemicals, land and water, is reaching its limits. It is therefore imperative to find ways to improve production, safeguarding food security and human health, while mitigating the associated environmental consequences.

The pressure on the environment due to the use of fossil resources has also led to the reintroduction of the use of renewable biomass for the production of biofuels and bio-based products. Due to the technological advantage, most of these raw materials are first generation (1G) feedstocks, those that compete with food, such as wheat and maize grains. However, in order not to jeopardize food security, efforts have been made to use agricultural and processing residues, such as lignocellulosic biomass. Despite notable efforts in sustainable agriculture and bio-based products, future research is essential to project environmental, socially and economically viable strategies, and ultimately, make bioeconomy and circular economy a standard in our society.

Chapter 1 emphasizes the importance of applying the concepts of circular economy and bioeconomy to reduce pressure on the environment and improve human well-being and ecosystem preservation. The thesis is divided into two main approaches: one has as its focal point the production of agricultural crops, residues and food products and the other focuses on the bio-based products from the

valorisation of agricultural crops or residues from industrial processing. Throughout the thesis, the environmental sustainability of these two approaches is assessed. Finally, an integrated overview of the main results and contributions of the thesis is presented.

1.1 THE CIRCULAR BIOECONOMY CONCEPT

With the increasing use of fossil resources, impacts on the ecosystem and human health, renewable raw materials appear as a fundamental source to overcome mankind's existing and future problems. The bioeconomy is a relatively new concept that has attracted the attention of governments and scientific communities and whose main direction is the shift from fossil-based products to biobased products and bioenergy. The bioeconomy is considered a key solution to many environmental problems that we face today, in particular, climate change (Bugge et al., 2016).

According to the European Commission, bioeconomy "*means using renewable biological resources from land and sea, such as crops, forests, fish, animals and microorganisms to produce food, materials and energy*". However, these renewable biological sources do not represent organic biomass from geological times, such as fossil fuels. The implementation of bioeconomy will help ensure the transition to circular and low-carbon economies. Moreover, bioeconomy is expected to improve ecosystem and human health, make sustainable value chains and industrial processes more environmentally friendly (European Commission, n.d.).

The bioeconomy encompasses ***food/feed systems***, such as agricultural crops; ***biofuels***, which are fuels produced from renewable biomass (e.g., sugar cane ethanol or wood energy); and ***bio-based products***, which are products made from partially or fully renewable feedstocks that are not intended for food, feed and biofuels. However, it is important to note that bio-based products also refer to food/feed products that were initially made from chemical synthesis but followed a bio-based route in their production process. In this thesis, ***"bioproduct"*** refers to all products that are made from renewable biomass, which comprises food/feed, biofuels and bio-based products.

Bio-based products and biofuels are not new concepts, as energy wood and fibres for clothing have been traditionally used for millennia. However, many new types of bioproducts are emerging for many functionalities, such as food ingredients, cosmetics, medicines and in the construction and automotive industries (Gomez San Juan et al., 2019). The concept of bioeconomy is often misunderstood, and it is important to know that bioeconomy alone is not necessarily sustainable. The use of renewable resources can benefit or harm the ecosystem and society. A good example is the issue of food security, land use change and biodiversity loss. Therefore, the bioeconomy must be properly managed in a sustainable and robust way.

In order to have a sustainable bioeconomy, strategies, such as the principles of the circular economy, must be implemented. The bioeconomy and circular economy are two complementary strategies that are considered as a panacea for achieving sustainability. Some studies are now integrating these two concepts into the “circular bioeconomy” (EEA, 2018). The circular economy is a very popular concept, which is based on three basic principles: 1) using waste as a valuable raw material and avoiding pollution; 2) maintaining circularity in the process, that is, reusing materials and energy as much as possible; and 3) regenerating natural systems (EMAF, 2013). The circular economy approach refuses the linear model of “take, make and dispose” and embraces the circular model of “make, use, reuse and recycle”.

In recent years, bioeconomy policies have gained worldwide attention. About 49 countries have included bioeconomy strategies in their policy agendas (Bioökonomierat, 2020). Furthermore, the bioeconomy strategy of the European Commission certifies the importance of integrating the bioeconomy and the circular economy (European Commission, 2018), fostering most European countries to adopt principles of the circular economy in their bioeconomy policy agendas (Stegmann et al., 2020). Figure 1.1 portrays the principles of a circular bioeconomy.

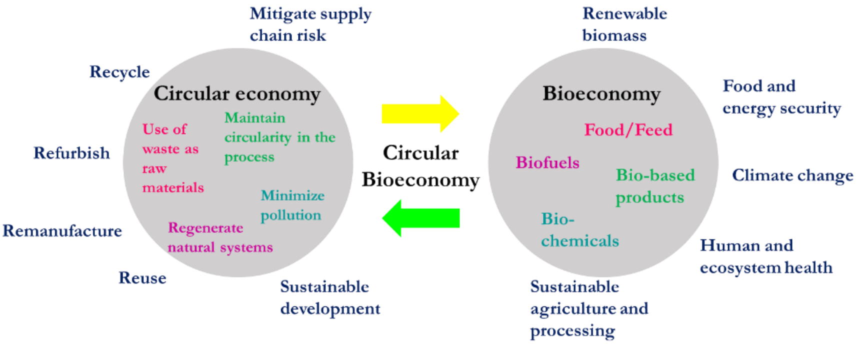

Figure 1.1 Circular bioeconomy scheme.

1.1.1. The biorefinery concept

The biorefinery concept emerges as a strategy to achieve a circular economy. It arises to increase the use of renewable biomass in contrast to fossil fuels, and also to avoid waste and environmental emissions in the production process (Ubando et al., 2020). According to the International Energy Agency (IEA) (IEA, 2012), “*Biorefinery is the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)*”.

The biorefinery concept is a facility that encompasses a broad array of technologies capable of fractioning renewable resources (e.g., maize, wheat, wood) into intermediate feedstocks (e.g. C5-C6 carbohydrates, proteins, oils), which are used in the production of bioproducts (Cherubini, 2010).

A biorefinery is classified into 4 systems (IEA, 2012): 1) Feedstocks, namely the renewable raw material, such as starch and sugar crops, lignocellulosic biomass and industrial waste; 2) Platforms, which are the key intermediate feedstocks in the production of bioproducts; 3) Products, which are the intended final product (food/feed, biofuels, bio-based products); and 4) Technologies, which can be divided into physical, chemical, thermochemical and biochemical processes (Figure 1.2).

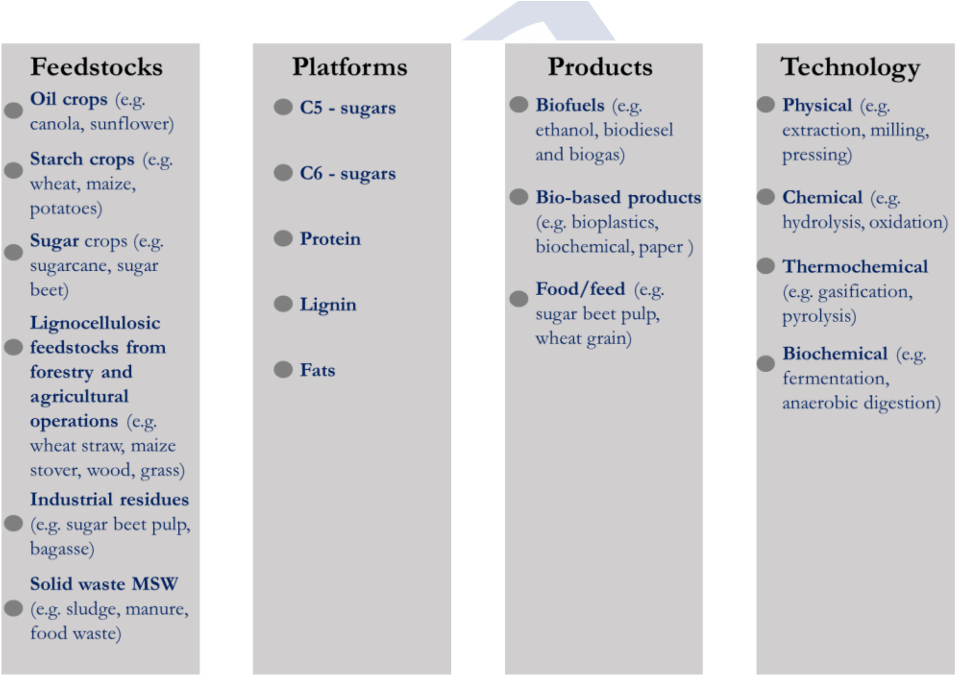

Figure 1.2 Example of a biorefinery system classification.

There are multiple feedstocks that can be used as alternative to fossil fuels and as raw materials in biorefineries. These raw materials are classified into 1) First-generation (1G) feedstocks, which are edible biomass, such as starch crops (e.g., wheat and maize grains); sugar crops (e.g., sugarcane and sugar beet); and oil crops (e.g., sunflower, canola). However, 1G biomass faces the challenge of competing with the food and feed markets, which can affect food prices and compromise food security and land use; 2) Second-generation (2G) feedstocks, that are non-edible lignocellulosic biomass from agricultural and forestry operations, such as maize stover, wheat straw, sugarcane straw, wood and grass. 2G feedstocks also includes residues from industrial operations, such as beet pulp from the beet sugar production process or bagasse from the cane sugar production process; 3) Third-generation (3G) feedstocks, which are algae biomass, namely micro and macroalgae. The cultivation of algae has advantages over 1G and 2G feedstocks, as it does not require arable land and there is no competition with food products; and 4) Fourth generation (4G) feedstocks are bio-engineering biomass that store carbon dioxide. They are able to produce energy while capturing and storing carbon dioxide (Moncada et al., 2016). The next section gives an overview of the feedstocks used in this thesis.

1.2 GENERAL OVERVIEW OF FEEDSTOCKS

Agriculture is a milestone in human history and began with the domestication of plants and animals about 10,000 years ago. Nomadic life slowly disappeared as civilizations grew over the agricultural evolution (Tauger, 2010). Since then, society has gone through several agricultural revolutions. We became dependent on plant and animal domestication, which triggered environmental implications, such as deforestation, pollution, water depletion and loss of biodiversity. Agriculture also shaped commerce, architecture, labour division, and political systems. Today, agriculture continues to shape modern civilizations and it is recognized for its intense mechanization and bioengineering (Herrera and Garcia-Bertrand, 2018). At Present, most of the human diet is dominated by a few crops that have a long history of specialization and domestication.

Since 1960, agricultural production has more than tripled. In the supply and value chain, there is no limit to the physical distance from agricultural production to food supply. In addition, food is increasingly processed and packaged, especially in large urban centres and developed regions. It is estimated that about half of the Earth's forests have been destroyed, resulting in a major loss of biodiversity, which is a major concern of this century. Modern agriculture is responsible for many of these environmental problems, mainly through deforestation, which leads to the destruction of ecosystems and the use of agrochemicals, responsible for a large part of greenhouse gas emissions (FAO, 2017).

There are many possible paths in the supply chain for agricultural systems, depending on the final product to be produced. Agricultural commodities are used as food and feed, but also as an input for the production of bio-based products and biofuels, as illustrated in Figure 1.3. As noted, edible feedstocks, such as maize, can serve as food/feed and also for non-edible purposes, such as bioplastic or bioethanol. Residues from maize crop, namely maize stover, can also be valuable as raw material for industrial fermentation processing, or as animal fodder. Industrial residues, such as beet pulp produced in the sugar beet production process, can also serve as biomass for the production of bio-based products or biofuels and for animal feed.

Maize, wheat, potato and sugar beet are considered important agricultural commodities worldwide. Maize, wheat and potatoes are valuable starch crops that are used for the production of many types of food and feed, while sugar beet is used primarily for the production of sucrose. This thesis focuses on these four cultures, including some of their residues, since most of this research is concentrated on the use of these raw materials, whether for agriculture, food production or for the production of bio-based products.

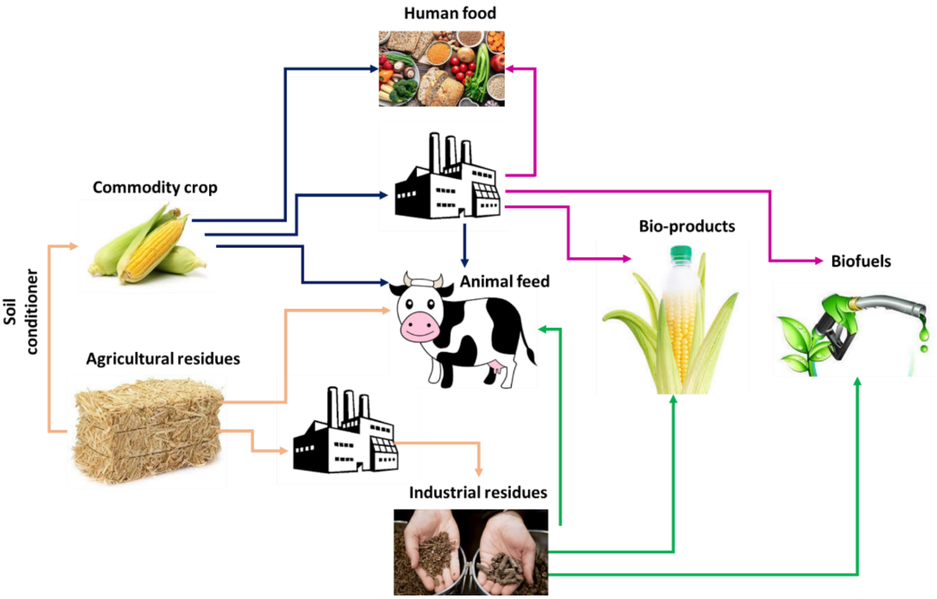

Figure 1.3 Pathways to agricultural food/feed production and bio-based products/biofuels.

1.2.1 Wheat

Wheat cultivation has been improved and developed over thousands of years along with the evolution of many civilizations (Curtis et al., 2002). This staple crop has a global average annual production of about 765 million tons and 215 million hectares of harvested area (FAOSTAT, 2019). Due to the long history of wheat cultivation and its importance to society, the composition and genetics of wheat are well known. Wheat composition varies according to geographical, climatic conditions and type of agricultural management (De Matos et al., 2015).

Considering average values, wheat is composed of 70% starch (carbohydrates) and 10% protein (Haard, 1999).

Beyond the use of wheat in the food sector, in the last decade, wheat grain has been investigated and targeted for industrial purposes (i.e., biofuels and bio-based products). A wide range of wheat-based products is available on the market, such as food, feed, biofuels, biochemicals, pharmaceuticals and bioplastics. As shown in Figure 1.4, wheat endosperm can be converted into starch and gluten: the former can be processed into food (e.g. food additives, sweeteners), paper, textiles, biofuels (e.g. ethanol) and bio-based products (e.g. bioplastics); the latter can also be converted into food (e.g. artificial meat, pet food, flour fortification) and bio-based products (Achten and Van Acker, 2016).

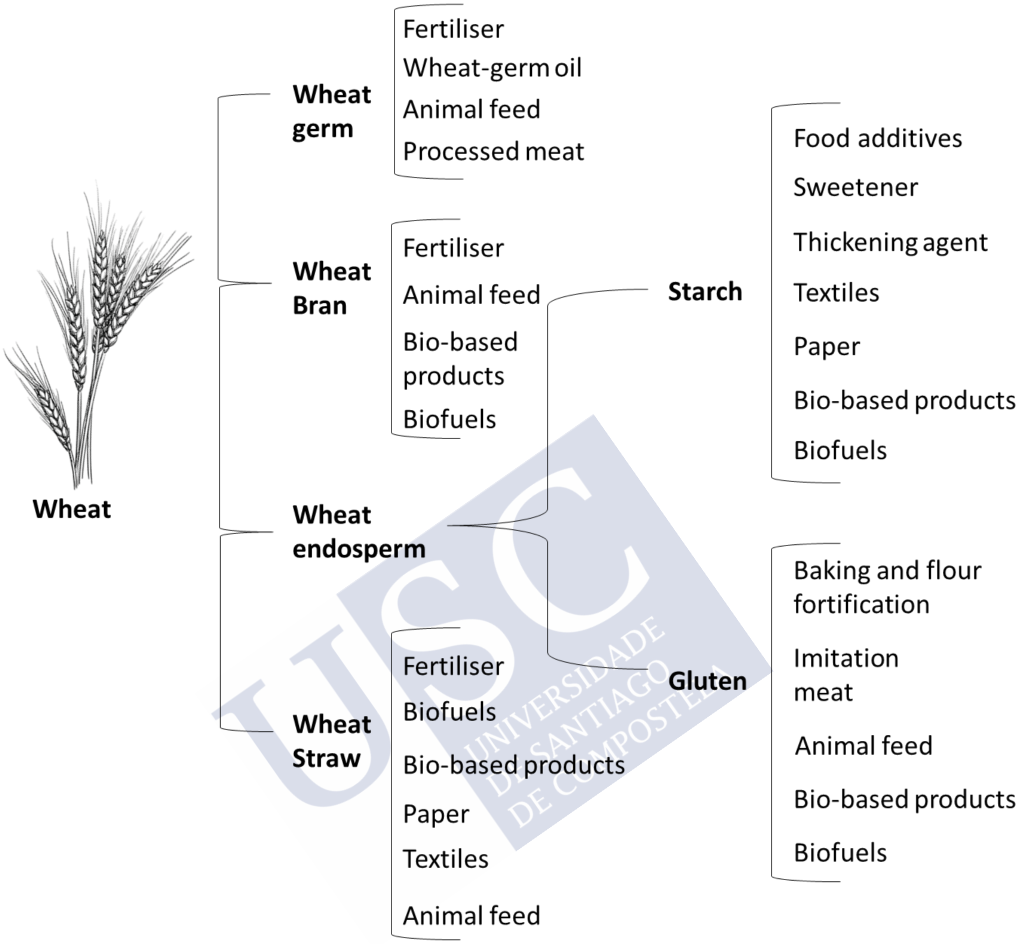

Figure 1.4 Multiple uses of wheat.

The most common wheat species are *T. turgidum* and *T. aestivum*. Wheat is classified into (1) winter wheat, sown in autumn (usually September to November) and harvested in summer or autumn of the following year; and 2) spring wheat, sown in spring and harvested in autumn. In addition, wheat cultivation can be divided into (i) hard wheat, with a higher protein content, or (ii) soft wheat, which yields a low-protein flour (De Matos et al., 2015). Both winter and spring wheat can be either hard or soft crops. Generally, mills blend wheat varieties to achieve the ideal composition of the desired final product.

Wheat cultivation in Europe accounts for up to 20% of total world production. Wheat is mainly a winter crop, with an average yield of 5 t ha^{-1} and more than 26 million hectares under cultivation. France, Germany and the United Kingdom are responsible for almost 50% of total production in Europe, as shown in Figure 1.5. Globally, China and India are the main producers, with China being responsible for almost the same production as all wheat production in Europe (Figure 1.6).

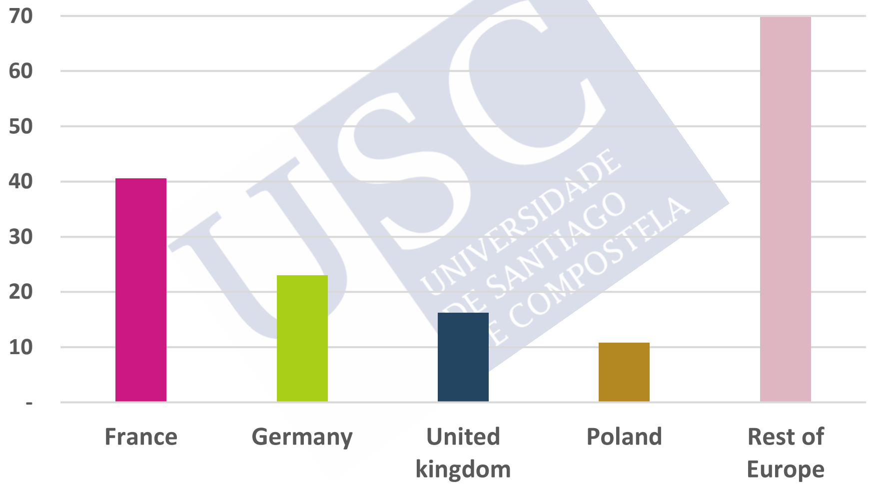

Figure 1.5 Main wheat producers in Europe in million tonnes. Total wheat grain produced in Europe: 155 million tonnes in 2019 (FAOSTAT, 2019).

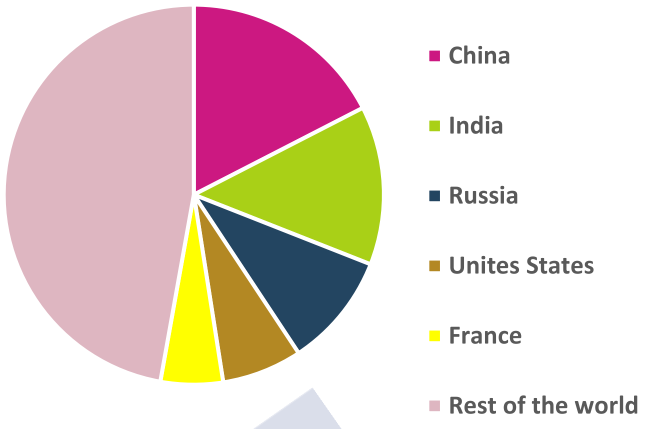

Figure 1.6 Share of world’s wheat producers. Total worldwide wheat produced: 765 million tonnes in 2019 (FAOSTAT, 2019).

In recent decades, agriculture has become more intensive and average yields have increased considerably, due to crop diversification and the use of chemical fertilisers and pesticides. Although conventional agriculture predominates, organic practices are also important in Europe. Ongoing work on wheat varieties and selections is increasing along with research efforts for the management and control of insect pests and weeds, which are the main constraints in organic farming. In addition, so far, organic wheat cultivation has required more land use and is much less productive than conventional practices (De Matos et al., 2015).

The dependence on chemical fertilisers and its subsequent environmental damage are leading to the investigation of crop rotation practices, alternating with other crops or legumes, for nitrogen fixation (Nemecek et al., 2015). In addition, reduced or no-tillage agriculture, unlike conventional agriculture, is also an alternative to avoid the negative side effects of ploughing, as this practice has the potential to increase the loss of organic matter and enhance soil erosion (Krauss et al., 2020).

The wheat cultivation process also leads to the production of wheat straw, which is sometimes collected after harvesting or is left in the field as soil amendment. In the bioeconomy framework, interest in wheat straw has increased relative to its potential use in biorefineries. Wheat straw is rich in lignocellulose and is classified as a second generation (2G) raw material. It is composed mainly of cellulose, hemicellulose and lignin, with cellulose being the main structural element of the plant cell wall (Saini et al., 2015). The composition of wheat straw may vary according to climatic, local and geographic conditions (Collins et al., 2014). However, it is usually composed of 30-45% cellulose, 20-25% hemicellulose, 15-20% lignin (Bakker et al., 2013).

Straw is seen as an essential biomass on the path to the bioeconomy. It is estimated that approximately 118,000 kton of wheat straw is produced in Europe (Bakker et al., 2013). Examples of the application of wheat straw are: 1) for the agricultural and livestock sectors: soil improvement, food supplements for animals, bedding for animals and compost industry; 2) outside the agricultural and animal sectors: building materials, fibre boards, insulating materials and energy production (Bakker et al., 2013).

In this thesis, wheat is used as a raw material for both food and bio-based products. The environmental sustainability of wheat grain and wheat bread is assessed in Chapters 2 and 3. In addition, wheat grain is used as a 1G feedstock to produce glucose, an important C6 sugar in fermentation processes (Chapter 6). Finally, in Chapter 8, wheat straw is used as lignocellulosic biomass to produce the biochemical butyric acid.

1.2.2 Maize

Along with rice and wheat, maize (*Zea mays* sp.) is considered one of the "big three" (Batey, 2017), providing almost 30% of the calories present in the food of the population in developing countries, while in developed countries maize is mainly used as feed. Originating from North and Central America, maize is considered a starch crop due to its high carbohydrate content. It is classified as a summer crop, as it requires optimal temperatures between 20-24°C. Despite these conditions, it is grown almost everywhere in the world, except in polar areas. The United States is the largest maize producer in the world and the largest producer of maize ethanol (USDA, 2020).

Normally, the sowing season begins in spring and is harvested in autumn. However, the sowing and harvesting periods rely on the type of maize, whether it is silage or grain. It also depends on the maturity class of the grain and the geo-climatic circumstances. For instance, in the north-western regions of Europe, where there are fewer summer hours, maize production is better suited to silage because the crop does not need to be fully matured, while the warmer regions of Europe produce mainly grain maize. Nitrogen fertilisation is essential in maize cultivation. In addition, the practice of irrigation is common in the Mediterranean region, in contrast to central and north of Europe, which is mostly rainfed (Kathage et al., 2016; Rüdelsheim and Smets, 2011).

In many countries, especially in the tropics, maize is grown mainly on a small scale, as a means of subsistence. On the other hand, large maize-producing countries use hybrid maize breeding, intensive fertilisation and mechanical operations with high diesel consumption (Ofori and Kyei-baffour, 2010). In addition to food and feed, maize production can have a plethora of uses, including the production of starch, sweeteners, beverages, biofuels and bio-based products (Kathage et al., 2016). Maize stover, which is a residue of maize crops, is composed of leaves, husks, stalks and cobs. It is rich as a soil amendment and can also be used as animal feed. It also has a high lignocellulose content, which makes it possible to produce biofuels and bio-based products from this waste. Maize stover contains about 38% cellulose, 26% hemicellulose and 19% lignin (Prasad et al., 2016). Figure 1.7 represents an overview of the numerous options for products made from maize.

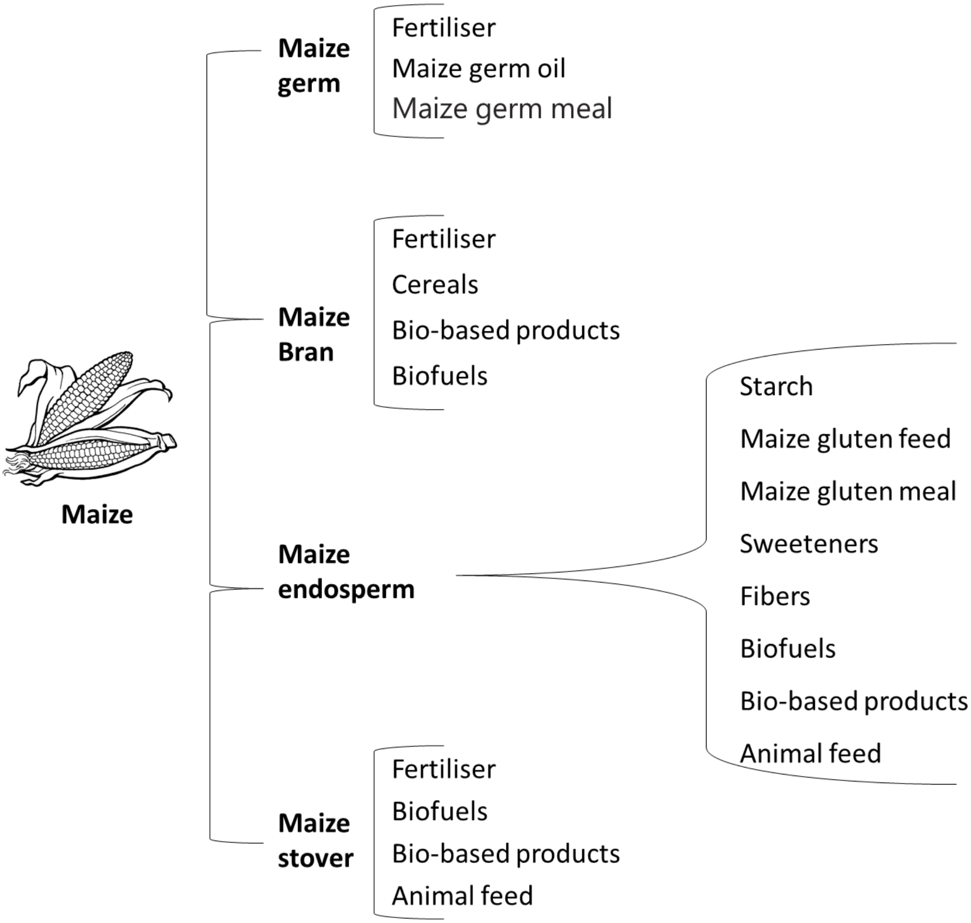

Figure 1.7 Multiple uses of maize.

In the last decade, world production has grown steadily. Since 2007, with about 792 million tonnes, 850 million tonnes in 2010 and 1150 million tonnes in 2019 (FAOSTAT, 2019). Currently, the global average yield is about 5.8 tonnes ha^{-1}, with a total of up to 200 million hectares of harvested area for maize cultivation in the world. Maize production in Europe is very modest, accounting for only 6% and 4% of the global production quantity and harvested area, respectively (FAOSTAT, 2019). As shown in Figure 1.8, the largest producers in Europe are Romania and France, followed by Hungary and Italy. In the world, the United States and China are by far the largest producers, with more than 50% of the total production (Figure 1.9).

In this thesis, maize stover is evaluated as a potential lignocellulosic biomass that can be an ingredient in feed production or a raw material to be used in biorefineries. The environmental and economic profile of maize stover production is assessed in Chapter 5. Additionally, the environmental impacts of fermentable sugars from maize grain and stover and butyric acid produced from maize stover are evaluated in Chapters 7 and 8, respectively.

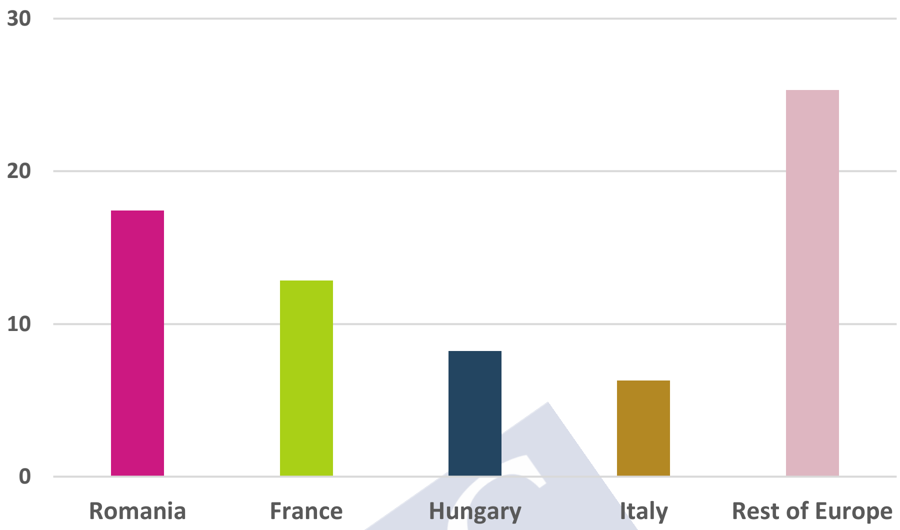

Figure 1.8 Main maize grain producers in Europe in million tonnes. Total maize grain produced in Europe: 70 million tonnes in 2019 (FAOSTAT, 2019).

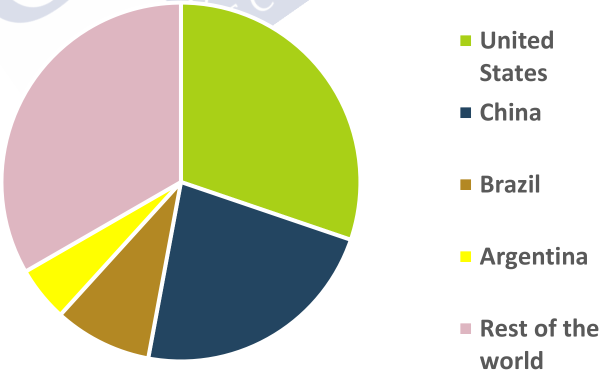

Figure 1.9 Share of world's maize producers. Total worldwide maize produced: 1150 million tonnes in 2019 (FAOSTAT, 2019).

1.2.3 Sugar beet

Sugar beet production increased in the Napoleonic period due to the disruption of the sugarcane market from the colonies to Europe. From the 20th century onwards, sugar beet cultivation changed from a very labour-intensive activity to an extensive system with the use of specific machinery that allowed higher yields to be obtained. Although sugar beet is grown worldwide, its cultivation is associated with temperate climates. In continental Europe, sugar beet crops are usually grown in spring until late autumn or early winter, when processing for sugar begins. In Mediterranean areas, sugar beet is sown in autumn and harvested in summer (Draycott, 2006).

Modern sugar beet is scientifically known as *Beta vulgaris* ssp. *vulgaris*. Thanks to photosynthesis, the plant starts to form sugar and store it in its root, which is composed of approximately 14% sucrose, 6% pulp and 4% molasses on a wet basis. (FAO, 2009). The amount of sugar produced by the plant varies according to geographical and climatic conditions, soil type, fertilisers, harvest date and storage time. After harvesting, there is a gradual loss of sugar content, so processing at the factory should be carried out as soon as possible so as not to decrease the yield of the product (Draycott, 2006).

The production of sugar beet has been mainly associated with the food sector. To date, beet sugar is not considered an important raw material in industrial fermentation processes. However, changes in dietary habits and competition with other sugars (e.g., sugarcane sucrose) are pushing sucrose consumption from beet in Europe to reach a tipping point. Natural and artificial sweetener options are gaining market share, such as high-fructose corn syrup (HFCS) as a source of low-cost sugars that have been incorporated into a wide variety of foods. On the other hand, in economic terms, European export policies facilitate the entry into the sugarcane market. Considering the possibility that the beet sugar market will shrink its market, it may be time to look for alternatives to beet sucrose. Therefore, the general supply chain needs to be evaluated, taking into account not only sucrose as a raw material, but also the use of by-products, such as leaves and branches of the plant, as well as those derived from the processing of beet (e.g. molasses and beet pulp)(Tomaszewska et al., 2018). Figure 1.10 summarizes the possible applications of sugar beet.

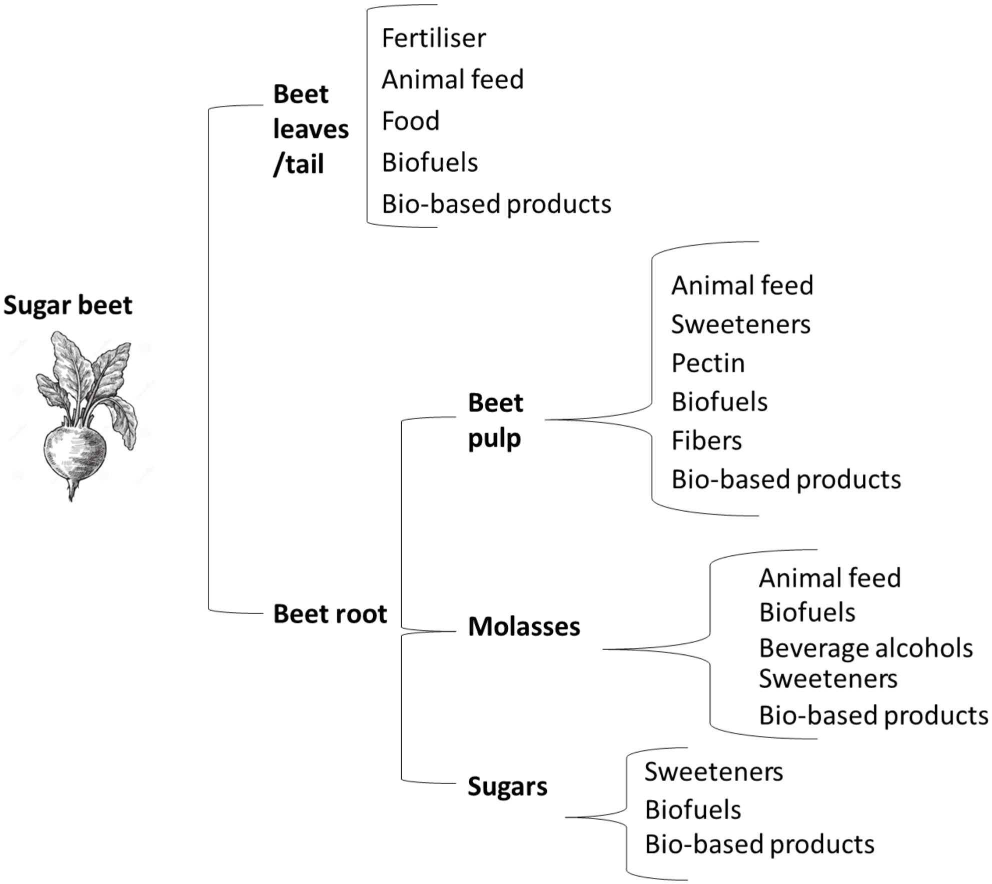

Figure 1.10 Multiple uses of sugar beet.

In relative percentages, Europe is the world's largest producer of sugar beet, with France, Germany, Poland and the United Kingdom being the largest producers (Figure 1.11). France and Germany together account for more than 55% and 24% of the European and world sugar beet production, respectively (Figure 1.12). There are more than 1.6 and 4.6 million ha of area harvested for sugar beet in Europe and in the World, respectively (FAOSTAT, 2019).

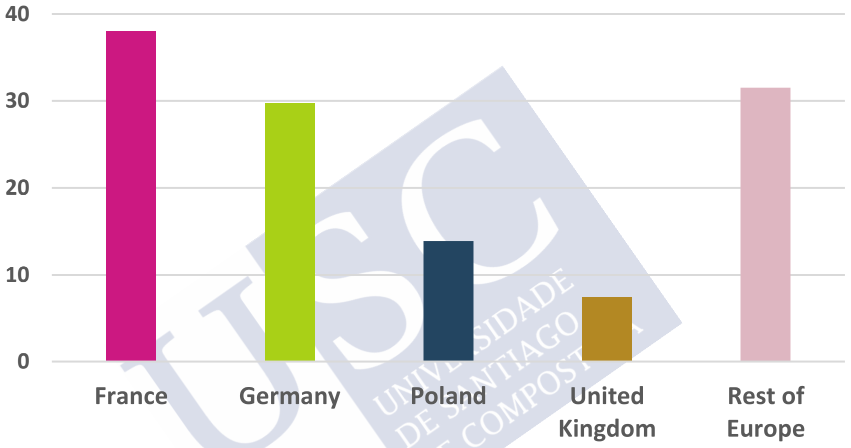

Figure 1.11 Main sugar beet producers in Europe in million tonnes. Total sugar beet produced in Europe: 120 million tonnes in 2019 (FAOSTAT, 2019).

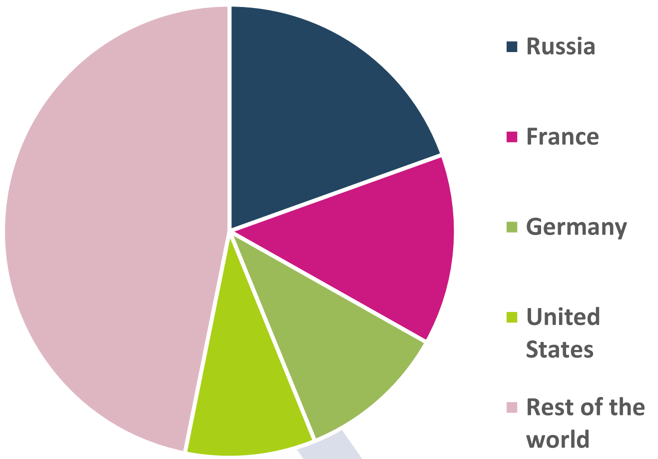

Figure 1.12 Share of world's sugar beet producers. Total worldwide sugar beet produced: 278 million tonnes in 2019 (FAOSTAT, 2019).

In this thesis, sugar beet is used to assess the sustainability profile of the use of its residues (beet pulp and molasses) that occur in the sugar production process. The environmental and economic profile of sugar beet pulp is assessed in Chapter 5. In addition, Chapters 7 and 8 describes the environmental impacts of fermentable sugars and biochemical butyric acid produced from beet pulp, respectively. Finally, Chapter 9 evaluates the environmental loads of methionine produced from molasses.

1.2.4 Potato

The potato originated in the Andean region of South America about 8,000 years ago. It was not introduced in Europe until the 16th century and spread around the world a century later (Jong, 2016). Today, the potato is grown almost all over the world. The potato has played and continues to play an important role in society, being a significant part of human and animal food. In addition, the possibility of storing it for a long time allows for greater food security. Although the potato is widely grown throughout the world, it is considered a cold-climate crop, usually planted in early spring in temperate areas or in late winter in warm zones. Potato cultivation is fast, taking 90 to 150 days and can be adapted to many environments. However, it has many implications with pests and diseases. Therefore, it is very common to cultivate potatoes under a crop rotation system (FAO, 2008). Under good conditions, potato yield can account for more than 50 tonnes per hectare (FAOSTAT, 2019).

Potato is a short-lived perennial plant. Nowadays, the most cultivated potatoes species in the world are *Solanum tuberosum* subsp. *Tuberosum.* The valuable part of the potato is the tuber, which grows underground and is rich in carbohydrates. Potatoes are composed of approximately 75% water, 21% carbohydrates, 2.5% protein and 1% fat. Potatoes are also known as starch crops, since 80% of the carbohydrates in potatoes are starch. Potatoes are recognized for their nutritional value and are able to produce more calories faster and with fewer hectares than the main agricultural commodities (Bradeen and Haynes, 2011). Potato is the fourth most consumed food crop in the world and about half of the potato is consumed fresh (Pathak et al., 2017). The rest is used in other food processing industries or in seed production (Birch et al., 2012). A variety of products can be made from potatoes, such as animal feed, potato chips and even bio-based products and biofuels made from industrial fermentation process of potato starch. Potato leaves can also be used as a soil conditioner, or even eaten fresh (Figure 1.13).

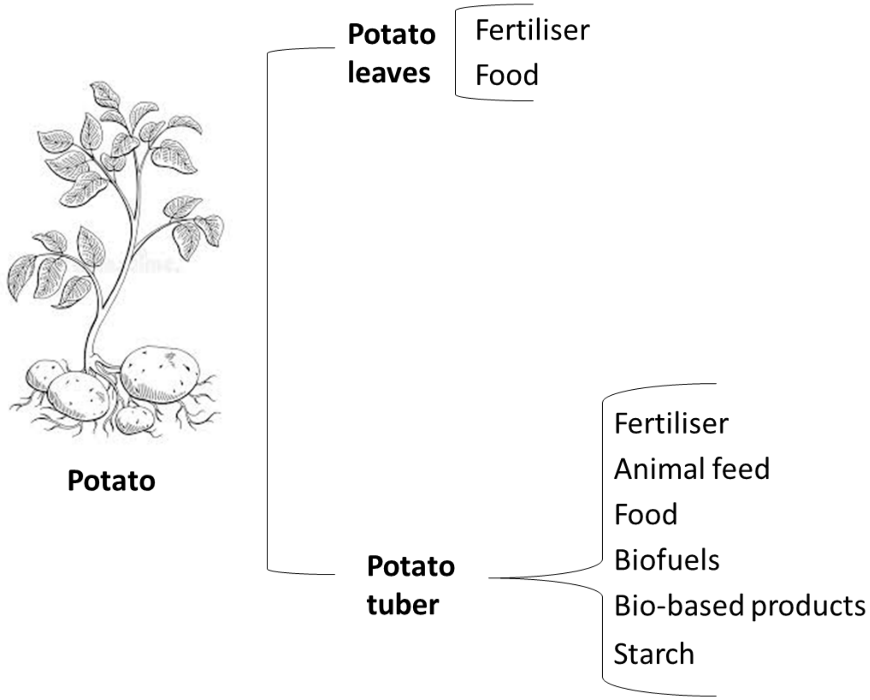

Figure 1.13 Multiple uses of sugar beet.

In the last decades there has been a large increase in the cultivation of potatoes, especially in Asian countries due to the change in the pattern of consumption (Jong, 2016). Potato farming in Europe fell dramatically from around 127 in 1961 to 56 million tonnes in 2019. In contrast, in Asia, it grew from 23 in 1961 to 190 million tons in 2019 (FAOSTAT, 2019). Germany, France, the Netherlands and Poland are the countries with the largest share of potato production in Europe (Figure 1.14), while China and India are the largest producers in the world (Figure 1.15).

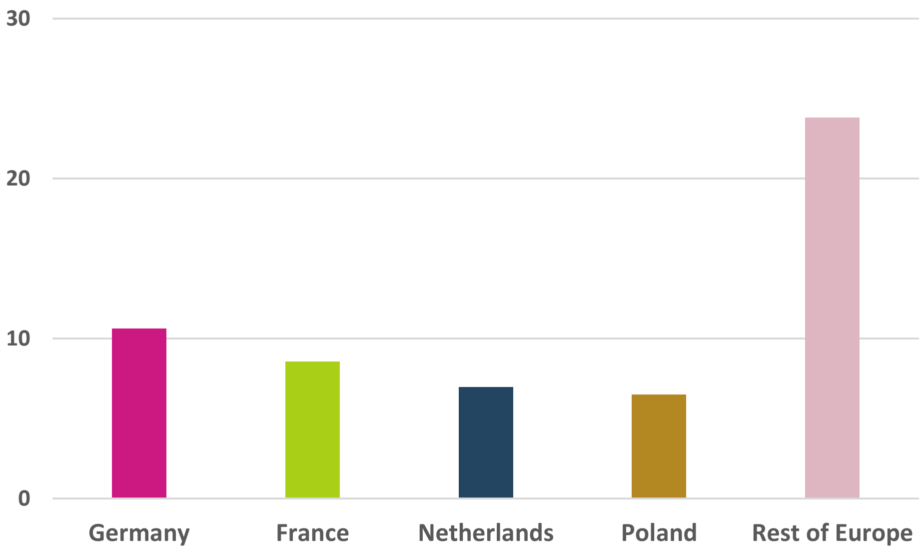

Figure 1.14 Main potatoes producers in Europe in million tonnes. Total potatoes produced in Europe: 56 million tonnes in 2019 (FAOSTAT, 2019).

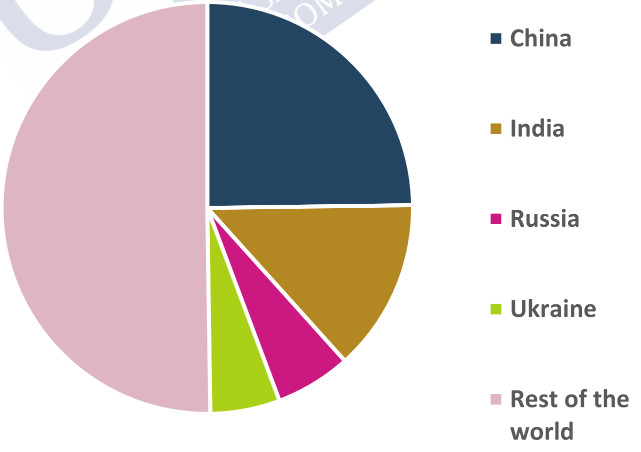

Figure 1.15 Share of world's potatoes producers. Total worldwide potatoes produced: 370 million tonnes in 2019 (FAOSTAT, 2019).

This thesis considers potatoes for food use only, where the environmental profile of potato cultivation under a crop rotation system in the region of Galicia (Spain) is assessed (Chapter 3). This area was chosen as a case study because Galicia is one of the most important potato-producing regions in Spain (Estatista, 2020).

1.3 SCOPE OF THE THESIS

The main objective of this doctoral thesis is to analyse the environmental and economic profile of different bioproducts in order to provide knowledge on their sustainability and help the transition to a circular bioeconomy. In this context, the thesis is composed of 4 sections and 10 chapters.

Section I: Contextualisation. This section is developed in Chapters 1 and 2. Chapter 1 presents the general concepts of the bioeconomy and circular economy frameworks. Moreover, it introduces general information about the raw materials used in this thesis. In addition, it presents the scope and outline of this thesis. Chapter 2 explains the methodologies used for environmental and economic assessment.

Section II: Agriculture and food context. This section consists of Chapters 3, 4 and 5. It represents the environmental and economic sustainability of bioproducts produced in the food context. Chapters 3 and 4 present the environmental impacts of wheat, potatoes and bread in the Galician region, while Chapter 5 describes the environmental and economic profile of maize stover and sugar beet pulp.

Section III: Agriculture and bio-based context. This section consists of Chapters 6, 7, 8 and 9. It represents the environmental sustainability of bioproducts produced in a bio-based context. Chapter 6 presents the environmental burden of glucose production in Europe.

Chapter 7 describes the environmental profile of fermentable sugars and Chapter 8 of the biochemical butyric acid. Finally, Chapter 9 discusses the environmental impacts of the production of methionine as a model amino acid.

Section IV: Conclusions. This section consists of Chapter 10. It provides an integrated overview of the main outcomes and contributions of the thesis.

Figure 1.16 illustrates a complete scheme of the raw materials, platforms, technology and products used throughout this thesis. As noted, this thesis evaluates 1G-feedstocks for agricultural crops (that is, grain wheat, grain maize, sugar beet, and potatoes); and 2G-raw materials from agricultural residues (i.e., wheat straw and maize stover) and from industrial processing (i.e., molasses and sugar beet pulp). In the case of bio-based products, the C6 platform from edible raw materials and the C5 platform from lignocellulosic biomass are being considered to produce fermentable sugars, butyric acid and methionine. The technologies used in this thesis vary from physical processes, i.e., wheat grain milling process in bread or beet pulp from sugar extraction process. Furthermore, chemical and biochemical processes are considered to transform C5/C6 sugars into valuable products.

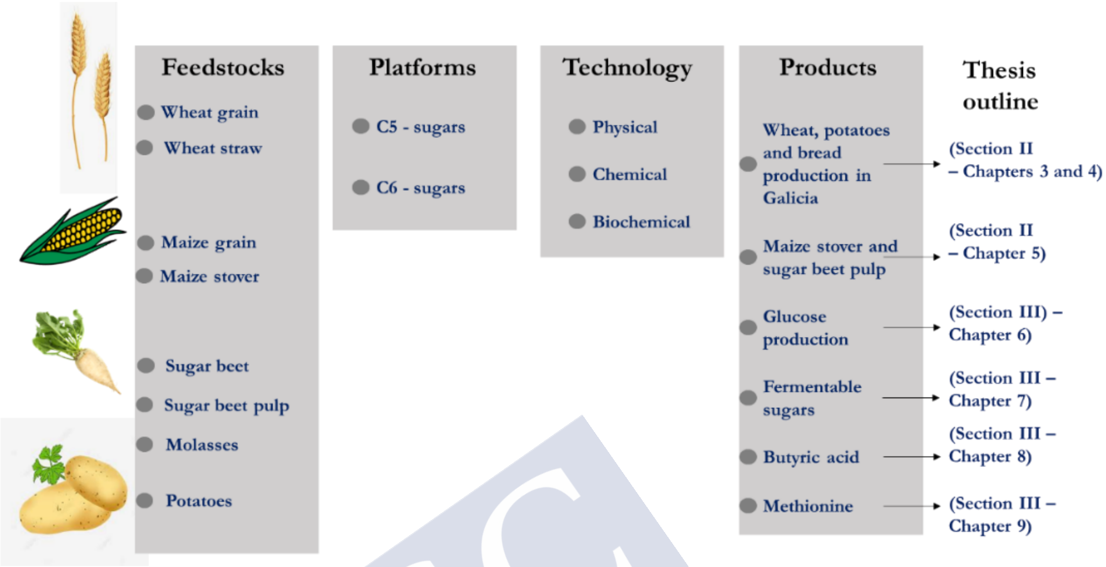

Figure 1.16 Representation of the thesis outline.

REFERENCES

Achten, W.M.J., Van Acker, K., 2016. EU-Average Impacts of Wheat Production: A Meta-Analysis of Life Cycle Assessments. J. Ind. Ecol. 20, 132–144. https://doi.org/10.1111/jiec.12278

Bakker, R., Elbersen, W., Poppens, R., Lesschen, J.P., 2013. Rice straw and Wheat straw. Potential feedstocks for the Biobased Economy. Wageningen.

Batey, I., 2017. The Diversity of Uses for Cereal Grains, in: Cereal Grains. Elsevier Ltd, pp. 41–53. https://doi.org/10.1016/B978-0-08-100719-8/00003-6

Bioökonomierat, 2020. International Bioeconomy Strategies [WWW Document]. URL https://biooekonomierat.de/en/international/ (accessed 1.19.21).

Birch, P.R.J., Bryan, G., Fenton, B., Gilroy, E.M., Hein, I., Jones, J.T., Prashar, A., Taylor, M.A., Torrance, L., Toth, I.K., 2012. Crops that feed the world: Potato: are the trends of increased global production sustainable ? Food Secur. 4, 477–508. https://doi.org/10.1007/s12571-012-0220-1

Bradeen, J.M., Haynes, K.G., 2011. Introduction to Potato, in: Genetics, Genomics and Breeding of Potato. pp. 1–15.

Bugge, M.M., Hansen, T., Klitkou, A., 2016. What Is the Bioeconomy ? A Review of the Literature. MDPI Sustain. 8, 1–22. https://doi.org/10.3390/su8070691

Cherubini, F., 2010. The biorefinery concept : Using biomass instead of oil for producing energy and chemicals. Energy Convers. Manag. 51, 1412–1421. https://doi.org/10.1016/j.enconman.2010.01.015

Collins, S.R.A., Wellner, N., Bordonado, I.M., Harper, A.L., Miller, C.N., Bancroft, I., Waldron, K.W., 2014. Variation in the chemical composition of wheat straw - the role of tissue ratio and composition. Biotechnol. Biofuels 7, 1–14.

Curtis, B.., Rajaram, S., Macpherson, H.., 2002. BREAD WHEAT. Improvement and Production, in: Plant Production and Protection Series. Rome, pp. 1–18.

De Matos, C.T., Garcia, J.C., Aurambout, J.-P., Kavalov, B., Manfredi, S., 2015. Environmental Sustainability Assessment of Bioeconomy Products and Processes – Progress Report 1. https://doi.org/10.2788/708144

Draycott, A.P., 2006. Sugar Beet, Blackwell Publishing. Blackwell Publishing. https://doi.org/10.1002/9780470751114

EEA, 2018. The circular economy and the bioeconomy. Partners in sustainability. Copenhagen. https://doi.org/10.2800/02937

EMAF, 2013. Towards the circular economy. Economic and business rationale for an accelerated transition. London.

Estatista, 2020. Producción de patatas en españa por comunidad autónoma [WWW Document]. URL https://es.statista.com/estadisticas/510906 /produccion-de-patatas-en-espana-por-comunidad-autonoma/ (accessed 11.25.20).

European Commission, 2018. A sustainable Bioeconomy for Europe : strengthening the connection between economy , society and the environment. https://doi.org/10.2777/478385

European Commission, n.d. Bioeconomy. Why the EU supports bioeconomy research and innovation [WWW Document]. URL https://ec.europa.eu/info/research-and-innovation/research-area/bioeconomy_en (accessed 1.18.21).

FAO, 2017. The future of food and agriculture - Trends and challenges. Rome.

FAO, 2009. Sugar Beet White Sugar, Agribusiness Handbooks.

FAO, 2008. The potato cultivation [WWW Document]. Int. Year Potato. URL http://www.fao.org/potato-2008/en/potato/cultivation.html (accessed 2.1.21).

FAOSTAT, 2019. Crop statistics [WWW Document]. URL http://www.fao.org/faostat/en/#data (accessed 1.10.19).

Gomez San Juan, M., Bogdanski, A., Dubois, O., 2019. Towards sustainable bioeconomy. Lessons learned from case studies. Rome.

Haard, N.F., 1999. Major Chemical Components of Cereal Grains, in: FERMENTED CEREALS. A GLOBAL PERSPECTIVE. pp. 1–25.

Herrera, R.J., Garcia-Bertrand, R., 2018. The Agricultural Revolutions, in: Ancestral DNA, Human Origins, and Migrations. pp. 475–509. https://doi.org/10.1016/B978-0-12-804124-6.00013-6

IEA, 2012. Bio-based Chemicals. Value Added Products from Biorefineries.

Jong, H. De, 2016. Impact of the Potato on Society. Am. J. Potato Res. 94, 415–429. https://doi.org/10.1007/s12230-016-9529-1

Kathage, J., Gómez-barbero, M., Rodríguez-cerezo, E., 2016. Framework for assessing the socio-economic impacts of Bt maize cultivation. https://doi.org/10.2788/739670

Krauss, M., Berner, A., Perrochet, F., Frei, R., Niggli, U., Mäder, P., 2020. Enhanced soil quality with reduced tillage and solid manures in organic farming – a synthesis of 15 years. Sci. Rep. 10, 4403. https://doi.org/10.1038/s41598-020-61320-8

Moncada, J.B., Aristizábal, V.M., Cardona A, C.A., 2016. Design strategies for sustainable biorefineries. Biochem. Eng. J. 116, 122–134. https://doi.org/10.1016/j.bej.2016.06.009

Nemecek, T., Hayer, F., Bonnin, E., Carrouée, B., Schneider, A., Vivier, C., 2015. Designing eco-efficient crop rotations using life cycle assessment of crop combinations. Eur. J. Agron. 65, 40–51. https://doi.org/10.1016/j.eja.2015.01.005

Ofori, E., Kyei-baffour, N., 2010. Agrometeorology of Some Selected Crops, in: Guide on Agricultural Meteorological Practices

(GAMP).WMO-No. 134. World Meteorological Organization (WMO), pp. 10–34.

Pathak, P.D., Mandavgane, S.A., Puranik, N.M., Jambhulkar, J., Kulkarni, B.D., 2017. Critical Reviews in Biotechnology Valorization of potato peel : a biorefinery approach. Crit. Rev. Biotechnol. 0, 1–13. https://doi.org/10.1080/07388551.2017.1331337

Prasad, A., Sotenko, M., Blenkinsopp, T., Coles, S.R., 2016. Life cycle assessment of lignocellulosic biomass pretreatment methods in biofuel production. Int. J. Life Cycle Assess. 21, 44–50. https://doi.org/10.1007/s11367-015-0985-5

Rüdelsheim, P.L.J., Smets, G., 2011. Baseline information on agricultural practices in the EU Maize (Zea mays L .). Brussels.

Saini, J.K., Saini, R., Tewari, L., 2015. Lignocellulosic agriculture wastes as biomass feedstocks for second-generation bioethanol production : concepts and recent developments. Biotech 3, 337–353. https://doi.org/10.1007/s13205-014-0246-5

Stegmann, P., Londo, M., Junginger, M., 2020. The circular bioeconomy : Its elements and role in European bioeconomy clusters. Resour. Conserv. Recycl. 6, 100029. https://doi.org/10.1016/j.rcrx.2019.100029

Tauger, M., 2010. Agriculture in World History, First. ed. Routledge, London. https://doi.org/https://doi.org/10.4324/9780203847480

Tomaszewska, J., Bieliński, D., Binczarski, M., Berlowska, J., Dziugan, P., Piotrowski, J., Stanishevsky, A., Witońska, I.A., 2018. Products of sugar beet processing as raw materials for chemicals and biodegradable polymers. RSC Adv. 8, 3161–3177. https://doi.org/10.1039/ C7RA12782K

Ubando, A.T., Felix, C.B., Chen, W., 2020. Biorefineries in circular bioeconomy : A comprehensive review. Bioresour. Technol. 299. https://doi.org/10.1016/j.biortech.2019.122585

USDA, 2020. U.S. Bioenergy Statistics [WWW Document]. Econ. Res. Serv. United States Dep. Agric. URL https://www.ers.usda.gov/data-products/us-bioenergy-statistics/ (accessed 1.17.21).

CHAPTER 2: SUSTAINABILITY ASSESSMENT TOOLS

SUMMARY

Pollution and climate change are elements that affect the quality of life and the integrity of ecosystems. The social perception of these problems and the desire to become aware of their consequences have initiated a movement for change with the aim of quantifying the global impacts and mitigating their effects. In the current context, it is essential to apply methodologies that allow evaluating the exploitation and use of resources and their impacts on sustainability and developing strategies based on plausible actions to mitigate these impacts.

The main objective of this chapter is to provide an overview of the history of sustainability and a brief description of sustainability tools. Special attention is given to the Life Cycle Assessment (LCA) methodology as an important approach to quantify the environmental impacts of bioproducts. The analysis of economic and environmental costs is also regarded as a complementary tool to strengthen the LCA methodology and the decision-making process.

2.1 A BRIEF HISTORY OF SUSTAINABILITY

In the history of human societies, man has become the dominant centre of the earth, capable, with the advance of technology, of controlling animals, plants and landscapes. Man has used natural resources exhaustively, in a chaotic and predatory manner, without concern for and/or knowledge of the adverse effects that human activity has on the environment. It was at the end of the 19th century that society began to become aware of the impact of its activities on the degradation of the environment. For instance, the overexploitation of land in the United States, led the President Theodore Roosevelt to establish, in 1905, the United States Forest Service (USFS), with the objective of protecting lands through the institution of national parks and public lands to ensure the integrity of the resources (NPS, 2017). In 1908, at the Conference on the Conservation of Natural Resources, Theodore Roosevelt stated that:

> *"We have become great because of the lavish use of our resources. But the time has come to inquire seriously what will happen when our forests are gone, when the coal, the iron, the oil, and the gas are exhausted, when the soils have still further impoverished and washed into the streams, polluting the rivers, denuding the fields and obstructing navigation."*

With the rise of industrial activity, environmental awareness increased considerably. This was especially evident in developed countries, the first to suffer serious industrial pollution tragedies. Among the most striking episodes was the great smog of London in 1952, which caused an unprecedented number of respiratory illnesses and deaths related to air pollution (Bell et al., 2004). The smog was caused by the burning of fossil fuels, mainly coal and crude oil for energy production and transportation. As a consequence, the British government established the Clean Air Act in 1956, which restricted the domestic use of coal and compelled industries to implement measures to control air pollution (HM Government, 1956).

The 1960s and 1970s were also marked by the emergence of NGOs and environmental activism in the world. In 1962, the publication of the book "Silent Spring", by the American marine biologist and conservationist Rachel Carson, contributed to the beginning of modern environmental awareness. In this work, she denounced the negative effect of the use of DDT (dichloro-diphenyl-trichloroethane) pesticides on the environment, so that a decade later DDT was banned for use in agriculture (EPA, 2017).

In 1968, the Club of Rome was created, composed by a group of scientists that aim to find and propose solutions to the problem of human overpopulation and overexploitation of resources. In 1972, the Club of Rome published the famous report "The Limits of Growth", a study on system dynamics linking population growth, resource exploitation and industrialization. This report has been revised and updated several times and the club still exists today. At present, several works use advanced mathematical models to predict future environmental consequences, such as the reports of the Intergovernmental Panel on Climate Change (IPCC), founded in 1988.

Growing concern about environmental pollution and social well-being led the United Nations to hold the first United Nations Conference on the Human Environment on June 5, 1972, which was taken as the reference for the celebration of World Environment Day and when the United Nations Environment Programme (UNEP) was created (Handl, 2013). In fact, it has become a global public outreach platform for promoting environmental action and brings together governments, businesses, and citizens around a pressing environmental issue.

Other important milestones were achieved in later years. In 1987, the term "Sustainable Development" was first mentioned in the Brundtland Report, entitled "Our Common Future". Sustainable development is an integrated thinking approach in which the social and economic aspects must be associated with the environmental. (WCED, 1987). In Rio 1992, the United Nations Conference on Environment and Development (UNCED) or "the Earth Summit" was held, which reinforced the concept of sustainable development at both the local and global levels. This conference also recognized that we must rethink the way we produce and consume today, and that new perceptions of the economy must be opened up. The conference had great achievements, such as the creation of the Convention on Biological Diversity (Grubb et al., 1993).

The first Conference of the Parties (COP) took place in Berlin in 1995 and since then has been held annually with the aim of resolving global climate change issues (UNFCCC, 2006). In 2015, a major expedition to map the "Great Pacific Garbage Patch" found that plastic waste was larger than expected. Located between Hawaii and California, plastic in the ocean covers an area 3 times the size of France (The Ocean Cleanup, 2021). In 2016, in an effort to tackle climate change, the Paris Agreement was adopted in which signatory countries agreed to limit global warming to below 2°C compared to pre-industrial levels (United Nations, 2015).

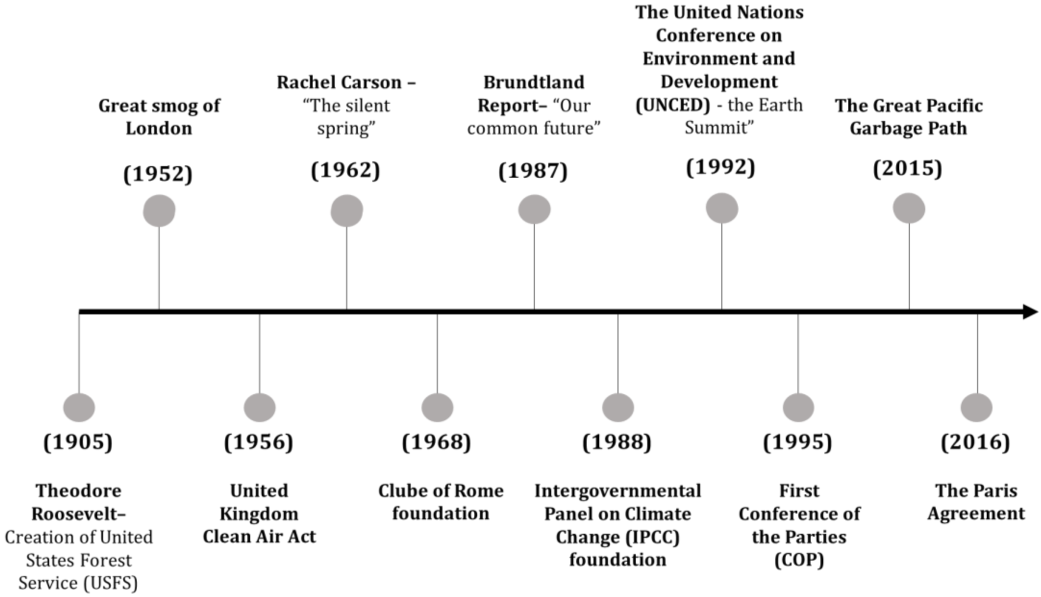

Figure 2.1 Summary of major environmental events.

Sustainability assessment tools grew along with the history of sustainability. To understand the economic, social and environmental impacts of human action in this century and to be able to make strategic decisions, assessment techniques have intensified and improved in the last decades. Some examples are Environmental Risk Assessment (ERA), Environmental Impact Assessment (EIA), Environmental Auditing (EA), Input-Output Analysis (IOA), Material Flow Analysis (MFA), Environmental Economics, and Life Cycle Assessment (LCA) (Thompson, 2014). Most of them embraces the "life cycle thinking" as principle. The following sections will discuss in more detail the methodology, tools and techniques for assessing sustainability applied in this thesis.

2.1 SUSTAINABILITY ASSESSMENT TOOLS

2.1.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) emerged in the 1960s, both in industry and in universities. However, the term "LCA" did not come into use until the 1990s. It was first based on inventories of material flows, energy and emissions. However, due to the difficulty of interpreting these data, environmental indicators such as global warming potential or acidification were adopted. Since 1990, life cycle impact assessment methods (e.g., CML, EPS and Eco-indicator 99) have evolved. In addition, the quality of databases has improved since this period, especially with the emergence of Ecoinvent in 2003. Due to the large amount of data and the difficulty of translating them into environmental impacts, software was also developed to estimate environmental impacts, e.g. SimaPro and Gabi (Bjørn et al., 2018b).

The application of the LCA methodology made it necessary to agree on harmonization protocols. Starting in 1997, a standard for LCA was created by the International Organization for Standardization (ISO), resulting in the widely recognized ISO 14040 (Principles and framework) and ISO 14044 (Requirements and guidelines) standards (ISO 14040, 2006; ISO 14044, 2006). Today, LCA is widely used by research institutes, companies, NGOs, governments and intergovernmental organizations. The interest in LCA studies has not only arisen in the field of environmental auditing, but also through scientific publications in which new analysis methodologies or the benchmarking of similar processes have been developed. As an example, LCA publications increased considerably, up to 10-fold, from the late 1990s to early 2010 (Bjørn et al., 2018b).

Although LCA was developed with a focus on the environmental profile, today LCA comprises the three pillars of sustainability: environmental (LCA), social (SLCA) and economic (LCC), where the triple perspective embraces the Life Cycle Sustainability Assessment (LCSA) tool. Although there is still much room for improvement, the environmental LCA is well developed and to a lesser extent the LCC, while the SLCA technique and especially the LCSA still need to mature. This thesis focuses mainly on environmental LCA and to a lesser extent on economic evaluation. Most of the evaluations in this thesis use SimaPro software and the Ecoinvent v3.5® database (Wernet et al., 2016). This thesis follows the ISO framework for LCA, which comprises 4 main steps: 1) Definition of the objective and scope; 2) Life cycle inventory (LCI); 3) Life cycle impact assessment (LCIA); and 4) Interpretation (Figure 2.2).

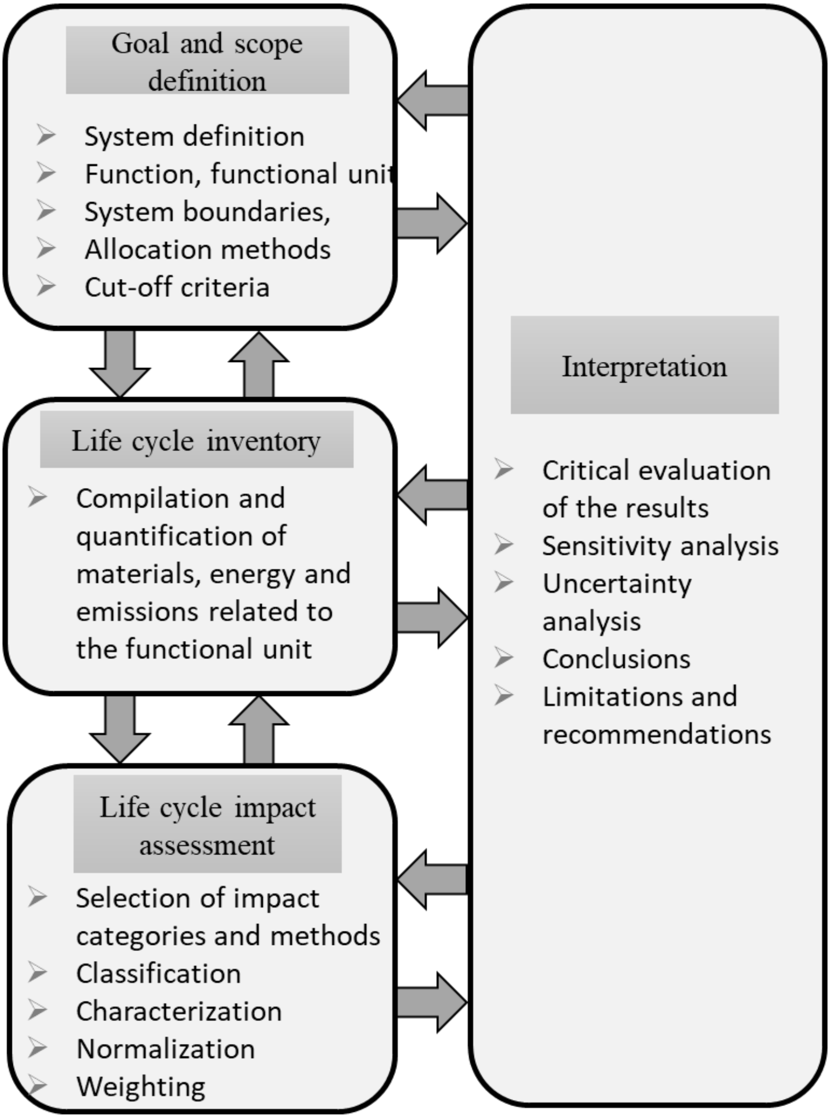

Figure 2.2 Life cycle assessment framework. Adapted from ISO 14040 (2006).

2.1.1.1 Goal and scope definition

The first step, the goal and scope definition, is the motivation for conducting the assessment. It is an essential step to have a clear vision of the study, as it will guide the next steps of the evaluation. However, the goal and scope may change as more knowledge is revealed in the next phases of the LCA. In this phase, the scope of the system should be well defined and should include the system description, function, functional unit (FU), system boundaries, allocation methods and cut-off criteria.

The selection of the function and the FU should be consistent with the objective of the study and is a very important step, as the environmental impacts will be interpreted according to the FU selected. By definition, the FU is the measurable value associated with the function. For example, when it comes to the LCA of wheat crop, the function is wheat production while the FU can be 1 kg of wheat produced or 1 hectare of wheat cultivation. A FU is a reference to which inputs and outputs are estimated, allowing comparison of results with other studies. For example, we can compare the environmental impacts of 1 kg of wheat production in an organic and conventional farming systems.

The system boundaries describe the unit processes to be examined. The choice of processes will depend on many factors, but mainly on the resources and time available to evaluate each process. For example, in the case of seed production in the wheat cultivation, no primary data on wheat seed will be included due to the lack of data and a generic database can be used. The system boundary comprises: 1) the foreground system, which includes processes that are specific to the product system (e.g., fertiliser application in a wheat cropping system) and 2) the background system, which consists of the processes that are not specific to the product system (e.g., fertiliser or diesel production) (Bjørn et al., 2018a). The cut-off criteria will determine which components will or will not be included in the system. For example, one can decide that those materials or processes that contribute less than 1% will not be included in the environmental impact analysis.

When two or more products are produced, it is necessary to resolve the issue of multifunctionality to allocate environmental impacts to the products. ISO guidelines (ISO 14040, 2006) state that allocation should be avoided whenever possible. Otherwise, it is necessary to choose an allocation method to be evaluated in a subsequent sensitivity study. The choice of the allocation method will depend on the product system. The most common methods are mass, economic and energy allocation. Agricultural systems and the processing of raw materials often involve the co-production of several components. In wheat grain production, part of the straw may be removed for feed production, which makes the straw also economically valuable. Wheat processing, e.g., for starch production, also generates by-products such as wheat gluten meal (Durlinger et al., 2017).

2.1.1.2 Life cycle inventory (LCI) analysis

LCI is the most time-consuming stage of an LCA study, as it involves data collection and calculation of material and energy flows of a product system. The LCI must be carried out in accordance with the goal and scope definition. In this phase, it is common to have a reassessment of the "goal and scope definition", and may even require a re-evaluation of both aspects, as many LCA studies face data, resource and time constraints. Typically, an LCA study includes both primary and secondary sources, which may be collected through calculations and questionnaires as well as from scientific publications, LCA databases and data published by government agencies.

The LCI is a list of elementary flows, which are the materials and/or energy entering and leaving the product system (e.g. water, coal, CO_2, noise) (European Commission, 2010). An elementary flow must have a name (e.g. “water”), a context (e.g. “to groundwater”) and a unit (e.g. m^3) (Edelen et al., 2018). The data for each process specified at the system boundary must be compiled and linked to the FU. That is, if the FU is 1 kg of wheat grain produced, the amount of fertiliser applied should be per kg of grain produced.

2.1.1.3 Life cycle impact assessment (LCIA)

Unless calculated manually, Life Cycle Impact Assessment (LCIA) is usually quick and automated with the help of LCA software, LCIA methods and databases. However, the LCA practitioner must have sufficient skills to choose the right indicators, database and LCA methods to be used in the analysis to have an accurate and complete interpretation of the results (Rosenbaum et al., 2018). The goal of LCIA is to translate the inventory data into environmental impact categories. According to ISO (ISO 14040, 2006; ISO 14044, 2006), LCIA should include three mandatory steps: selection of impact categories, classification and characterization. Optional steps include normalization, grouping and weighting.

The *selection of impact categories* must be aligned with the goal and scope definition and the LCA practitioner should define which impact categories are relevant for assessing the environmental burdens of a product system, such as Climate Change or Land Use indicators. *Classification* is the assignment of the LCI to the impact categories. For instance, CO_2 emissions are related to Climate Change and land occupation to Land Use. It is important to note that one inventory data can contribute to different impact categories, such as SO_2 that causes Acidification and Human Toxicity. In *Characterization*, elementary flows are multiplied by their corresponding characterization factors (CF), so that quantitative results are aggregated within the same impact category, resulting in a single unit per impact category. Both classification and characterization steps are normally conducted automatically with the help of LCA software.

Impact categories have different units, which makes them not comparable. To make this possible, the *normalization* step can be performed by calculating the impact categories relative to a reference system. Standard references include geographical regions (e.g., country, continent) and population (e.g., inhabitants of a certain region). *Grouping* consists of assigning impact categories into groups, e.g., according to priority, from the lowest, medium or highest importance. *Weighting* is the most debatable step and can only be carried out after the normalization step, where each normalized impact categories have a subjective weight value, and all weighted impact categories have the same unit. This thesis only applied classification and characterization steps.

Characterization models and impact categories

Several LCIA methods are currently available, namely ReCiPe, CML, IMPACT 2002+, Eco-indicator 99, ILCD 2011, USEtox. However, with an increasing number of LCIA methods and impact categories ready for use, the mission to select one involves a substantial effort to identify the main attributes of these techniques and to track improvements in LCIA methods. Therefore, the selection of the impact categories and the LCIA method must be done carefully. It must have international acceptance, include those that are relevant to the product system under study, allow traceability, avoid double counting, and not overshadow the significant impact category (Rosenbaum et al., 2018). The LCA practitioner may also choose different LCIA methods to present their results. The Product Environmental Footprint Category Rules Guidance (PEFCR) provides a list of recommended impact categories from different characterization models for LCA studies (European Commission, 2017).

There are two types of impact categories: midpoint and endpoint. Midpoint indicators are related to specific environmental issues, such as eutrophication or climate change. On the other hand, endpoint indicators are the aggregation of midpoint impacts into 3 levels: 1) impact on human health; 2) impact on ecosystem; and 3) resource scarcity. Although endpoint categories make the analysis of LCA results straightforward, they also carry a great deal of uncertainty. Figure 2.3 shows an example of midpoint and endpoint indicators in the ReCiPe methodology, which includes 18 midpoints and 3 endpoint impact categories. Table 2.1 shows the 18 midpoint indicators and their corresponding units. The ReCiPe methodology was the most used in this thesis. However, other methods were also applied, such as CML (Guinée et al., 2002), ILCD2011 (Fazio et al., 2018), USEtox (Rosenbaum et al., 2008) and the UNEP recommended model for particulate matter (Fantke et al., 2016), which will be further explained in the other chapters of this thesis.

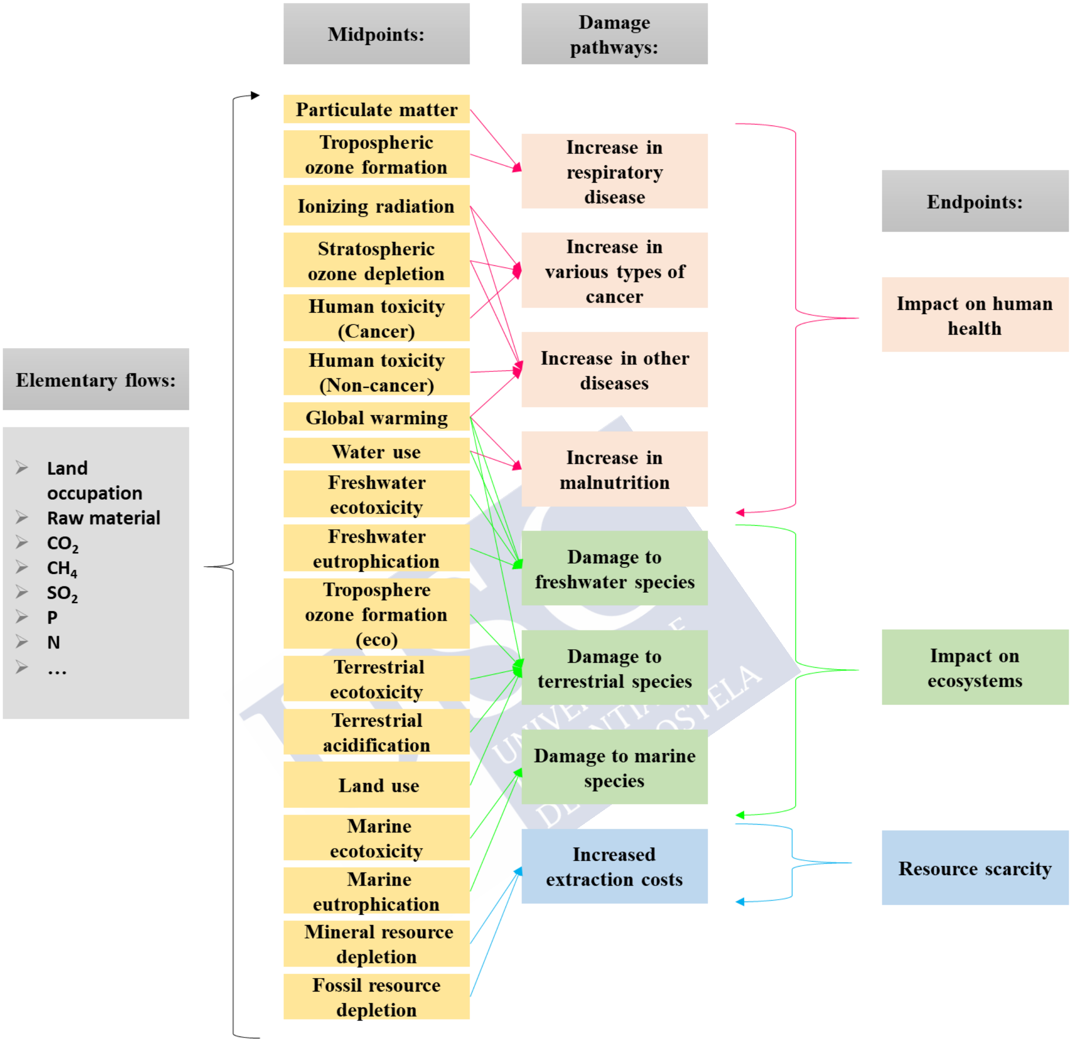

Figure 2.3. Elementary flows, midpoints, damage pathways and endpoints in ReCiPe methodology. Adapted from Huijbregts et al., (2017).

Table 2.1. Impact categories, units and indicators in ReCiPe methodology. Adapted from Huijbregts et al.,(2017).

Impact category	Unit	Indicator
Particulate matter	kg PM2.5 to air	PM2.5 population intake increase
Tropospheric ozone formation (human health)	kg NOx to air	Tropospheric ozone population intake increase (M6M)
Ionizing radiation	kg Bq Co-60 to air	Impact of radioactive substances
Stratospheric ozone depletion	kg CFC-11 to air	Stratospheric Ozone decrease
Human toxicity (cancer)	kg 1,4- DCB to urban air	Risk increase of cancer Disease incidence
Human toxicity (non-cancer)	kg 1,4- DCB to urban air	Risk increase of noncancer disease incidence
Global warming	kg CO_2 to air	Infra-red radiative forcing increase
Water use	m^3 of water consumed	Increase of water consumed
Freshwater ecotoxicity	kg 1,4- DCB to fresh water	Hazard weighted increase in fresh waters
Freshwater eutrophication	kg P to fresh water	Phosphorus increase in fresh water
Tropospheric ozone formation (ecosystem quality)	kg NOx to air	Tropospheric ozone increase (AOT40)
Terrestrial ecotoxicity	kg 1,4- DCB to industrial soil	Hazard weighted increase in natural soils
Terrestrial acidification	kg SO_2 to air	Proton increase in natural soils
Land use	m^2 ×yr annual crop land	Occupation and time integrated transformation
Marine ecotoxicity	kg 1,4- DCB to marine water	Hazard weighted increase in marine water
Marine eutrophication	kg N to marine water	Nitrogen increase in marine water
Mineral resource depletion	kg Cu	Ore grade decrease
Fossil resource depletion	kg oil	Oil grade decrease

2.1.1.4 Interpretation

Interpretation is the final phase of an LCA study, providing a critical evaluation of the results and pointing out the main findings and conclusions. It may also include a sensitivity and uncertainty analysis to assess the quality of the data. In addition, limitations and future recommendations of the study are also provided. Depending on the goal and scope of the study, this phase is important in the decision-making process for many stakeholders, such as consumers, governments, intergovernmental organizations and companies.

2.1.2 Economic assessment

An economic evaluation may include internal and external costs. Internal costs include capital costs (CAPEX) and operating costs (OPEX). CAPEX comprises fixed costs, such as construction of facilities, land and purchase of equipment. OPEX considers the expenses that a company must carry out its normal operations, such as labour costs and rent of production facility. External costs are associated with hidden costs that are not included in the price of the product but are paid by the population. External costs are related to the adverse impacts generated by a productive activity (e.g. pollution, soil erosion) (Özkan et al., 2016). The total costs are the sum of internal and external costs.

In this thesis, the Environmental Price Handbooks method has been applied to calculate external costs (De Bruyn et al., 2018). This methodology considers the ReCiPe LCIA method and uses European average prices for 2015. External costs are calculated considering the price per impact category, for example, the external price that must be included in a product or service for causing the emission of 1 kg of CO_2-eq is 0.05 €.

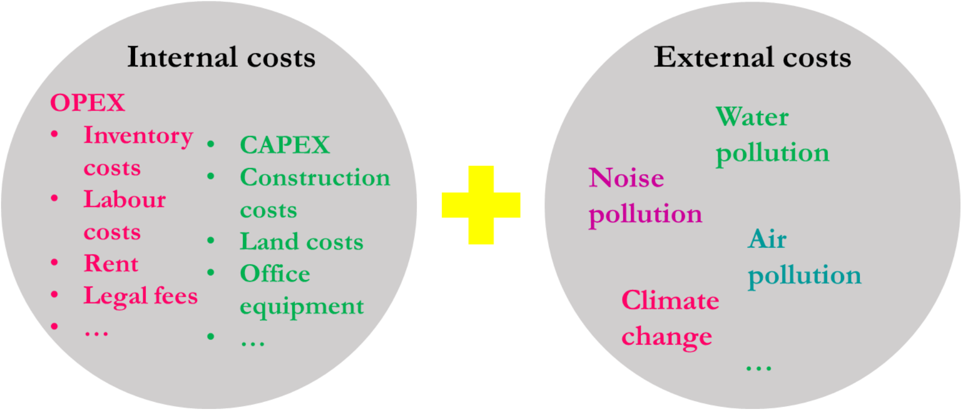

Figure 2.4. Total costs – internal and external costs.

2.1.3 Assessing the sustainability of bioproducts

Population growth and demand for food have increased in recent decades, leading to growing concerns about environmental damage and food safety. Consequently, interest in the sustainability of food products has increased. Agricultural systems have depleted resources and contribute to climate change, loss of biodiversity, loss of soil fertility and eutrophication of water bodies. It is estimated that food production will increase by 60% by 2050 and, if no action is taken, will lead to severe environmental impacts (Notarnicola et al., 2017).

In this context, particular attention has been paid to the agricultural sector because of its importance in food production. In fact, agriculture, forestry and other land uses are responsible for about 24% of global GHG emissions (EPA, 2020). Consequently, LCA has been widely applied to assess the environmental sustainability of agricultural crops. Agriculture-related LCA has paid increased attention to environmental indicators of climate change, energy demand, acidification, eutrophication, and land use (Achten and Van Acker, 2016). The most common functional units used in agricultural systems are by mass (e.g. kg of crop produced) (Boone et al., 2016) or by land management (e.g.

1 ha) (Murphy and Kendall, 2013). Crop LCA studies have been assessed at regional (Noya et al., 2015; Tabatabaie et al., 2016), national (Liang et al., 2018) and continental (Achten and Van Acker, 2016) levels.

Most of the literature on the LCA of agricultural products are farm-to-gate studies, i.e., from the production of agricultural inputs to the harvesting process. The most common agricultural inputs are fertilisers, pesticides, seeds, farm machinery and diesel fuel. The transport of these materials to the farm can have a considerable geographic range. The production and use of these inputs pose an environmental burden. Chemical fertilisers, especially nitrogen (N), are known for their intensive energy use and contribution to GHG emissions (Dimitrijevic et al., 2020). In addition, phosphate rock, from which phosphorus (P) is extracted, is a finite and non-renewable source. Moreover, phosphate rock is not well distributed spatially, with Morocco dominating about 70% of the world reserves. However, forecasting the availability of phosphate rock is highly controversial among researchers. (Daneshgar et al., 2018). The environmental impacts related to the production of agricultural machineries are usually small, due to its long life-time (Dijkman et al., 2017).

In the agricultural phase, agricultural inputs are used to produce the crop. The most important processes in agriculture are the application of fertilisers and pesticides, agricultural operations, irrigation and harvesting. The application of agrochemicals causes direct emissions and may also trigger bioaccumulation in the harvested plant, which can contribute to toxicity-related impacts. Fertiliser application causes environmental impacts in all three compartments: atmosphere, water bodies and soil. The most common on-field emissions in agriculture are ammonia (NH_3), nitrous oxide (N_2O), nitrogen oxides (NOx), nitrate (NO_3^-) and phosphate (PO_4^{3-}).

Agricultural operations require fuel consumption. On a traditional farm, it is usually necessary to plough the soil before planting. Other common operations are the application of agrochemicals, harvesting and transportation of the product. The fuels used in agricultural activities are usually of fossil origin, and burning them causes environmental damage, specifically on the impact of climate change. The operation of machinery also has a negative impact on soil quality, making the land less productive, resulting in increased fertiliser inputs to maintain production. In the long term, unsustainable agricultural systems can trigger irreversible land degradation. Irrigation is also a major contributor to global water depletion. On average, irrigated agriculture is responsible for 70% of total freshwater withdrawal, leading to significant environmental, social and economic impacts (FAO, 2017).

Once the crop is harvested, a processing phase usually takes place, where the product is either packaged (e.g., packaged maize) or goes through an industrial process to be transformed into a food item (e.g., maize starch) or even a non-food item (e.g., bioplastic from maize). The industrial processes are diverse, and the environmental impacts vary according to the type of product, the feedstock considered, the complexity of the product supply chain and the technology used.

Consumers are increasingly aware of sustainable and local consumption. Many products are transported from places far away from their consumption. In addition, locally produced and consumed food is also associated with values such as taste, authenticity, local economy and food heritage. However, it is important to note that, from an environmental point of view, local food should not be seen only from the perspective of distance, as there are other aspects that cause great environmental damage, such as production and fertiliser application. Therefore, local food should also look at other ways to reduce pollution in agriculture. One solution can be the use of organic fertilisers and crop rotation (Dijkman et al., 2017).

The literature review of studies in the agricultural area shows that there is a lack of uniformity in terms of methodological choices, making it difficult to compare agricultural systems. In addition, when contrasted to other economic activities, agricultural systems have geoclimatic aspects that make each agriculture a unique system. This makes the inventory data very variable, for example, irrigation can be used or not depending on the rain conditions in the region or the loss of biodiversity due to land use can affect some regions more intensely than others. This variability limits the environmental assessment because most LCA methods do not take spatial and temporal aspects into account (Notarnicola et al., 2017). Important environmental factors are not properly explored in the LCA of agricultural systems and there is still limited methodological consensus, for example, in the quantification of indirect land use change (iLUC), toxicity-related impacts, loss of biodiversity and water depletion (Dijkman et al., 2017).

Despite the lack of methodological consensus, it is possible to find common conclusions in the interpretation of LCA results in most agricultural systems, with the production of agrochemicals, especially nitrogen (N), and on-field emissions as the main contributors to most impact categories (Cambria et al., 2016; Mancuso et al., 2019). Moreover, Bacenetti et al. (2014) highlighted that the approach selected to calculate emissions associated with nitrogen has great influence on the environmental results. Another conclusion is that the assessment of the same crop in different locations may present very different results due to geoclimatic conditions and type of management systems (Boone et al., 2016; Cambria et al., 2016). In addition, the evaluation of the same crop, but of different genotype also influences the results, mainly due to the difference in yields they present (Mancuso et al., 2019; Noya et al., 2015).

Currently, most LCA studies on agricultural crops evaluated single crops over a one-year period (Achten and Van Acker, 2016; Mancuso et al., 2019; Noya et al., 2015; Tamburini et al., 2015). The practice of crop rotation has been carried out for centuries, but has declined in recent decades due to the intensification of agriculture, triggering negative environmental effects (EIP - AGRI, 2019; Nemecek et al., 2015). Due to the growing concern about the environmental burden caused by monocultures, increased attention has been paid to crop rotation and interest in LCA studies in this field has grown in the last decade (Knudsen et al., 2014; Nemecek et al., 2015; Tenuta et al., 2019; Yang et al., 2019). It is known that the use of crop rotation, if properly managed, can help improve ecosystem services (Mousavi and Eskandari, 2014; Nemecek et al., 2015; Selim, 2019). However, there are methodological challenges regarding the LCA of crop rotation due to the complexity of dealing with nutrient exchanges between crops (Brankatschk and Finkbeiner, 2015).

In the current context of the bioeconomy, there is a growing interest in bioproducts, as well as an increasing need for information on the environmental profile of biofuels and bio-based products in relation to their fossil-based equivalents. (Vaskan et al., 2017). Sustainability initiatives for biofuels are more developed than bio-based products. In Europe, Biofuels have had the Renewable Energy Directive (RED— Directive 2009/28/EC) since 2009, whose main objective was to reach 20% of renewable energy by 2020. Subsequently, RED II was established, setting as goal 32% of renewable energy by 2030 (European Commision, 2021). The RED methodology also applies rules for LCA of biofuels to create a common language among disclosure reports (Whittaker et al., 2011). Sustainability initiatives for bio-based products are now increasing, a great example is the European standard EN 16760 (CEN, 2015), which "*provides specific LCA requirements and guidance for bio-based products, excluding food, feed and energy, based on ISO 14040 and ISO 14044*" .

Most of the literature emphasizes the production of biofuels, such as ethanol from fermentable sugars (Bernesson et al., 2006; Gnansounou et al., 2008; Muñoz et al., 2014). However, the number of studies on LCA of bio-based products is growing (Changwichan et al., 2018; Eerhart et al., 2012; Forte et al., 2016). To a lesser extent, studies also investigated the environmental profile of intermediate platforms (e.g. glucose), that is, upstream processes, as feedstock for the production of biofuels or bio-based products (Moncada et al., 2018; Prasad et al., 2016; Vargas-Ramirez et al., 2017).

Due to the lack of consensus and uniformity in the application of LCA in bio-based products, there is a wide variety of conclusions in studies comparing bio-based products with fossil-based products. However, it is possible to observe some similarities between them. When the climate change category is assessed, most bio-based products have lower environmental impacts than their fossil counterparts. However, in the analysis of other impact categories, bio-based products do not necessarily have the best profile, especially regarding land use and eutrophication potential and, to a lesser extent, acidification. The figures may change considerably when GHG emissions from iLUC are taken into account in the analysis (Hjuler and Hansen, 2018).

The literature has also extensively studied the economic evaluation of bioproducts, such as biochemicals (Baroi et al., 2017; Dros et al., 2015), fermentable sugars (Moncada et al., 2018), biofuels (Joelsson et al., 2016; Seber et al., 2014), agricultural crops (Vasileiadis et al., 2017; Wendt et al., 2018). However, most studies focus on internal costs (e.g., OPEX and CAPEX), excluding external costs related to environmental pollution. The consolidation of environmental and economic assessment in view of internal and external costs, from a life cycle perspective, has recently gained notoriety in research (Özkan et al., 2016; Tamburini et al., 2015). Table 2.2. provides some examples of

LCA studies of agricultural crops, food, raw fermentable sugars, biofuels and bio-based products.

Table 2.2 Examples LCA studies of Bioproducts. Adapted from Camara-Salim et al., (2020).

Authors	**Feedstock**	**Geographical coverage**	**Functional unit (FU)**
		Agriculture	
(Ness, 2011)	Sugar beet	Sweden	50 000 ha of arable land in southern Sweden
(Soheili-Fard and Kouchaki-Penchah, 2015)	Sugar beet	Iran	1 tonne of sugar beet
Murphy and Kendall (2013)	Maize	US	1 ha of maize and stover production
Jayasundara et al. (2014)	Maize	Ontario, Canada	1Mg of grain and 1 Mg of stover
Boone et al. (2016)	Maize	Belgium	1 kg of maize grain
Noya et al. (2015)	Wheat, maize	Italy	1 kg of wheat grain
Cambria et al. (2016)	Wheat	France, United Kingdom and Italy	1 hectare
Kowalczyk (2019)	Potato	Poland	1 hectare
Wang et al. (2014)	wheat-maize rotation	China	1 ton of grain
		Food context	

Authors	Feedstock	Geographical coverage	Functional unit (FU)
Klenk et al. (2012)	Sugar beet	Europe	1 tonne of white sugar
Maravíc et al. (2015)	Sugar beet	Serbia	1 Mg of beet sugar
Spoerri and Kägi (2016)	Sugar beet	Europe	1 tonne of white beet sugar
Kulak et al. (2015)	Wheat	Europe	1 kg of bread at consumer´s home
Goucher et al. (2017)	Wheat	United Kingdom	A single wholegrain loaf of bread,
	Biofuels and bio-based context		
Moncada et al. (2018)	Spruce and maize	Generic	kg of C6 sugars
Tsiropoulos et al. (2013)	Maize grain	Europe	kg of glucose
Renouf et al. (2008)	Sugar beet, sugarcane and maize	United Kingdom, Australia and United States	kg monosaccharide
Foteinis et al. (2011)	Sugar beet	Greece	35 Gcal of bioethanol from sugar beet
Alexiades et al. (2018)	Sugar beet	California	1 MJ ethanol
Buratti et al. (2008)	Maize	Generic	1 MJ ethanol
Changwichan et al. (2018)	Sugarcane and cassava	Thailand	1000 disposable takeaway bio-based food boxes

Authors	**Feedstock**	**Geographical coverage**	**Functional unit (FU)**
Forte et al. (2016)	Wheat straw	Italy	1 kg of bio-based Butanediol
Kim et al. (2020)	Generic lignocellulosic biomass	Generic	1 kg of 2,5-furandicarboxylic acid (FDCA)

REFERENCES

Achten, W.M.J., Van Acker, K., 2016. EU-Average Impacts of Wheat Production: A Meta-Analysis of Life Cycle Assessments. J. Ind. Ecol. 20, 132–144. https://doi.org/10.1111/jiec.12278

Alexiades, A., Kendall, A., Winans, K.S., Kaffka, S.R., 2018. Sugar beet ethanol (Beta vulgaris L.): A promising low-carbon pathway for ethanol production in California. J. Clean. Prod. 172, 3907–3917. https://doi.org/10.1016/ j.jclepro.2017.05.059

Bacenetti, J., Fusi, A., Negri, M., Guidetti, R., Fiala, M., 2014. Environmental assessment of two different crop systems in terms of biomethane potential production. Sci. Total Environ. 466–467, 1066–1077. https://doi.org/10.1016/ j.scitotenv.2013.07.109

Baroi, G.N., Gavala, H.N., Westermann, P., Skiadas, I. V., 2017. Fermentative production of butyric acid from wheat straw: Economic evaluation. Ind. Crops Prod. 104, 68–80. https://doi.org/10.1016/ j.indcrop.2017.04.008

Bell, M.L., Davis, D.L., Fletcher, T., 2004. A Retrospective Assessment of Mortality from the London Smog Episode of 1952 : The Role of Influenza and Pollution. Environ. Health Perspect. 112, 6–8. https://doi.org/10.1289/ehp.6539

Bernesson, S., Nilsson, D., Hansson, P.A., 2006. A limited LCA comparing large- and small-scale production of ethanol for heavy engines under Swedish conditions. Biomass and Bioenergy 30, 46–57. https://doi.org/10.1016/ j.biombioe.2005.10.002

Bjørn, A., Owsianiak, M., Laurent, A., Olsen, S.I., Corona, A., Hauschild, M.Z., 2018a. Scope Definition, in: Life Cycle Assessment: Theory and Practice. pp. 75–116. https://doi.org/10.1007/978-3-319-56475-3_8

Bjørn, A., Owsianiak, M., Molin, C., Hauschild, M.Z., 2018b. LCA History, in: Life Cycle Assessment: Theory and Practice. pp. 17–29. https://doi.org/10.1007/978-3-319-56475-3

Boone, L., Van, V., Meester, S. De, Vandecasteele, B., Muylle, H., Roldán-ruiz, I., Nemecek, T., Dewulf, J., 2016. Environmental life cycle assessment of grain maize production : An analysis of factors causing variability. Sci. Total Environ. 553, 551–564. https://doi.org/10.1016/ j.scitotenv.2016.02.089

Brankatschk, G., Finkbeiner, M., 2015. Modeling crop rotation in agricultural LCAs - Challenges and potential solutions. Agric. Syst. 138, 66–76. https://doi.org/10.1016/j.agsy.2015.05.008

Camara-Salim, I., Feijoo, G., Moreira, M.T., 2020. Upstream Environmental Assessment, in: Transition Towards a Sustainable Biobased Economy. The Royal Society of Chemistry, pp. 12–43. https://doi.org/10.1039/ 9781839160271-00012

Cambria, D., Vazquez-Rowe, I., Gonzalez-Garcia, S., Teresa Moreira, M., Feijoo, G., Pierangeli, D., 2016. Comparative life cycle assessment study of three winter wheat production systems in the European Union. Environ. Eng. Manag. J. 15, 1755–1766.

CEN, 2015. Bio-based products - Life Cycle Assessment.

Changwichan, K., Silalertruksa, T., Gheewala, S.H., 2018. Eco-efficiency assessment of bioplastics production systems and end-of-life options. MDPI Sustain. 10, 1–15. https://doi.org/10.3390/su10040952

Daneshgar, S., Callegari, A., Capodaglio, A.G., Vaccari, D., 2018. The Potential Phosphorus Crisis : Resource Conservation and Possible Escape Technologies : A Review. MDPI Resour. 7, 1–22. https://doi.org/10.3390/resources7020037

De Bruyn, S., Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., Vergeer, R., Ahdour, S., 2018. Environmental Prices Handbook EU28 Version. Methods and numbers for valuation of environmental impacts. CE Delft 175.

Dijkman, T.J., Basset-Mens, C., Antón, A., Núñez, M., 2017. LCA of Food and Agriculture, in: Life Cycle Assessment: Theory and

Practice. Springer, Cham, pp. 723–754. https://doi.org/10.1007/978-3-319-56475-3

Dimitrijevic, A., Gavrilovic, M., Ivanovic, S., Mileusnic, Z., Miodragovic, R., Todorovic, S., 2020. Energy Use and Economic Analysis of Fertilizer Use in Wheat and Sugar Beet Production in Serbia. MDPI energies 13, 1–12. https://doi.org/10.3390/en13092361

Dros, A.B., Larue, O., Reimond, A., De Campo, F., Pera-Titus, M., 2015. Hexamethylenediamine (HMDA) from fossil- vs. bio-based routes: an economic and life cycle assessment comparative study. Green Chem. 17, 4760–4772. https://doi.org/10.1039/C5GC01549A

Durlinger, B., Koukouna, E., Broekema, R., Van Paassen, M., Scholten, J., 2017. Agri-footprint 4.0. Gouda.

Edelen, A., Ingwersen, W.W., Rodríguez, C., Alvarenga, R.A.F., Almeida, A.R. de, Wernet, G., 2018. Critical review of elementary flows in LCA data. Int. J. Life Cycle Assess. 1, 1–13. https://doi.org/10.1007/s11367-017-1354-3.

Eerhart, A.J.J.E., Faaij, A.P.C., Patel, M.K., 2012. Replacing fossil based PET with biobased PEF; process analysis, energy and GHG balance. Energy Environ. Sci. 5, 6407. https://doi.org/10.1039/c2ee02480b

EIP - AGRI, 2019. Workshop Cropping for the future : networking for crop rotation and crop diversification FINAL REPORT [WWW Document]. Final Rep. https://doi.org/https://ec.europa.eu/eip/agriculture/ sites/agri-eip/files/eip-agri_ws_cropping_for_the_future_final_report_2019_en.pdf

EPA, 2020. Global Greenhouse Gas Emissions Data [WWW Document]. URL https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (accessed 5.26.20).

EPA, 2017. DDT - A Brief History and Status [WWW Document]. United States Environ. Prot. Agency. URL https://www.epa.gov/ingredients-used-pesticide-products/ddt-brief-history-and-status#:~:text=In 1972%2C EPA issued a,based on studies in animals. (accessed 2.5.21).

European Commision, 2021. Renewable energy directive [WWW Document]. Energy. URL https://ec.europa.eu/energy/topics/ renewable-energy/ renewable-energy-directive/overview_en (accessed 3.1.21).

European Commission, 2017. PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3.

European Commission, 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. https://doi.org/10.2788/38479

Fantke, P., Evans, J., Hodas, N., Joshua, A., Jantunen, M., Jolliet, O., Mckone, T.E., 2016. Health impacts of fine particulate matter, in: Global Guidance for Life Cycle Impact Assessment Indicators. p. 166.

FAO, 2017. Water for Sustainable Food and Agriculture A report produced for the G20 Presidency of Germany. Rome.

Fazio, S., Castellani, V., Sala, S., Schau, E., Secchi, M., Zampori, L., Diaconu, E., 2018. Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment method New models and differences with ILCD. https://doi.org/10.2760/671368

Forte, A., Zucaro, A., Basosi, R., Fierro, A., 2016. LCA of 1,4-Butanediol Produced via Direct Fermentation of Sugars from Wheat Straw Feedstock within a Territorial Biorefinery. MDPI Mater. 9, 1–22. https://doi.org/10.3390/ma9070563

Foteinis, S., Kouloumpis, V., Tsoutsos, T., 2011. Life cycle analysis for bioethanol production from sugar beet crops in Greece. Energy Policy 39, 4834–4841. https://doi.org/10.1016/j.enpol.2011.06.036

Gnansounou, E., Dauriat, A., Panichelli, L., Villegas, J., 2008. Energy and greenhouse gas balances of biofuels: Biases induced by LCA modelling choices. J. Sci. Ind. Res. (India). 67, 885–897. https://doi.org/NA

Goucher, L., Bruce, R., Cameron, D.D., Lenny Koh, S.C., Horton, P., 2017. The environmental impact of fertilizer embodied in a wheat-to-bread supply chain. Nat. Plants 3, 1–5. https://doi.org/10.1038/nplants.2017.12

Grubb, M., Koch, M., Munson, A., Sullivan, F., Thomson, K., 1993. The "Earth Summit" Agreements: A Guide and Assessment. An Analysis of the Rio "92 UN Conference on Environment and Development. London. https://doi.org/10.4324/ 9780429273964

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.., De Bruijn, J.A., Van Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards.

Handl, G., 2013. Declaration of the United Nations Conference on Human Environment (Stockholm declaration), 1972 and the Rio Declaration on Environment and Development, 1992. United Nations Audiov. Libr. Int. Law.

Hjuler, S.V., Hansen, S.B., 2018. LCA of Biofuels and Biomaterials, in: Life Cycle Assessment: Theory and Practice. pp. 755–782. https://doi.org/10.1007/978-3-319-56475-3_30

HM Government, 1956. Clean Air Act 1956 [WWW Document]. Natl. Arq. URL https://www.legislation.gov.uk/ukpga/Eliz2/4-5/52/enacted

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Zelm, R. Van, 2017. ReCiPe2016 : a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y

ISO 14040, 2006. Environmental management — Life cycle assessment — Principles and framework [WWW Document]. Int. Organ. Stand. URL https://www.iso.org/standard/37456.html (accessed 2.15.21).

ISO 14044, 2006. Environmental management — Life cycle assessment — Requirements and guidelines [WWW Document]. Int. Organ. Stand. URL https://www.iso.org/standard/38498.html (accessed 2.15.21).

Jayasundara, S., Wagner-Riddle, C., Dias, G., Kariyapperuma, K.A., 2014. Energy and greenhouse gas intensity of corn (*Zea mays* L.) production in Ontario: A regional assessment. Can. J. Soil Sci. 94, 77–95. https://doi.org/10.4141/cjss2013-044

Joelsson, E., Erdei, B., Galbe, M., Wallberg, O., 2016. Techno-economic evaluation of integrated first- and second-generation ethanol production from grain and straw. Biotechnol. Biofuels 9, 1–16. https://doi.org/10.1186/s13068-015-0423-8

Kim, H., Lee, S., Ahn, Y., Lee, J., Won, W., 2020. Sustainable Production of Bioplastics from Lignocellulosic Biomass: Technoeconomic Analysis and Life-Cycle Assessment. ACS Sustain. Chem. Eng. 8, 12419–12429. https://doi.org/10.1021/acssuschemeng.0c02872

Klenk, I., Landquist, B., de Imana, O.R., 2012. The Product Carbon Footprint of EU beet sugar. Sugar Ind. J. 137, 169–177.

Knudsen, M.T., Meyer-Aurich, A., Olesen, J.E., Chirinda, N., Hermansen, J.E., 2014. Carbon footprints of crops from organic and conventional arable crop rotations - Using a life cycle assessment approach. J. Clean. Prod. 64, 609–618.

https://doi.org/10.1016/j.jclepro.2013.07.009

Kowalczyk, Z., 2019. Life cycle assessment (LCA) of potato production. E3S Web Conf. 132, 1–6. https://doi.org/https://doi.org/10.1051/e3sconf /20191320 020 3

Kulak, M., Nemecek, T., Frossard, E., Chable, V., Gaillard, G., 2015. Life cycle assessment of bread from several alternative food networks in Europe. J. Clean. Prod. 90, 104–113. https://doi.org/10.1016/ j.jclepro.2014.10.060

Liang, L., Lal, R., Ridoutt, B.G., Du, Z., Wang, D., Wang, L., Wu, W., Zhao, G., 2018. Life Cycle Assessment of China's agroecosystems. Ecol. Indic. 88, 341–350. https://doi.org/10.1016/j.ecolind.2018.01.053

Mancuso, T., Verduna, T., Blanc, S., Di Vita, G., Brun, F., 2019. Environmental sustainability and economic matters of commercial types of common wheat. Agric. Econ. 65, 194–202. https://doi.org/10.17221/ 172/2018-agricecon

Maravíc, N., Kiss, F., Seres, L., Bogdanovic, Branislav, Bogdanovic, Biljana, Seres, Z., 2015. Economic analysis and LCA of an advanced industrial-scale raw sugar juice purification procedure. Food Bioprod. Process. 5, 19–26. https://doi.org/10.1016/j.fbp.2015.02.004

Moncada, J., Vural Gursel, I., Huijgen, W.J.J., Dijkstra, J.W., Ramírez, A., 2018. Techno-economic and ex-ante environmental assessment of C6 sugars production from spruce and corn. Comparison of organosolv and wet milling technologies. J. Clean. Prod. 170, 610–624. https://doi.org/ 10.1016/j.jclepro.2017.09.195

Mousavi, S.R., Eskandari, H., 2014. A General Overview on Intercropping and Its Advantages in Sustainable Agriculture. J. Appl. Environ. Biol. Sci. 1, 482–486.

Muñoz, I., Flury, K., Jungbluth, N., Rigarlsford, G., I Canals, L.M., King, H., 2014. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int. J. Life Cycle Assess. 19, 109–119. https://doi.org/10.1007/ s11367-013-0613-1

Murphy, C.W., Kendall, A., 2013. Life cycle inventory development for corn and stover production systems under different allocation methods. Biomass and Bioenergy 58, 67–75. https://doi.org/10.1016/ j.biombioe.2013.08.008

Nemecek, T., Hayer, F., Bonnin, E., Carrouée, B., Schneider, A., Vivier, C., 2015. Designing eco-efficient crop rotations using life cycle assessment of crop combinations. Eur. J. Agron. 65, 40–51. https://doi.org/10.1016/ j.eja.2015.01.005

Ness, B., 2011. An Intergrated Sustainability Assessment of the Swedish Sugar Production System from a Life-Cycle Perspective: 2003-2015. Interdiscip. Descr. Complex Syst. 9, 23–38.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. J. Clean. Prod. 140, 399–409. https://doi.org/ 10.1016/j.jclepro.2016.06.071

Noya, I., González-García, S., Bacenetti, J., Arroja, L., Moreira, M.T., 2015. Comparative life cycle assessment of three representative feed cereals production in the Po Valley (Italy). J. Clean. Prod. 99, 250–265. https://doi.org/10.1016/ j.jclepro.2015.03.001

NPS, 2017. Theodore Roosevelt and Conservation [WWW Document]. Natl. Park Serv. URL https://www.nps.gov/thro/learn/historyculture/ theodore-roosevelt-and-conservation.htm (accessed 2.5.21).

Özkan, A., Günkaya, Z., Tok, G., Karacasulu, L., Metesoy, M., Banar, M., Kara, A., 2016. Life cycle assessment and life cycle cost analysis of magnesia spinel brick production. Sustain. 8, 1–13. https://doi.org/10.3390/ su8070662

Prasad, A., Sotenko, M., Blenkinsopp, T., Coles, S.R., 2016. Life cycle assessment of lignocellulosic biomass pretreatment methods in biofuel production. Int. J. Life Cycle Assess. 21, 44–50. https://doi.org/10.1007/s11367-015-0985-5

Renouf, M.A., Wegener, M.K., Nielsen, L.K., 2008. An environmental life cycle assessment comparing Australian sugarcane with US corn and UK sugar beet as producers of sugars for fermentation. Biomass and Bioenergy 32, 1144–1155. https://doi.org/10.1016/j.biombioe.2008.02.012

Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A.J., Jolliet, O., Juraske, R., Koehler, A., Larsen, H.F., MacLeod, M., Margni, M., Mackone, T.E., Payet, J., Schuhmacher, M., Van De Meent, D., Hauschild, M.Z., 2008. USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int. J. Life Cycle Assess. 13, 532–546. https://doi.org/10.1007/s11367-008-0038-4

Rosenbaum, R.K., Hauschild, M.Z., Boulay, A.-M., Fantke, P., Laurent, A., Núñez, M., Vieira, M., 2018. Life Cycle Impact Assessment, in: Life Cycle Assessment: Theory and Practice. pp. 167–270. https://doi.org/10.1007/978-3-319-56475-3_10

Seber, G., Malina, R., Pearlson, M.N., Olcay, H., Hileman, J.I., Barrett, S.R.H., 2014. Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. Biomass and Bioenergy 67, 108–118. https://doi.org/10.1016/ j.biombioe.2014.04.024

Selim, M.M., 2019. A Review of Advantages, Disadvantages and Challenges of Crop Rotations. Egypt. J. Agron. 41, 1–10. https://doi.org/10.21608/ agro.2019.6606.1139

Soheili-Fard, F., Kouchaki-Penchah, H., 2015. Assessing environmental burdens of sugar beet production in East Azerbaijan province of I.R. Iran based on farms size levels. Int. J. Farming

Allied Sci. 4, 489–495.

Spoerri, A., Kägi, T., 2016. Case study European Sugar : important insights for environmental footprinting, in: LCA Food 2016 - – 10th International Conference on Life Cycle Assessment of Food 2016. pp. 1–9.

Tabatabaie, S.M.H., Tahami, H., Murthy, G.S., 2016. A regional life cycle assessment and economic analysis of camelina biodiesel production in the Pacific Northwestern US. J. Clean. Prod. 172, 2389–2400. https://doi.org/10.1016/ j.jclepro.2017.11.172

Tamburini, E., Pedrini, P., Marchetti, M.G., Fano, E.A., Castaldelli, G., 2015. Life cycle based evaluation of environmental and economic impacts of agricultural productions in the Mediterranean area. Sustain. 7, 2915–2935. https://doi.org/10.3390/su7032915

Tenuta, M., Amiro, B.D., Gao, X., Wagner-Riddle, C., Gervais, M., 2019. Agricultural management practices and environmental drivers of nitrous oxide emissions over a decade for an annual and an annual-perennial crop rotation. Agric. For. Meteorol. 276–277. https://doi.org/10.1016/j.agrformet.2019.107636

The Ocean Cleanup, 2021. The Great Pacific Garbage Patch [WWW Document]. URL https://theoceancleanup.com/great-pacific-garbage-patch/(accessed 2.15.21).

Thompson, D., 2014. Tools for Environmental Management: A Practical Introduction and Guide: A Practical Introduction & Guide. Calgary University Press.

Tsiropoulos, I., Cok, B., Patel, M.K., 2013. Energy and greenhouse gas assessment of European glucose production from corn-a multiple allocation approach for a key ingredient of the bio-based economy. J. Clean. Prod. 43, 182–190. https://doi.org/10.1016/ j.jclepro.2012.12.035

UNFCCC, 2006. United Nations Framework Convention on Climate Change Handbook. Bonn.

United Nations, 2015. The Paris Agreement. Paris.

Vargas-Ramirez, J.M., Wiesenborn, D.P., Ripplinger, D.G., Pryor, S.W., 2017. Carbon footprint of industrial-beet sugars stored as raw thick juice for use as a fermentation feedstock. J. Clean. Prod. 162, 1418–1429. https://doi.org/10.1016/j.jclepro.2017.06.153

Vasileiadis, V.P., Dachbrodt-Saaydeh, S., Kudsk, P., Colnenne-David, C., Leprince, F., Holb, I.J., Kierzek, R., Furlan, L., Loddo, D., Melander, B., Jørgensen, L.N., Newton, A.C., Toque, C., van Dijk, W., Lefebvre, M., Benezit, M., Sattin, M., 2017. Sustainability of European winter wheat- and maize-based cropping systems: Economic, environmental and social ex-post assessment of conventional and IPM-based systems. Crop Prot. 97, 60–69. https://doi.org/10.1016/ j.cropro.2016.11.002

Vaskan, P., Ruiz Pachón, E., Gnansounou, E., 2017. Life Cycle Assessment of Sugar Crops and Starch-Based Integrated Biorefineries, in: Life-Cycle Assessment of Biorefineries. pp. 97–146.

Wang, C., Li, X., Gong, T., Zhang, H., 2014. Life cycle assessment of wheat-maize rotation system emphasizing high crop yield and high resource use efficiency in Quzhou County. J. Clean. Prod. 68, 56–63. https://doi.org/10.1016/ j.jclepro.2014.01.018

WCED, 1987. Our Common Future.

Wendt, L.M., Smith, W.A., Hartley, D.S., Wendt, D.S., Ross, J.A., Sexton, D.M., Lukas, J.C., Nguyen, Q.A., Murphy, J.A., Kenney, K.L., 2018. Techno-Economic Assessment of a Chopped Feedstock Logistics Supply Chain for Corn Stover. Front. Energy Res. 6, 1–14. https://doi.org/10.3389/fenrg.2018.00090

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Whittaker, C., McManus, M.C., Hammond, G.P., 2011. Greenhouse gas reporting for biofuels: A comparison between the RED, RTFO and PAS2050 methodologies. Energy Policy 39, 5950–5960. https://doi.org/10.1016/j.enpol.2011.06.054

Yang, X., Sui, P., Zhang, X., Dai, H., Yan, P., Li, C., Wang, X., Chen, Y., 2019. Environmental and economic consequences analysis of cropping systems from fragmented to concentrated farmland in the North China Plain based on a joint use of life cycle assessment, emergy and economic analysis. J. Environ. Manage. 251. https://doi.org/10.1016/ j.jenvman.2019.109588

SECTION II

AGRICULTURE AND FOOD CONTEXT

CHAPTER 3: ENVIRONMENTAL ASSESSMENT OF WHEAT AND BREAD PRODUCTION IN THE REGION OF GALICIA, SPAIN[1]

SUMMARY

Bread and wheat are one of the most important sources of nutrients worldwide. Today, modernization in agriculture and food processing have increased yields and altered the genetic and dietary facets of crops and foods. The Galician bread is an example of the Spanish food heritage, which is produced from a mixture of indigenous Galician wheat and commercial Spanish wheat. The identification of the environmental profile as a support criterion in decision making is important not only to analyse the environmental sustainability of the product, but also in the search for product excellence to enhance consumer awareness.

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[1] Chapter based on the publication:

Iana Câmara-Salim[a], Fernando Almeida-García[b,d], Sara González-García[a], Angeles Romero-Rodríguez[c], Benigno Ruíz-Nogueiras[d], Santiago Pereira-Lorenzo[d], Gumersindo Feijoo[a], Maria Teresa Moreira[a]. Life cycle assessment of autochthonous varieties of wheat and artisanal bread production in Galicia, Spain, Science of The Total Environment, Volume 713, 2020, 136720, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2020.136720.

[a] CRETUS Institute, Department of Chemical Engineering, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain
[b] Grupo Da Cunha, 15175 Carral, Spain
[c] Dept. of Analytical Chemistry, Faculty of Sciences, Universidade de Santiago de Compostela, 27002 Lugo, Spain
[d] Dept. of Crop Production and Engineering Projects, High Polytechnich School of Engineering, Universidade de Santiago de Compostela, 27002 Lugo, Spain

This chapter has a twofold perspective for the evaluation of the environmental impacts of wheat and bread, using life cycle assessment (LCA) approach, that is 1) the comparison of the different types of wheat farming systems (i.e., Galician wheat following a strategy of monoculture and crop rotation; certified Galician seed production; and commercial Spanish wheat cultivation) and 2) the environmental profile of Galician bread. The functional units chosen are 1 kg of wheat grain transported to the milling facility and 1 kg of Galician bread.

In the life cycle of Galician bread production, the results show that wheat cultivation is the most polluting phase, primarily due to the fertilisers application and on-field emissions. When analysing only the wheat cultivation systems, wheat that follows a crop rotation has the best profile, as chemical fertilisers are not applied in the field. In comparative terms with many staple foods produced in Europe, Galician bread has a low environmental impact. The overall environmental results of bread production draw attention to the dependence of bread and flour manufacturers on the agricultural sector, highlighting the need to share responsibilities across the supply chain. In addition, this study contributes to the stakeholder debate on environmental impacts related to food heritage.

3.1 INTRODUCTION

Wheat has been around for millennia and endures one of the core diets worldwide. Different types of genetic diversity crops have been developed for distinct consumption purposes. About 95% of the world production is common wheat, also called bread wheat (*Triticum aestivum*) and the remaining 5% is durum wheat (*Triticum durum*), used mainly for the production of pasta and couscous (Taylor, 2017). Milling and baking industries evaluate wheat composition (e.g., starch and protein content) and other specifications (e.g., bulk density and shape) to meet their demand (Mancuso et al., 2019).

As aforementioned in Chapter 1, there are currently about 215 million ha of wheat-growing areas in the globe. World production amounts to about 770 million t, of which 5 countries (China, India, Russia, USA and France) account for more than half of the world production (FAOSTAT, 2019). In Europe, total production represents about 155 million t, with Spain representing only 3% of total European production, concentrated mainly in the autonomous regions of Castile & Leon and Andalusia (Calatrava et al., 2018). In Galicia, wheat cultivation is less representative in quantitative terms (about 0.5% of Spanish production).

The grain of native Galician wheat can be classified in the varieties of wheat "Caveeiro" and "Callobre", which is a winter and soft wheat that, compared to durum wheat, has more starch and less gluten. Galician bread is a reference of quality at national level, which is largely attributed to the variety of native wheat that offers a distinct flavour and taste to bread as well as to its differentiated production scheme, such as the use of fermented dough and the requirement of long times of fermentation and baking in stone ovens. In an increasingly industrialised agriculture, the search for more traditional varieties that preserve the genuine organoleptic properties of bread is a growing demand. In this sense, the consumer is not only interested in preserving the food heritage associated with ingredients and artisanal production techniques (Kulak et al., 2015), but also prefers to buy a product of higher quality and taste, accredited as organic or produced according to sustainable production patterns (Ingrao et al., 2018). Beyond product excellence, the assessment of the environmental profile associated with agricultural activities can provide information on the strategy for marketing healthier and more sustainable food products.

There are different LCA studies on wheat cultivation. A number of authors have investigated wheat cultivation for non-food markets, such as for bioenergy systems (De Matos et al., 2015; Gissén et al., 2014; Muñoz et al., 2014; Röder et al., 2015). Others have focused on common wheat varieties (Mancuso et al., 2019) and different management practices, e.g. comparison of different winter wheat cropping systems (Cambria et al., 2016). The use of wheat in a crop rotation system (Wang et al., 2014) and its comparison with other arable crops, such as maize and soybean has also been investigated (Romeiko, 2019; Williams et al., 2010).

In relation to LCA studies on bread as a product, the environmental impacts of the production and consumption of bread in the United Kingdom have been assessed for white and wholemeal bread (Espinoza-Orias et al., 2011), loaf of bread, (Goucher et al., 2017), traditional durum-bread in the region of Sicilia, Italy (Ingrao et al., 2018) and bread production in Indonesia (Laurence et al., 2018). Two publications evaluated different types of bread which are traditionally consumed in the European countries (Kulak et al., 2015; Notarnicola et al., 2017b).

Within this context, this chapter attempts to combine a broader approach to the environmental assessment of an artisanal product, in which the quality of the cereal and the product are fundamental variables. Not only must it be produced sustainably, but it must also ensure that the product achieves premium quality. This study adds greater scientific relevance in this field by comparing the different systems of wheat cultivation in this region. In addition, two different bread production scenarios are compared, one using native wheat grains produced under crop rotation and the other under monoculture systems.

3.2 MATERIALS AND METHODS

3.2.1 Study area

The study area comprises three regions of Galicia (Figure 3.1): Carral, Laracha and Xinzo. The three regions represent a population of approximately 27,000 dwellers and 300 square kilometres of surface area. The inventory data for the environmental assessment correspond to average production of 51 farmers supplying Galician wheat grains to a single bakery. With an area of 320 hectares (ranging from 0.4 to 7 ha), they produce the traditional wheat of Galicia, called "trigo del país".

Most agricultural wheat fields go through a crop rotation system, which uses only organic composting material as fertiliser. The different types of crop rotation are: 1) Wheat, rapeseed and lupine in the Carral region; 2) Wheat and maize in the Laracha region; 3) Wheat and potatoes in the Xinzo region. Although to a lesser extent, wheat farming under a monoculture system is also carried out in these regions.

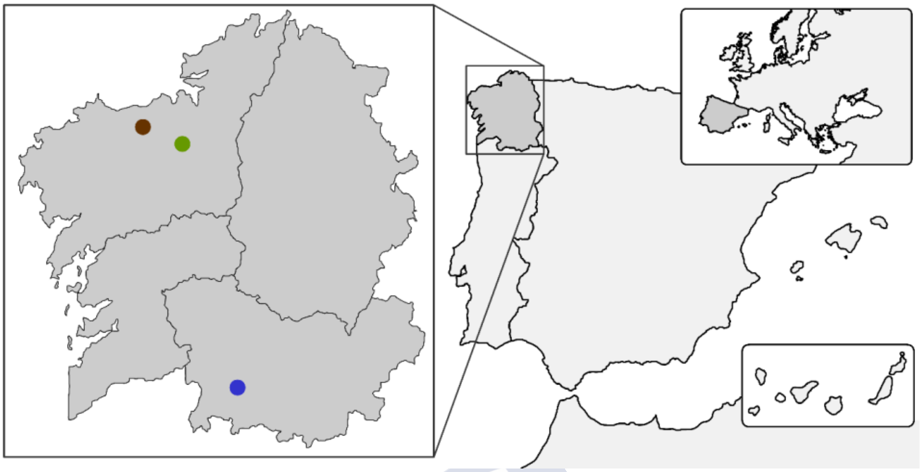

Figure 3.1 Geographical coverage of the area under study: Xinzo de Limia (blue colour), Laracha (brown colour) and Carral (green colour).

3.2.2 Goal and scope definition

This chapter has a twofold perspective: 1) to perform a cradle-to-farm LCA of different types of wheat cultivation and 2) a cradle-to-Galician bread LCA. The boundaries of the system for wheat and bread production are depicted in Figure 3.2. In the cultivation process, 1 kg of wheat grain was selected as the functional unit (FU). In the stages of bread preparation, the FU of 1 kg of bread was selected because it is the average weight of a common Galician bread and also to facilitate comparison with other studies using similar FU (Kulak et al., 2015; Notarnicola et al., 2017b)

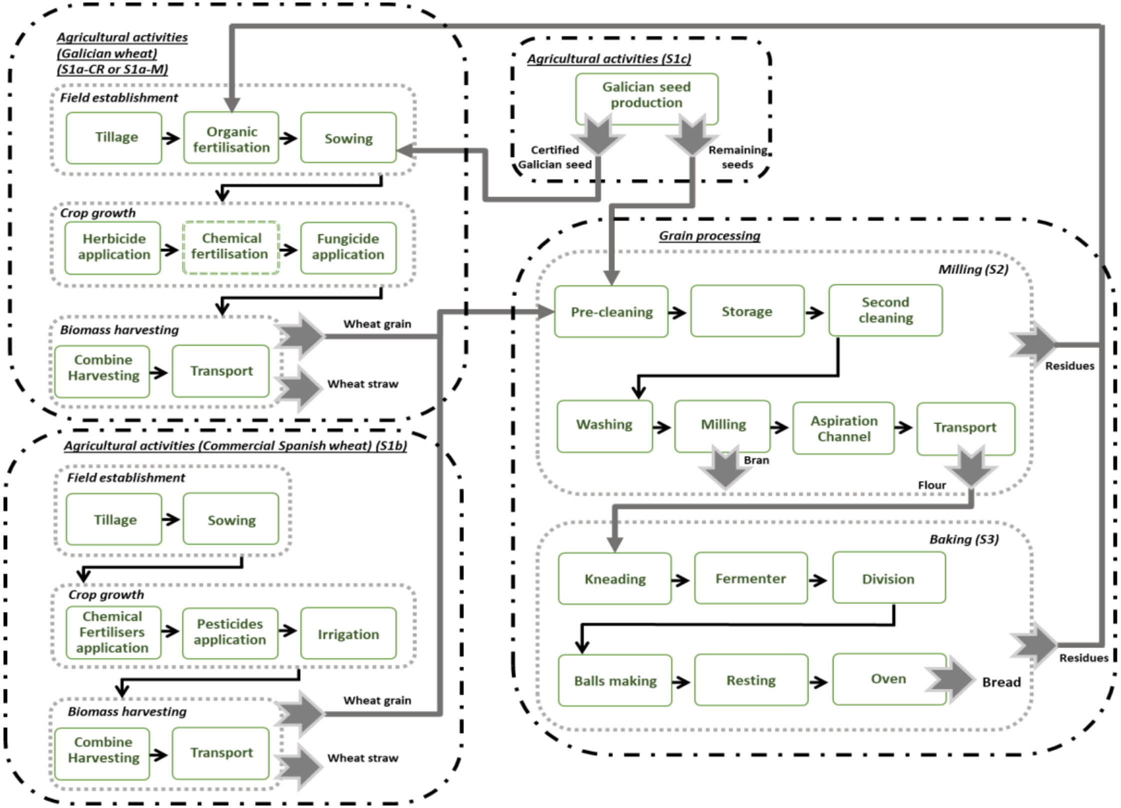

Figure 3.2 System description of the Galician bread production. Acronym: S1a -CR - Galician wheat farming system under a crop rotation system; S1a -M - Galician wheat farming system under a monoculture system; S1b – Commercial wheat farming system in the Castile & Leon and Andalusia region, Spain; S1c - Certified Galician seed production. Milling (S2) is the process of converting wheat grain into flour; Baking (S3) is the process of converting flour into bread.

3.2.3 System description and inventory data

3.2.3.1 Galician wheat ("trigo del país") (S1a -CR; S1a-M and S1c)

The subsystem S1a-CR represents wheat grown with a crop rotation system. One of the advantages of crop rotation is nutrient sequestration in the soil, avoiding costs and pollution by additional chemical fertilisation. However, longer periods are required to grow wheat. This system uses only rabbit straw manure as fertiliser. On the other hand, S1a-M represents wheat under a monoculture system, characterized by the use of rabbit straw manure and ammonium nitrate. Additional field operation is required to apply chemical fertiliser; therefore, more impacts associated to increased diesel consumption and machinery use are expected.

The wheat cultivation takes place after the harvest of the previous crop. Agricultural activities start with the field establishment, where the soil is prepared for sowing. Firstly, the tillage process with the use of a disc plough is carried out in November-December. In parallel, slurry is applied through a manure spreader. This slurry is composed of wheat straw (50%) and rabbit manure (50%). After 15 days, the seeds are scattered on the ground (about 135 kg seed·ha $^{-1}$). After the sowing process, the crop growth phase takes place. In 2-3 days, a spraying machine applies herbicides, i.e., Prosulfocarb and Diflufenican. In February-March, chemical fertilisation with ammonium nitrate is applied, only when crop rotation is not carried out in the fields. In May-June, a spraying machine applies fungicides (Tebuconazol) and finally in July-August wheat is harvested with a combine harvester, separating the wheat grain from the straw. The period between August and November corresponds to a fallow period for the land to regenerate its original state of productivity.

Table 3.1 shows the inventory and field operations by agricultural stage of the production of Galician wheat grains. To calculate the kg of machines and implements used per hectare, it is necessary to obtain information on their useful life and total weight, as explained in the formula below. The data related to the time of operation were collected on site and the data of weight and useful life of the agricultural machines were collected in the Ecoinvent® database v.2.0 (Nemecek and Kägi, 2007) (See Table 3.2).

$$kg\ of\ machinery\ used\ = weight\ (kg) \times \\ operation\ time\ \left(\frac{h}{ha}\right) \div lifetime\ (h)$$

This wheat grain has about 11-13% moisture and 13-14% protein and a bulk density of 70-75 kg·hL^{-1}. Having the correct density is very important, as it is a grain quality standard for market purposes (Charrondiere et al., 2012). The transport of grain varies from 20 to 200 km from the farm to the milling plant. However, 50% of production is between 2 and 50 km away. In this cultivation system, 100% of the straw is removed from the field. Half of the wheat straw is used for animal feed and the rest sent to composting. The weight of the straw corresponds to 40% of the weight of the wheat grain. The transport of the straw was not taken into account, as the composting process is carried out in the field and the remaining straw used for animal feed was considered to be delivered at a very close distance, and therefore can be disregarded.

A part of the land is reserved for the production of wheat seeds from Galicia (S1c). Of the total grains, between 20 and 25% do not reach the specific weight necessary to be certified as native Galician seeds. Rejected seeds are used directly for flour production. Seed production uses the same agricultural activities mentioned above for Scenario S1a-CR and S1a-M. The only exception is the selection of seeds after the harvesting process. The grain passes through a series of cleaning and sorting machines. The aim is to select the grain with the highest specific weight, also discarding weeds and other impurities. All the Galician scenarios S1a-CR, S1a-M and S1c have an average yield of 2500 kg·ha^{-1}.

Table 3.1. Inventory data and stages of agricultural activities in the production of Galician wheat grains S1a -CR, S1b-M and S1c (per ha). Yield = 2500 kg ha^{-1}.

Activities	Period	Tractor	Implement	Implement	Diesel	Inputs
		kg machinery	Type	kg machinery	kg	
Tillage	Nov - Dec	0.64	Disc plough	1.76	5.59	-
Slurry fertilisation	November	0.64	Manure spreader	0.66	3.78	Slurry (10 - 15 m^3)
Sowing	15 days	1	Disc sowing	-	13.44	Seeds (135 kg)
Herbicides application	2 – 3 days	0.19	Sprayer (24 m)	0.40	1.17	Prosulfocarb (3.5 L) and Diflufenican (120 mL)
Chemical fertilisation	Feb – March	0.19	Disk fertiliser	0.10	1.17	Ammonium nitrate (200 kg)[a]
Fungicides application	May – June	0.19	Sprayer (24 m)	0.40	1.17	Tebuconazol (1 L)
Harvesting	July - August	9.33	Combine harvester	-	5.88	-
Electricity used in seed selector machine[b]	August	-	-	-	-	100 kWh
Transportation to mill (lorry)	August	-	-	-	-	20-200 km

a This field operation only occurs for wheat cultivation under a monoculture system (S1b-M)

b This activity only occurs for Galician wheat seed cultivation (S1c)

Table 3.2. Weight and lifetime of tractors and implements used in the production of Galician wheat grains S1a -CR, S1b-M and S1c (Nemecek and Kägi, 2007).

Activities	**Weight Tractor (kg)**	**Lifetime Tractor (h)**	**Implement Type**	**Weight Implement (kg)**	**Lifetime Implement (h)**	**Operation time (h/ha)**
Tillage	7000	7200	Disc plough	2000	750	0.66
Slurry fertilisation	7000	7200	Manure spreader	6000	6000	0.66
Sowing	1500	750	Disc sowing	-	-	0.50
Herbicides application	7000	7200	Sprayer (24 m)	2000	1000	0.20
Chemical fertilisation	7000	7200	Disk fertiliser	500	1000	0.20
Fungicides application	7000	7200	Sprayer (24 m)	2000	1000	0.20
Harvesting	14000	1500	Combine harvester	-	-	1.00

3.2.3.2 Commercial Spanish wheat (S1b)

This subsystem (S1b) takes place after the harvest of the previous crop. This stage represents a typical wheat production in the regions of Castile & Leon and Andalusia (Spain), with average yield of 3000 kg·ha^{-1} and at a moisture content of 15%. This wheat represents a conventional variety of grains and, due to climatic conditions, irrigation is required. Straw represents 25% of the weight of the wheat grain. In this scenario, it was assumed that straw remains entirely in the field as a soil amendment. As for the transport of commercial wheat, it was assumed a distance of 300 km between the region of Castile & Leon and Carral in Galicia. Table 3.3 depicts the main processes considered in this subsystem in the Ecoinvent® database v.3.5 (Wernet et al., 2016)

Table 3.3. Processes considered in Ecoinvent® database v3.5 for commercial wheat cultivation (S1b).

Process name	**Unit**
Ammonium nitrate, as N {GLO}| market for | Cut-off, U	kg
Application of plant protection product, by field sprayer {GLO}| market for | Cut-off, U	ha
Combine harvesting {GLO}| market for | Cut-off, U	ha
Fertilising, by broadcaster {GLO}| market for | Cut-off, U	ha
Irrigation {ES}| market for | Cut-off, U	m^3
Pesticide, unspecified {GLO}| market for | Cut-off, U	kg
Phosphate fertiliser, as P2O5 {GLO}| market for | Cut-off, U	kg
Potassium chloride, as K2O {GLO}| market for | Cut-off, U	kg
Sowing {GLO}| market for | Cut-off, U	ha
Tillage, cultivating, chiselling {GLO}| market for | Cut-off, U	ha
Tillage, ploughing {GLO}| market for | Cut-off, U	ha
Tillage, rolling {GLO}| market for | Cut-off, U	ha
Transport, tractor and trailer, agricultural {GLO}| market for | Cut-off, U	tkm
Wheat seed, for sowing {GLO}| market for | Cut-off, U	kg
Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	tkm

3.2.3.3 Grain milling (S2)

The milling plant is located in Carral, with capacity of 7-10 tons of flour per day. Wheat flour is composed of Galician wheat grains (Scenarios S1a-CR or S1a-M), rejected certified Galician seeds (s1c) and commercial wheat grains (Scenario S1b). The bread must be a mixture of certified native Galician wheat grains and commercial Spanish wheat. This is because Galician wheat gives the aroma of bread while commercial wheat provides the right volume.

In this subsystem (S2), a pre-cleaning process is carried out to remove some of the impurities. With a sieve separator with suction, particles of different diameters are removed from the grain. At the same time, an air current removes light elements. It is an important phase to achieve a correct conservation of the material in the silo. At this stage, between 0.5 and 1.5% of impurities are generated as a by-product used in composting or animal feed.

The grain is then stored in silos for a period of 2 months. During this phase, ventilation and insecticides (pyrethrin) are applied to preserve the quality of the grain. It is a post-harvest stage in which the grain acquires an adequate consistency that favours the milling and baking processes. The grain that is ground and baked at a time very close to the harvest does not give an optimal result in the quality of the bread.

A second cleaning process is also carried out with a sieve separator with suction, equipped with sieves with a more precise mesh diameter. The machine has a lower grain flow, so there is deeper cleaning per size. It is used to remove small grains, damaged grains, small stones and dust. About 1.5% are impurities, partly composed of germs, which are used for animal feed or agricultural composting. Immediately after cleaning, a washing step is performed, also generating an average of 1.5% impurities, which are used again for breeding and composting. The most important step, the milling process is carried out delivering 70% flour and 30% bran. The flour is transported by pneumatic aspiration (aspiration channel) for storage, while the bran is sold for animal feed.

3.2.3.4 Baking (S3)

The baking facility is located 2 km from the milling site. One day of bread production uses between 7 and 10 tons of processed flour and generates 80 kg of waste for composting. Approximately 1 kg of flour produces 1.4 kg of bread. The baking activity (S3) begins with the kneading process, in which flour, water, salt and yeast are used as raw materials, with an approximate duration of 30 min. Kneading is an important step that gives strength and elasticity to the dough. A proper kneading process will facilitate the next step of fermentation, in which the yeast, by consuming carbohydrates, releases carbon dioxide that is trapped in the dough. The fermentation time in Galician bread is approximately 2 hours. A machine cuts the dough to make the shape of the bread into balls in 10 s and then goes through a 30-min resting process, in which the dough will become larger due to the effect of the yeast. Finally, the dough is baked for 75 min in a stone oven, loaded with wood pellets.

As for the inventory of the life cycle of the baking process, this factory has been evaluated as representative of the production system of this type of Galician bread. Other Galician bakeries in Galicia may have different bread production processes. It is important to bear in mind that, in fact, there are many varieties of bread in this factory. However, to facilitate the evaluation, a common production of Galician bread was assumed, which is approximately 1 kg in weight. Table 3.4 shows the inventory data for flour and bread production.

Table 3.4. Inventory data for one kg of bread production.

Inputs	**Amount**	**Description**
		Grain milling:
Wheat grain	1.1 kg	- 60% of the wheat is Spanish commercial wheat (S1b), 35% from Galician wheat (S1a) and 5% from rejected seeds from seed cultivation (S1c); - Data from S1a and S1c are collected through interviews in the bakery partner. - Data for commercial wheat S1b are adapted from Ecoinvent®: ´Wheat production, ES´. Pesticides and heavy metals field emissions were excluded from this process to have a fair comparison with the other Galicia wheat farming systems (see Table 3.3 to see the processes included in this subsystem). - Price of certified Galicia wheat grain: 400 € t^{-1}; - Price of Galicia wheat straw: 50 € t^{-1}.
Water	0.33 L	- All the water is recycled and/or absorbed in the process. There is no wastewater. Ecoinvent®:´Water, process, unspecified natural origin/m^{3}´
Pyrethrin 0.2 % (pesticides)	0.55 g	- This pesticide is used for pest control during the storing period. Ecoinvent®: ´Pyrethroid-compound {GLO}|´
Energy	0.06 kWh	- This energy is considered a medium voltage, used in the milling process. Data were gathered from Ecoinvent® background process: ´Electricity, medium voltage {ES}|´
Transport to bakery facility (lorry)	2 km	- Transportation by lorry. To calculate the emissions, the Ecoinvent® process was chosen: ´Transport, freight, lorry, unspecified {RER}|´
Outputs:	**Amount**	
Flour	0.71 kg	- Price of flour: 610-670 € t^{-1}
Bran	0.30 kg	- Price of bran: 180 € t^{-1}
Residues	0.04 kg	- This residue has no market price and is normally used for composting
		Baking:
Flour	0.71 kg	

Inputs	Amount	Description
Water	0.60 L	- All the water is recycled and/or absorbed in the process. There is no wastewater. Ecoinvent® process: ´Water, process, unspecified natural origin/m^3´
Salt	14.29 g	- Ecoinvent®: ´Sodium chloride, powder {RER}|´
Yeast	0.15 kg	- Due to lack of reliable data for yeast production, it is replaced by sodium bicarbonate in the Ecoinvent® 3.5 database as this substance has fermenting property. Ecoinvent®: ´Sodium bicarbonate {GLO}| market for sodium bicarbonate |´
Pellets	12 g	- Pellets are used as a power source for baking in stone oven. Ecoinvent®: ´Wood pellet, measured as dry mass {RER}| market for wood pellet |´
Energy	0.05 kWh	- Data were gathered from Ecoinvent® background process: ´Electricity, medium voltage {ES}|´
Outputs:	**Amount**	
Bread	1 kg	
Residues	8.5 g	- Residues are used for composting or animal feed
Emissions to air:		
Ethanol	23 g	
CO_2 biogenic	24 g	Source: Journal article (Ingrao et al., 2018)

a All information on the amount of energy and materials used in the manufacturing process, as well as the price of certain products and by-products were provided by the bakery partner, except for emissions to the atmosphere from the fermentation process.

Primary data on materials and energy required for the Galician wheat, flour and bread production were obtained through interviews and questionnaires. Information concerned the production of commercial wheat cultivation in Spain was gathered from the Ecoinvent® database v.3.5 (Wernet et al., 2016). As regards background processes of production of agrochemicals, emissions from fuel combustion in field operations, and transportation were also assessed through the Ecoinvent® database.

Field emissions from slurry and chemical fertilisation were obtained in the literature. For emissions to air, nitrous oxide N_2O (Nemecek et al., 2015); nitrogen dioxide NO_2 and ammonia NH_3 (EEA, 2013) were considered. For emissions to waterbodies, nitrate (NO_3^-) and phosphorus (P) leaching as well as phosphorus (P) runoff were taken into account (Faist Emmenegger et al., 2009; Nemecek et al., 2015). With the aim to calculate field emissions from slurry fertilisation, their nitrogen, phosphorus and potassium content were also assessed (Gross, 2016; Li-li et al., 2013). Direct pesticides and heavy metals emissions were not considered in this study. It was assumed wheat has been cultivated for many years in this area, leading to no land use change. Therefore, CO_2 emissions related to soil carbon stocks are not considered in this study.

3.2.4 Allocation

Valuable by-products are generated along the supply chain of bread production. Therefore, economic allocation was performed to account a fair division of the environmental burdens. The prices of straw, grain and flour were gathered from the industrial partner. We consider that it is not fair to perform a mass allocation between straw and wheat, as well as flour and bran, giving the price and value disparity for these products. The price of certified Galician wheat is 8 times higher than straw and flour up to 4 times higher than bran.

However, not all by-products have an economic value as in the case of lower quality seeds in the seed production phase (S1c) that are used in flour production. For this purpose, a mass allocation was made to evaluate the impacts of grain residues that have no value as certified Galician wheat grain. The prices and mass adopted in this study are depicted in Table 3.4.

3.3 RESULTS AND DISCUSSION

The Recipe 1.12 hierarchist (Goedkoop et al., 2009) methodology was chosen for LCIA and the following impact categories were selected to account the environmental burdens of wheat cultivation and Galician bread production: climate change (CC) – kg CO_2-eq, terrestrial acidification (TA) - kg SO_2-eq, freshwater eutrophication (FE) - kg P-eq, human toxicity (HT) - kg 1,4-DCB, and fossil depletion (FD) - kg oil-eq.

3.3.1 Wheat cultivation

Table 3.5 shows the absolute results for each scenario and impact category. Moreover, Figure 3.3 shows the comparative profile for each impact category of the different wheat farming systems for 1 kg of wheat grain transported to the milling facility. The results show considerable differences between the four scenarios. According to the results, Scenario (S1a-CR), which comprises the production of traditional Galician wheat grain under a crop rotation system, presents the best environmental performance in all impact categories. The input of ammonium nitrate-based fertilisers is the main factor contributing to the highest values of the environmental impacts in scenario (S1a-M), compared to (S1a-CR).

On the other hand, commercial wheat cultivation (S1b) presents the worst-case scenario for almost all impact categories, except for the climate change (CC) indicator, in which the Galician monoculture scenario (S1a-M) was the most unfavourable due to the use of the nitrogen chemical fertiliser ammonium nitrate and additional field operation for chemical fertiliser application. The two scenarios of production of Galician seeds (S1c) and wheat grains under a crop rotation scheme (S1a-CR) have identical agricultural systems, using the same inputs and energy until harvest. However, the higher results of

S1c over S1a-CR are due solely to the energy used in the seed selection machine after harvesting the seed and selecting the best grains.

Table 3.5. Absolute values of the different wheat agricultural systems. Acronym: M – Monoculture; CR – Crop rotation. FU: 1 kg of transported wheat grain.

Impact category	**(S1a-M)**[a]	**(S1a-CR)** [b]	**(S1b)**[c]	**(S1c)**[d]
CC – kg CO_2-eq	0.95	0.68	0.90	0.82
TA – kg SO_2-eq	$1.7 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$	$4.8 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
FE – kg P-eq	$2.1 \cdot 10^{-4}$	$1.8 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$2.4 \cdot 10^{-4}$
HT – kg 1,4-DCB	$1.1 \cdot 10^{-2}$	$9.2 \cdot 10^{-3}$	$3.2 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$
FD – kg oil-eq	$8.9 \cdot 10^{-2}$	$5.4 \cdot 10^{-2}$	0.18	$7.3 \cdot 10^{-2}$

a This scenario represents the Galician wheat cultivation under a monoculture system.

b This scenario represents a Galician wheat cultivation under a crop rotation system.

c This scenario represents a commercial wheat cultivation in the Castile & Leon and Andalusia regions, Spain.

d This scenario represents a Galician seed cultivation system.

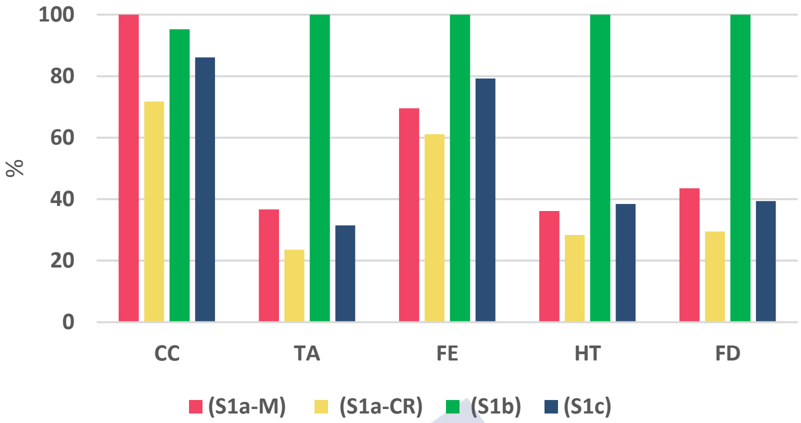

Figure 3.3. Environmental profile of the different wheat agricultural systems per kg of grain transported. Acronyms: (S1a-M) - Galician wheat monoculture; (S1a-CR) - Galician wheat cultivation in crop rotation system; (S1b) - commercial wheat cultivation in the Autonomous Community of Castile & Leon, Spain; (S1c) - Galician seed cultivation system. Climate change (CC) – kg CO_2-eq, terrestrial acidification (TA) - kg SO_2-eq, freshwater eutrophication (FE) - kg P-eq, human toxicity (HT) - kg 1,4-DCB, fossil depletion (FD) - kg oil-eq.

Figure 3.4 shows the results of the different scenarios by agricultural activities, providing a broader perspective of the environmental hotspots. In general, field emissions, fertilisers and field operations are contributing considerably to the global environmental impacts of wheat cultivation. As noted, field emissions play a key role in CC and FE, while the production and use of fertilisers contribute considerably to TA, HT and FD. Field emissions contributing to CC and FE are higher in the agricultural fields of the Galician scenarios (S1a-M, S1a-CR and S1c) than in the commercial wheat crop (S1b), due to the lower amount of nitrogen fertilisers used in this scenario. Field operation is a significant environmental hotspot in all the impact categories, especially for FD, due to the use of diesel as fuel in agricultural machineries. Only the scenario S1b uses water for irrigation, which has an important contribution to the environmental outcomes, mainly for HT, owing to background processes of water production.

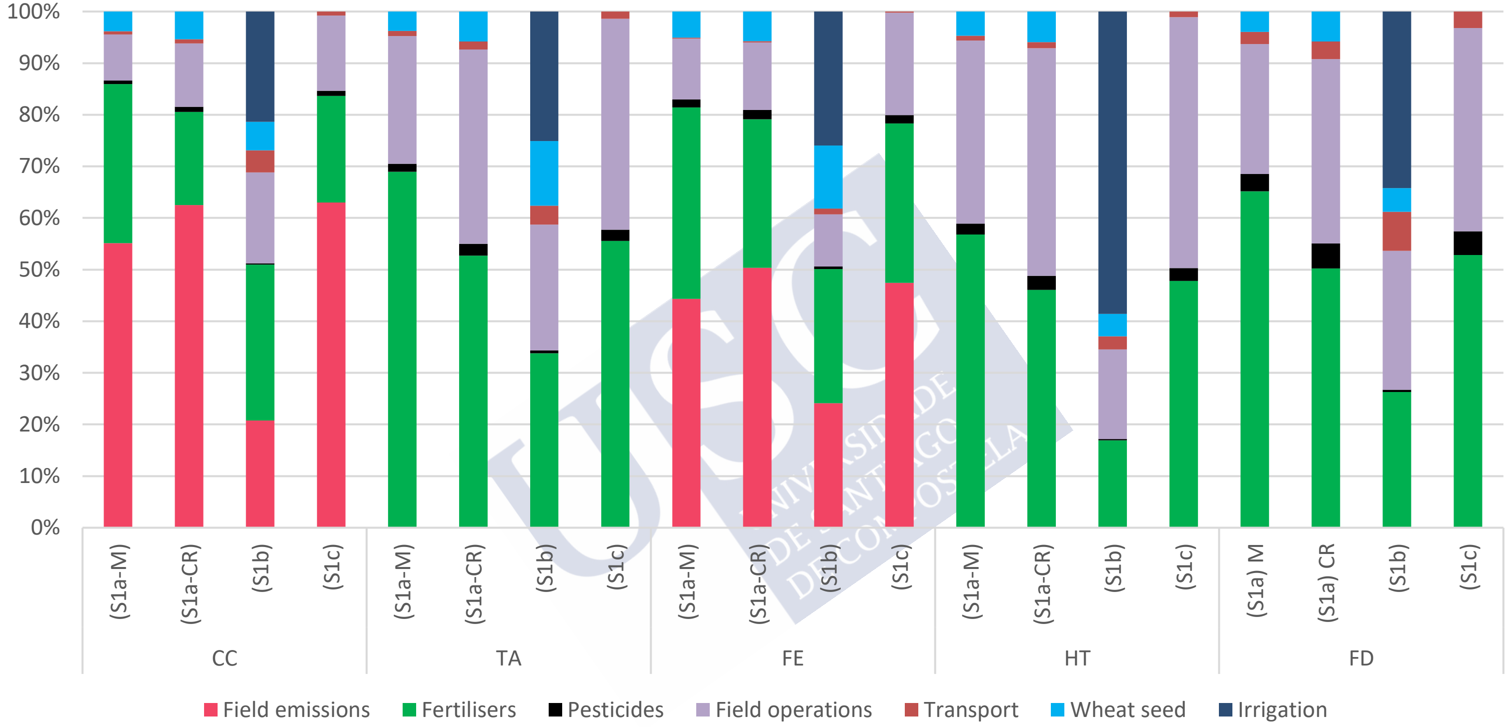

Figure 3.4. Environmental profile for 1 kg of wheat grain per agricultural activities. Acronym: (S1a-M) - Galician wheat cultivation under a monoculture system; (S1a-CR) - Galician wheat cultivation under a crop rotation system; (S1b) - commercial wheat cultivation in the Castile & Leon and Andalusia region, Spain; (S1c) - Galician seed cultivation process. Climate change (CC) – kg CO_2-eq, terrestrial acidification (TA) - kg SO_2-eq, freshwater eutrophication (FE) - kg P-eq, human toxicity (HT) - kg 1,4-DCB, fossil depletion (FD) - kg oil-eq.

In general, the results of the LCA on wheat cultivation differ between studies, making the comparison not straightforward, as many of the published studies used different methods and impact units. In addition, each agriculture has specific characteristics that influence farming systems, such as geoclimatic conditions. Table 3.6 shows the environmental impacts per kg of wheat grain of the different LCA studies on wheat cultivation. Overall, the environmental burdens of this study are relatively high for CC but low for TA, EF, HT, and FD when compared to other LCA studies. This is due to the higher amount of chemical fertilisation in other wheat producing regions and the different calculation methods for evaluating emissions in the field. Furthermore, commercial wheat in Spain and traditional Galician wheat show relatively low yields compared to other wheat crops in other regions. The wheat harvest yield for the case study in Italy (Noya et al., 2015) is more than double that of this present study.

Table 3.6. Comparison of the environmental results with different studies. FU: 1 kg of wheat grain. Acronym: Climate change (CC) – kg CO2-eq, terrestrial acidification (TA) - kg SO2-eq, freshwater eutrophication (FE) - kg P-eq, human toxicity (HT) - kg 1,4-DCB, fossil depletion (FD) - kg oil-eq.

Authors	CC	TA	FE	HT	FD
(Achten and Van Acker, 2016)	0.3 – 1.07	$(1.95\text{-}6.35)\cdot10^{-3}$	-	-	-
(Câmara-Salim et al., 2019)	0.49 – 0.93	-	$(0.5 – 4)\cdot10^{-4}$	-	-
(Romeiko, 2019)	0.56 – 0.64	$(6.6–6.8)\cdot10^{-3}$	-	-	-
(De Matos et al., 2015)	0.12 – 0.74	$7.5\cdot10^{-4} – 2.6\cdot10^{-2}$	-	-	-
(Cambria et al., 2016)	0.27 – 0.32	$(1.8–3.7)\cdot10^{-3}$	-	-	-
(Noya et al., 2015)	0.49	-	$8\cdot10^{-5}$	0.02	0.03
Present study (Castile & Leon scenario S1b)	0.91	$3.56\cdot10^{-3}$	$3.03\cdot10^{-4}$	0.03	0.18
Present study (Galician scenarios)[a]	0.82	$1.5\cdot10^{-3}$	$2.4\cdot10^{-4}$	0.01	0.07

a The results are presented in terms of the average results of the environmental impact of the different agricultural scenarios in Galicia considered in this study. That is, the average of scenarios (S1a-M), (S1a-CR), and (S1c)

3.3.2 Bread cultivation

The results in Table 3.7 show that for 1 kg of bread production, the cereal-growing stage in (S1abc -M) and (S1abc – CR) plays an important role in the global environmental impacts, representing more than 50% in all impact categories, and, to a lesser extent, the baking process (S3) followed by wheat milling (S2). The impacts of baking come mainly from the kneading process, due to the greater use of materials and energy required. Bread production using grains from crop rotation (Bread-CR) instead of monocultures (Bread-M) reduced the impacts for CC and FD by 9% and 5%, respectively (Figure 3.5). Therefore, one possible way to reduce emissions from Galician bread production and, consequently, from agriculture, is through crop rotation. In addition, the environmental impact of bread production would be reduced if more Galician grains were used, instead of commercial wheat. However, caution is required if more native grains are included in the grinding process so as not to compromise the quality of Galician bread.

Table 3.7. Environmental impacts for 1 kg of bread production. Acronym: (S1abc -M)- a mixture of wheat grains composed of Galician wheat under a monoculture system (S1a-M), commercial wheat (S1b) and rejected seeds from Galician seed production (S1c); (S1abc-CR) - a mixture of wheat grains composed of Galician wheat under a crop rotation system (S1a-CR), commercial wheat (S1b) and rejected seeds from Galician seed production (S1c); S2 – grain milling process ; S3 – baking process; Bread (M) – bread made only with S1abc-M wheat grains and Bread (CR) - Bread made only with S1abc-CR wheat grains.

Impact categories	**Agriculture (S1abc -M)**	**Agriculture (S1abc – CR)**	**Milling (S2)**	**Baking (S3)**	**Bread (M)**	**Bread (CR)**
CC – kg CO_2-eq	0.98	0.87	0.02	0.25	1.25	1.15
TA – kg SO_2-eq	$3.8\cdot10^{-3}$	$3.6\cdot10^{-3}$	$1.1\cdot10^{-4}$	$1.9\cdot10^{-3}$	$5.9\cdot10^{-3}$	$5.6\cdot10^{-3}$
FE – kg P-eq	$2.8\cdot10^{-4}$	$2.7\cdot10^{-4}$	$7.9\cdot10^{-6}$	$1.3\cdot10^{-4}$	$4.3\cdot10^{-4}$	$4.2\cdot10^{-4}$
HT – kg 1,4-DCB	$2.6\cdot10^{-2}$	$2.5\cdot10^{-2}$	$7.9\cdot10^{-4}$	$1.2\cdot10^{-2}$	$3.9\cdot10^{-2}$	$3.8\cdot10^{-2}$
FD – kg oil-eq	0.15	0.14	$5.8\cdot10^{-3}$	$5.\cdot10^{-2}$	0.21	0.19

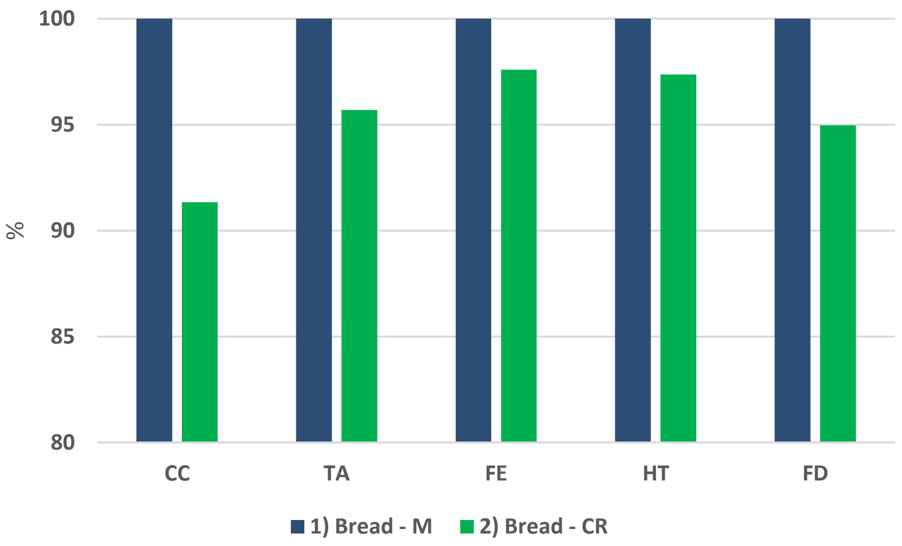

Figure 3.5. Environmental profile per kg of Bread production. 1) Bread with wheat grain which is cultivated under a monoculture system (M) and 2) Bread using wheat grain that undergoes a crop rotation system (CR). Climate change (CC) – kg CO_2-eq, terrestrial acidification (TA) - kg SO_2-eq, freshwater eutrophication (FE) - kg P-eq, human toxicity (HT) - kg 1,4-DCB, fossil depletion (FD) - kg oil-eq.

Based on the study of LCA in 21 different types of European breads, Notarnicola et al. (2017b) shows a remarkable variation in the results of 0.5 to 6.6 kg CO_2-eq per kg of bread, demonstrating that this present study has lower environmental impacts than most types of bread in Europe. Most of the LCA studies on bread production proved that the agricultural stage is the main environmental burden (Goucher et al., 2017; Ingrao et al., 2018; Kulak et al., 2015). Therefore, upstream environmental assessment of agri-food systems is imperative for understanding their global impacts, as agricultural activities (especially field emissions and agrochemical inputs) are important environmental hotspots in food production (Notarnicola et al., 2017a). The comparison of the environmental results of the Galician bread with other studies is not as straightforward as the analysis of wheat grain cultivation due to a smaller number of LCA studies on bread production chains. In addition, breads have different types of ingredients depending on the region, and the units and methods used to quantify environmental impacts are often different.

3.3.3 General discussion

Overall, three agricultural elements stand out as major environmental polluters: the application of mineral nitrogen fertiliser and its production; direct field emissions from the application of chemical fertiliser and slurry; and emissions from combustion of diesel used in the field operations. Fertiliser application such as ammonium nitrate and slurry lead to various emissions such as nitrous oxide (N_2O), which is a powerful greenhouse gas, as well as other greenhouse gases, ammonia (NH_3) and nitrogen oxides (NO_x). High nutrient loads into to soil also leads to pollution in water bodies, owing to eutrophication. Although not within the scope of this study, the application of agrochemicals causes direct emissions of pesticides and heavy metals, with negative impacts on the ecosystem.

The production of chemical fertiliser is a very high energy intensive process which emits large amount of N_2O and CO_2. Not to mention that these materials may come from great distances, sometimes in places of socio-political and economic conflict. Europe relies heavily on imports of nitrogenous mineral fertilisers, with approximately 3 million t per year (European commission, 2019). Hence, choosing a farming system which do not use chemical fertilisers avoids all the direct and indirect negative implications of mineral fertiliser use in the field.

According to the environmental outcomes, commercial wheat cultivation (S1b) showed the worst environmental profile in almost all impact categories, except for climate change. Therefore, choosing for commercial wheat grains that are produced in an agricultural system that has fewer agricultural operations (e.g., low tillage) and/or under an organic farming system could reduce the environmental burden of wheat and hence the production of Galician bread. On the other hand, wheat growing in Galicia under crop rotation (S1a-CR) represents the best-case scenario. This is mainly due to the use of no chemical fertilisation, avoiding dependence on chemical fertilisers, as well as background emissions from nitrogen fertiliser production, known for their high environmental load.

As aforementioned, attention should be paid when the functional unit is presented in terms of kg of grains, as yields have a large influence on environmental outcomes and vary considerably between agricultural fields and countries. The Spanish system of wheat cultivation does not have a high yield, with an average of 3 $t \cdot ha^{-1}$ for commercial wheat and 2.5 $t \cdot ha^{-1}$ for Galician wheat, in comparison with other agricultural fields, as in Germany, which has an average yield of $7.6 \cdot t\ ha^{-1}$ (FAOSTAT, 2019). The higher yields benefit from the environmental results if the chosen FU is 1 kg of grain, since the share of the impacts will be divided by the amount produced per hectare.

As mentioned, Galician bread that uses native wheat grains in a crop rotation system (Bread - CR) has less environmental impacts than the monoculture scenario (Bread - M). The major contributor to the production of bread in Galicia is by far the agricultural phase. Milling and baking manufacturer should be aware that their choice on wheat grain have a great influence on their environmental profile.

Galician bread is a product of food heritage with cultural and social identity. In addition, to be considered a food heritage, traditional knowledge is preserved, where there is a protocol on the quantity and quality of ingredients, as well as the production method, giving less flexibility for the use of substitute inputs for bread production. The environmental burden of bread production would be considerably reduced if high yields on wheat cultivation were achieved in Spain.

However, the quality of native Galician grain is precisely imposed because it is located in this region, which has no geoclimatic conditions leading to high yields. In addition, the use of commercial wheat grains from other major producing countries, such as France, would undermine the authenticity of this Spanish bread.

Food heritage products are usually found in tiny parts of the world, as it is the case of Galician bread. Although it seems unrepresentative at the global level, food heritage products are of great matter to local society and their value are difficult to estimate because of its historical, socio and cultural characteristics, which attract not only the local economy but also tourism. The environmental sustainability of Galician products, which is considered part of the Atlantic diet, have been assessed for some products (Esteve-Llorens et al., 2019; González-García et al., 2013). In addition, environmental LCA of traditional bread was also investigated in the region of Sicilia, Italy, to evaluate a protected designation of origin (PDO) durum-bread (Ingrao et al., 2018). This shows that interest in the environmental profile of specialty products has grown in importance between science and society.

3.4 CONCLUSIONS

This chapter identified the environmental impacts of bread production in a specific region of Galicia (Spain) using wheat grains under a system of monoculture and crop rotation. The bread is made of flour that combines Galician and commercial certified wheat grains. It is evident that the cultivation phase is by far the main environmental burden of bread production, mainly due to fertilisation and field emissions. Therefore, bread and flour producers should consider purchasing wheat crops with better environmental performance to reduce their overall environmental impacts. The use of crop rotation also proved to be an interesting alternative for mitigating impacts by reducing the use of chemical fertilisers.

There are a considerable number of LCA studies that have investigated wheat cultivation, demonstrating that yields have a great influence on the results if the functional unit is 1 kg of wheat grain produced. The comparison with other LCA studies on wheat cultivation highlights that the environmental impacts of this study are relatively low in almost all impact categories, except in the case of CC. Other studies have investigated the environmental impacts of different types of bread in various regions, showing significant differences in the results, although the cultivation phase is in most cases the main contributor to the global impacts. Galician bread production has been shown to have less impact on climate change than many European breads. However, the particularity of this product makes it difficult to compare with other types of bread, as the ingredients and production methods vary considerably.

The preservation of the food heritage is not only the responsibility and motivation of the industry, but also of the consumer who demands the product. This, combined with a growing environmental awareness of consumption, may increase the pressure for traditional agri-food products with environmental sustainability claims.

This study is, to the best of our knowledge, the first LCA study of native wheat and bread production in the region of Galicia and also in Spain. It provides a complete inventory of data and results that can be used to increase knowledge of many stakeholders, such as LCA experts and researchers; farmers; flour and bread producers, as well interested parties in food heritage products. Although this research is focused on the environmental assessment of bread production in Galicia, it opens room for future socioeconomic assessments to evaluate the full sustainability of bread production in this region.

REFERENCES

Achten, W.M.J., Van Acker, K., 2016. EU-Average Impacts of Wheat Production: A Meta-Analysis of Life Cycle Assessments. J. Ind. Ecol. 20, 132–144. https://doi.org/10.1111/jiec.12278

Calatrava, C.A., Spiegelberg, P.S., Díaz, I.B., Piferrer, S.J., 2018. Avances nacionales de superficies y producciones agrícolas. Madrid. https://doi.org/013-17-028-6

Câmara-Salim, I., González-García, S., Feijoo, G., Moreira, M.T., 2019. Assessing the environmental sustainability of glucose from wheat as a fermentation feedstock. J. Environ. Manage. 247, 323–332. https://doi.org/10.1016/ j.jenvman.2019.06.016

Cambria, D., Vazquez-Rowe, I., Gonzalez-Garcia, S., Teresa Moreira, M., Feijoo, G., Pierangeli, D., 2016. Comparative life cycle assessment study of three winter wheat production systems in the European Union. Environ. Eng. Manag. J. 15, 1755–1766.

Charrondiere, U.R., Haytowitz, D., Stadlmayr, B., 2012. FAO/ INFOODS Databases: Density Database Version 2.0. Rome.

De Matos, C.T., Garcia, J.C., Aurambout, J.-P., Kavalov, B., Manfredi, S., 2015. Environmental Sustainability Assessment of Bioeconomy Products and Processes – Progress Report 1. https://doi.org/10.2788/708144

EEA, 2013. Crop production and agricultural soils, EMEP/EEA emission inventory guidebook.

Espinoza-Orias, N., Stichnothe, H., Azapagic, A., 2011. The carbon footprint of bread. Int. J. Life Cycle Assess. 16, 351–365. https://doi.org/10.1007/s11367-011-0271-0

Esteve-Llorens, X., Darriba, C., Moreira, M.T., Feijoo, G., González-García, S., 2019. Towards an environmentally sustainable and healthy Atlantic dietary pattern: Life cycle carbon footprint and nutritional quality. Sci. Total Environ. 646, 704–715. https://doi.org/10.1016/ j.scitotenv.2018.07.264

European commission, 2019. Fertilisers in the EU. Prices, trade and use. EU Agricultural Markets Briefs.

Faist Emmenegger, M., Reinhard, J., Zah, R., 2009. Sustainability Quick Check for Biofuels. Intermediate background report. Dübendorf.

FAOSTAT, 2019. Crop statistics [WWW Document]. URL http://www.fao.org/ faostat/en/#data (accessed 1.10.19).

Gissén, C., Prade, T., Kreuger, E., Nges, I.A., Rosenqvist, H., Svensson, S.E., Lantz, M., Mattsson, J.E., Börjesson, P., Björnsson, L., 2014. Comparing energy crops for biogas production - Yields, energy input and costs in cultivation using digestate and mineral fertilisation. Biomass and Bioenergy 64, 199–210. https://doi.org/10.1016/ j.biombioe.2014.03.061

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., Zelm, R. Van, 2009. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. https://doi.org/10.029/2003JD004283

González-García, S., Hospido, A., Moreira, M.T., Feijoo, G., Arroja, L., 2013. Environmental life cycle assessment of a galician cheese: San Simon da Costa. J. Clean. Prod. 52, 253–262. https://doi.org/10.1016/ j.jclepro.2013.03.006

Goucher, L., Bruce, R., Cameron, D.D., Lenny Koh, S.C., Horton, P., 2017. The environmental impact of fertilizer embodied in a wheat-to-bread supply chain. Nat. Plants 3, 1–5. https://doi.org/10.1038/ nplants.2017.12

Gross, P., 2016. What's the nutrient value of wheat straw? [WWW Document]. Michigan State Univ. Ext. URL https://www.canr.msu.edu/news/ whats_the_nutrient_value_of_wheat_straw (accessed 7.17.19).

Ingrao, C., Licciardello, F., Pecorino, B., Muratore, G., Zerbo, A., Messineo, A., 2018. Energy and environmental assessment of a traditional durum-wheat bread. J. Clean. Prod. 171, 1494–1509. https://doi.org/10.1016/j.jclepro.2017.09.283

Kulak, M., Nemecek, T., Frossard, E., Chable, V., Gaillard, G., 2015. Life cycle assessment of bread from several alternative food networks in Europe. J. Clean. Prod. 90, 104–113. https://doi.org/10.1016/ j.jclepro.2014.10.060

Laurence, Hartono, N., Christiani, A., 2018. Case study of life cycle assessment in bread production process. IOP Conf. Ser. Earth Environ. Sci. 195. https://doi.org/10.1088/1755-1315/195/1/012043

Li-li, B., Tie-jun, Y., Bin, W., Lin, B., De-gui, T., Xiang-chao, F., 2013. Evaluation and comparison of composting rabbit manure mixed with mushroom residue and rice straw. J. Agric. Sci. Technol. 15, 1069–1081.

Mancuso, T., Verduna, T., Blanc, S., Di Vita, G., Brun, F., 2019. Environmental sustainability and economic matters of commercial types of common wheat. Agric. Econ. 65, 194–202. https://doi.org/10.17221/ 172/2018-agricecon

Muñoz, I., Flury, K., Jungbluth, N., Rigarlsford, G., I Canals, L.M., King, H., 2014. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int. J. Life Cycle Assess. 19, 109–119. https://doi.org/10.1007/ s11367-013-0613-1

Nemecek, T., Bengoa, X., Lansche, J., Mouron, P., Riedener, E., Rossi, V., Humbert, S., 2015. Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 3.0. Lausanne and Zurich.

Nemecek, T., Kägi, T., 2007. Life Cycle Inventories of Agricultural Production Systems. Data v2.0. Ecoinvent report No. 15.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017a. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. J. Clean. Prod. 140, 399–409. https://doi.org/

10.1016/j.jclepro.2016.06.071

Notarnicola, B., Tassielli, G., Renzulli, P.A., Monforti, F., 2017b. Energy flows and greenhouses gases of EU (European Union) national breads using an LCA (Life Cycle Assessment) approach. J. Clean. Prod. 140, 455–469. https://doi.org/10.1016/j.jclepro.2016.05.150

Noya, I., González-García, S., Bacenetti, J., Arroja, L., Moreira, M.T., 2015. Comparative life cycle assessment of three representative feed cereals production in the Po Valley (Italy). J. Clean. Prod. 99, 250–265. https://doi.org/10.1016/ j.jclepro.2015.03.001

Röder, M., Whittaker, C., Thornley, P., 2015. How certain are greenhouse gas reductions from bioenergy ? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. Biomass and Bioenergy 79, 50–63. https://doi.org/10.1016/j.biombioe.2015.03.030

Romeiko, X.X., 2019. A comparative life cycle assessment of crop systems irrigated with the groundwater and reclaimedwater in Northern China. MDPI Sustain. 11, 1–17. https://doi.org/10.3390/su11102743

Taylor, R.D., 2017. Outlook of the U.S. and World Wheat Industries, Agribusiness & Applied Economics. Fargo, North Dakota.

Wang, C., Li, X., Gong, T., Zhang, H., 2014. Life cycle assessment of wheat-maize rotation system emphasizing high crop yield and high resource use efficiency in Quzhou County. J. Clean. Prod. 68, 56–63. https://doi.org/10.1016/ j.jclepro.2014.01.018

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Williams, A.G., Audsley, E., Sandars, D.L., 2010. Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling. Int. J.

Life Cycle Assess. 15, 855–868. https://doi.org/10.1007/s11367-010-0212-3

CHAPTER 4: ENVIRONMENTAL ASSESSMENT OF POTATO-WHEAT CROP ROTATION IN THE REGION OF GALICIA, SPAIN[2]

SUMMARY

The intensive production of agricultural crops has negative environmental consequences. For this reason, the use of crop rotation appears as a prospect to enhance the environmental sustainability of farming systems. In the region of Galicia in north-western Spain, potato and wheat are important commodities and essential foods in the diet. This chapter investigates the environmental profile of three agricultural crops managed under a crop rotation system and following a conventional arable farming: the main rotation crop, which is the potato in the first year (cP), followed by a second year of commercial wheat (cW) and autochthonous Galician wheat (GcW) in the third year. The Life Cycle Assessment (LCA) methodology was performed using four types of functional units: in terms of productivity (kg^{-1}); land

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[2] Chapter based on the publication:

Iana Câmara-Salim[a], Fernando Almeida-García[b,c], Gumersindo Feijoo[a], Maria Teresa Moreira[a] and Sara González-García[a]. Environmental consequences of wheat-based crop rotation in potato farming systems in Galicia, Spain. Journal of Environmental Management. Volume 287, 2021, 112351, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2021.112351.

[a] CRETUS, Department of Chemical Engineering, School of Engineering, Universidade de Santiago de Compostela, Rúa Lope Gómez de Marzoa, S/n, 15782, Santiago de Compostela, Spain
[b] Grupo Da Cunha, 15175, Carral, Spain
[c] Dept. of Crop Production and Engineering Projects, High Polytechnic School of Engineering, Universidade de Santiago de Compostela, 27002, Lugo, Spain

management (ha^{-1}·$year^{-1}$); a financial function (euros $€^{-1}$ of income from sales) and energetic value (MJ^{-1}).

The outcomes of the analysis show that the GcW has the lowest environmental impact when the functional units refer to land management, financial function and energetic value. However, if analysed in terms of productivity, cP is presented as the best crop due to its comparatively higher yield, reaching a production ratio 10 times higher than wheat. In the specific case of wheat, compared to the previous Chapter 3, the environmental impacts are lower when grown in a crop rotation system in contrast to monoculture. This article demonstrates the relevance of using LCA for diverse stakeholders (e.g., farmers, consumers and researchers) to understand the environmental impacts of regional agricultural systems. In addition, it serves as a basis for future work aimed at comparing rotational agricultural systems in this region, integrating economic and social aspects.

4.1 INTRODUCTION

Agricultural development is marked by advanced technologies to increase crop yields through mineral fertilisers, pesticides, seed diversification, etc. However, this progress seems to have reached a limit, both in terms of agricultural productivity and land use (Brandão et al., 2010). About 24% of global CO_2 emissions come from agriculture, forestry and other land uses (EPA, 2020). In addition, in 2015, 10% of total CO_2 emissions in Europe are produced by the agricultural sector (European Commission, 2019a). As a result of agricultural intensification, there has been a negative impact on ecosystem services, leading to considerable loss of biodiversity (Traba and Morales, 2019). Therefore, the agricultural sector must strive to apply adaptation and mitigation measures, always seeking sustainability.

Agriculture under a monoculture system is recognized for its harmful effect on the environment. On the other hand, the use of crop rotation, if well managed, can help to improve ecosystem services (Mousavi and Eskandari, 2014; Nemecek et al., 2015; Selim, 2019). Crop rotation is an interesting approach that represents a complex combination of crops in number and variety, adjusting them to geoclimatic conditions and pedological factors. It is based on the empirical observation of an improvement in the crop when it is alternated with another in the same area in a rotation cycle. Crop rotation has been carried out for centuries, but has been reduced in recent decades due to the intensification of agriculture, causing adverse environmental impacts (EIP - AGRI, 2019; Nemecek et al., 2015). However, due to the growing concern about the environmental burden caused by agriculture, interest in crop rotation is gradually returning as it is considered an important measure to improve soil quality and it is advised by the common agricultural policy (CAP) of the European Commission (European Commission, 2019b).

Crop rotation is particularly interesting to reduce the use of mineral fertilisers, since the crop uses the remaining nutrients and the residues of previous crops. Therefore, a well-planned crop rotation system can enhance the efficiency of nutrient use, reduce the need for fertilisers and minimize the impact of pests and diseases (Brankatschk and Finkbeiner, 2015; Nemecek et al., 2015). Moreover, the cultivation of legumes included in the crop rotation system has the potential to fix nitrogen, consequently reducing the need for nitrogen fertiliser inputs (Nemecek et al., 2015). However, the complexity of crop rotation requires careful planning so that it contributes to the reduction of environmental impacts effectively (Nemecek et al., 2015). One of the main challenges in planning a crop rotation system is to harmonize the nutrients released and/or fixed from the previous crop with the nutrient demand for the next crop (Tidåker et al., 2014).

The assessment of the environmental profile of agricultural production requires a tool capable of evaluating different aspects of agricultural systems, considering regional conditions such as geoclimatic and temporal aspects when considering the time from sowing to harvest. The Life Cycle Assessment (LCA) methodology allows for the evaluation of the environmental impacts of agricultural production. To date, agricultural LCA studies are mostly related to single crops for a period of one year (Achten and Van Acker, 2016; Mancuso et al., 2019; Noya et al., 2015; Tamburini et al., 2015). As interest in the practice of crop rotation has increased, there has been a growing interest in LCA studies in this field over the last decade (Knudsen et al., 2014; Nemecek et al., 2015; Tenuta et al., 2019; Yang et al., 2019). In this evaluation framework, methodological challenges need to be addressed, as the interdependence of crop rotation has to be properly assessed (Brankatschk and Finkbeiner, 2015).

So far there is no consensus on how to harmonize the effects of crop rotation on LCA. For instance, whether environmental emissions from crop residues left in the field of the previous crop should be allocated to the subsequent crop and/or consider the avoided emissions from fertiliser application due to nutrient inputs from these residues (Jeswani et al., 2018). A challenge in LCA studies is the selection of an appropriate functional unit. This choice will have a substantial influence on the interpretation of the result. Current studies have reported their functional units in different ways: per land management (e.g. hectare x year), with the aim of understanding the impacts in terms of area and time of the entire agricultural system (Ankathi et al., 2019; Knudsen et al., 2014; Nemecek et al., 2015; Yang et al., 2019); per target product productivity (e.g. kg of feedstock), allowing the evaluation of the product units (Ankathi et al., 2019; Knudsen et al., 2014; Tidåker et al., 2014; Yang et al., 2019); per economic value (e.g. Euros €$^{-1}$) to focus on the perspective of farmers' income (Ankathi et al., 2019; Deytieux et al., 2012; Nemecek et al., 2015, 2011b); or even per nutritional value (e.g. percentage of protein) to enable the assessment of different crops with a variable nutrient composition (MacWilliam et al., 2014). Another functional unit per cereal unit (CU) was proposed by (Brankatschk and Finkbeiner, 2014), which takes into account animal feed values, such as proteins and carbohydrates and their energy content. It is interesting because it is possible to compare agricultural crops and livestock production, for example, using the same functional unit (Volanti et al., 2021).

The main objective of this chapter is to evaluate the environmental profile of potato and wheat production under a crop rotation system in the region of Galicia, Spain. These raw materials are intended for human and animal consumption. The system comprises a cradle-to-farm analysis of 3-year rotation cycle, so that in the first year the potatoes are grown, the second year corresponds to the production of commercial wheat with great productive potential, and, in the third year, a variety of native wheat is planted, which is adapted to the Galician climate and soils and endowed with great rusticity. It is a system that allows to mitigate the impact of certain pests and diseases, which significantly affects the yield of the main crop: the potato. In addition to this, it is possible to take full advantage of the residual fertility that the potato leaves in the soil (a crop that is usually abundantly fertilised).

This rotation system for potato and wheat crops was chosen by many producers as it is considered the most efficient from an economic, quality and soil health point of view. In the previous Chapter 3, wheat production was evaluated in the region of Galicia. However, it did not take into consideration the complex interactions between wheat grain production with the other cropping systems. This chapter aims to go further in assessing impacts by considering the effects that the predecessor crop has on the second crop, such as the value of straw left in the field as soil amendment.

4.2 MATERIALS AND METHODS

This chapter evaluates the environmental impacts of a potato-wheat crop rotation system in the region of Galicia, NW Spain. The selection of this region as a case study is due to the fact that Galicia is one of the most important potato producing regions in Spain (Estatista, 2020). For this purpose, an attributional life cycle assessment (LCA) methodology will be used, following the guidelines of the ISO 14040 and ISO 14044 standards (ISO 14040, 2006; ISO 14044, 2006). Four functional units (FU) are considered: 1) $ha^{-1}·year^{-1}$, that has a land management function; 2) kg^{-1} of crop, with the aim of analysing its productivity; 3) MJ^{-1}, to assess the energetic value; and 4) euro $€^{-1}$, as a financial function from the farmers' perspective. This financial function takes into consideration the gross income from sales, not considering any deduction, such as cost of production. This farm-to-gate LCA is a 3-year potato-wheat rotation system (Figure 4.1), with potato (cP) being the crop of the first year (Figure 4.2), followed by commercial wheat (cW) (Figure 4.3) and finally Galician wheat (GcW) in the third year

(Figure 4.4). The agricultural practices carried out in the three crops correspond to conventional farming systems, since they are based on the use of phytosanitary chemicals and mineral fertilisers.

The potato-wheat rotation system under study is located in the region of Galician, NW Spain and encompasses about 600 ha. This region is characterised by an oceanic climate, with annual precipitation ranging from 7500 to 1000 mm and average annual temperature of 14°C. Its characteristic climate is the result of coastal, Mediterranean, continental, and mountainous variants. The soil is acidic, with a high organic matter content and well-drained.

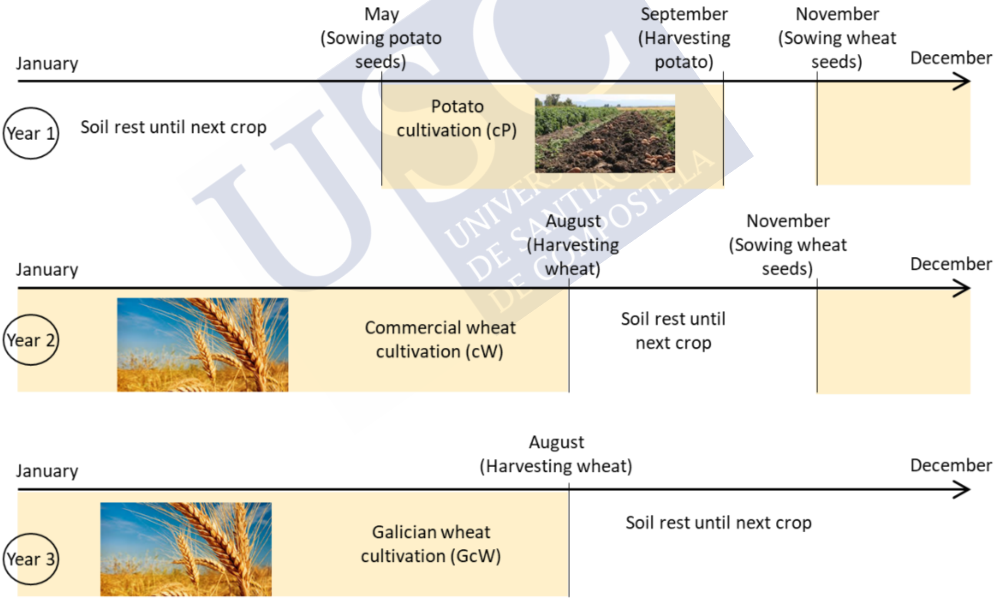

Figure 4.1. Description of the crop rotation period.

The three crops encompass three management steps. 1) *Field establishment*, where the land is prepared for sowing; 2) *Crop growth*, which is characterized by the addition of nutrients, such as nitrogen, through fertilisers as well as pesticides to strengthen plant growth; and 3) *Biomass harvesting*, when the plant finally is harvested. The processes involved in these three management steps will vary according to the type of crop. Table 4.1 summarizes some important attributes of each crop. Inventory data were collected through *in situ* interviews and questionnaires. Each agricultural system involved in this crop rotation is analysed in this study. The following sections will describe in detail the system boundaries and life cycle inventory phase.

Table 4.1. Summary of the main characteristics of the potato crops (cP), commercial wheat (cW) and Galician wheat (GcW).

	Potatoes (cP)	Commercial wheat (cW)	Galician wheat (GcW)	Unit
Area cultivated in the region^{+}	600	600	600	ha
Time of cultivation	4	10	10	months
Product yield	31.5	5.5	2.8	t·ha^{-1}
Residues yield	3.5	2.2	2.7	t·ha^{-1}
Residues left in the field	0	15	100	%
Product moisture content (MC)	80	12	12	%
Residues moisture content (MC)	80	15	-	%
Product Gross caloric value	3.14	15.9	15.9	MJ·kg^{-1}
Protein content	2.3	10	14	%
Starch content	14.8	60	58	%
Product price	0.16	0.18	0.40	€·kg^{-1}
Residues price	0.05	0.07	-	€·kg^{-1}
Product destination	Potatoes Frying industry	Bread production	Bread production	-
By-product destination	Animal feed	Animal feed	-	-

4.2.1 System boundaries

4.2.1.1 Conventional potato cultivation (cP)

Potato cultivation takes place from May in the first year (Figure 4.2). The potato, namely *Solanum tuberosum*, has a moisture content of 80%

and is composed of 14.8% starch, 2.3% protein, 2.1% fibre and 0.1% lipids. In May, the field preparation starts with a deep tillage using a mouldboard ploughing, then a reduced tillage with a chisel ploughing. Furthermore, mineral fertilisers are applied to the soil, and then a ground milling machine to finally proceed to the sowing process. During the crop growth, the herbicide treatment is first applied twice with the use of Metribuzin 70% and Bentazon 48%. In sequence, an insecticide treatment with Lambda Cyhalothrin 10% is performed. Furthermore, fertilisation is carried out with calcium ammonium nitrate (CAN 27%). Subsequently, another 4 series of pesticides are applied in the field in the following order: Metalaxyl fungicide; Cypermethrin 10% insecticides; a mix of fungicides Benalaxyl 6% + Cymoxanil 3.2% + Mancozeb 40%; and finally, another mixture of fungicides Chlorothalonil 39.95% + Dimetomorf 7.99%. During the harvest, the yield of the potato is approximately 35 t·ha^{-1}. However, about 10% of the potatoes do not reach the quality standards and are used for animal feed. Potatoes are marketed, in particular for the frying industry.

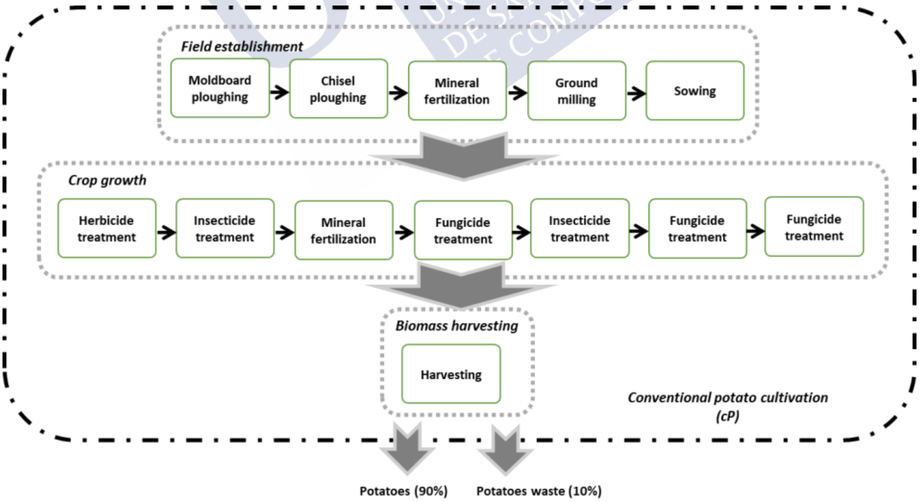

Figure 4.2. Description of conventional potato cultivation (cP) system.

4.2.1.2 Conventional commercial wheat cultivation (cW)

The second year of this agricultural system starts with the commercial wheat (*Triticum aestivum*) cultivation (Figure 4.3). This type of wheat (bread wheat) has a moisture content of 12% (MC) and is composed of 10% protein, 60% starch and 2% lipids. To meet quality criteria, the wheat grain should have less than 3% impurities and a specific weight of 73 kg·hL^{-1}. To achieve this level of quality in this region, only cleaning and storage are carried out, and drying of the wheat is not necessary. However, cleaning and storage have been disregarded in this LCA study because they use little energy and materials. In November, just before sowing, the soil is prepared with a mouldboard ploughing to turn the topsoil, followed by NPK mineral fertiliser application and ground milling, with the aim of enriching the nutrients in the soil surface. The use of phytosanitary products as a method of crop control is carried out by means of herbicides: initially the combination of Chlorotoluron and Diflufenican and later, in a second application, a mixture of Tribenuron-methyl and Pinoxaden 6%. Subsequently, calcium ammonium nitrate (CAN 27%) fertilisation takes place and Epoxiconazole fungicide is applied. The yields of wheat grain and straw are approximately 5.5 and 2.2 t·ha^{-1}, respectively. A small fraction of the straw residue is left in the field (15%) and the rest is removed and baled. The wheat grain is sold to the bakery for bread production and the straw for animal feed.

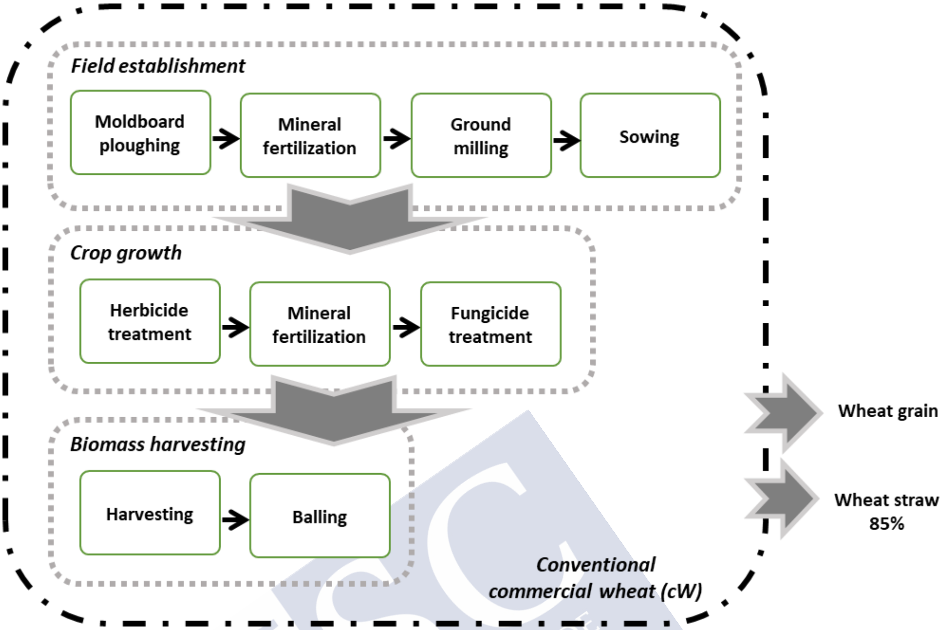

Figure 4.3. Description of the commercial wheat (cW) cultivation system.

4.2.1.3 Conventional Galician wheat cultivation (GcW)

After the harvest of the previous crop in August, the land rests two months until September. During the third year, the conventional Galician wheat crop is cultivated on the area (Figure 4.4). This wheat type is an autochthonous grain of Galicia, known as Caaveiro, which has genuine properties that differentiate it from other grains. Its moisture content is 12% (MC) and is composed of 14% protein, 58% starch, 2% lipids, less than 3% impurities and a specific weight of 73 kg·hL^{-1}. Like the commercial wheat (cW), it is not necessary to carry out the wheat drying process. Only wheat storage and cleaning are performed but their contribution is negligible. During the field establishment, the same steps as those of the previous crop are used (Figure 4.3), excluding the application of mineral fertilisation. During the crop growth, herbicide treatment is applied once with the combined use of Chlorotoluron+Diflufenican. In sequence, calcium ammonium nitrate (CAN 27%) fertilisation takes place. Subsequently, Teboconazole 25% fungicide is used in the field. The wheat grain and straw yields are approximately 2.8 and 2.7 t·ha^{-1}, respectively and 100 % the straw residue is left in the field. Straw is a natural soil conditioner, which improves soil quality. Wheat seed production goes through the same agricultural management stages as Galician wheat. The only additional process is the inclusion of a seed selection mechanism. The wheat grain is sold to the bakery for bread production.

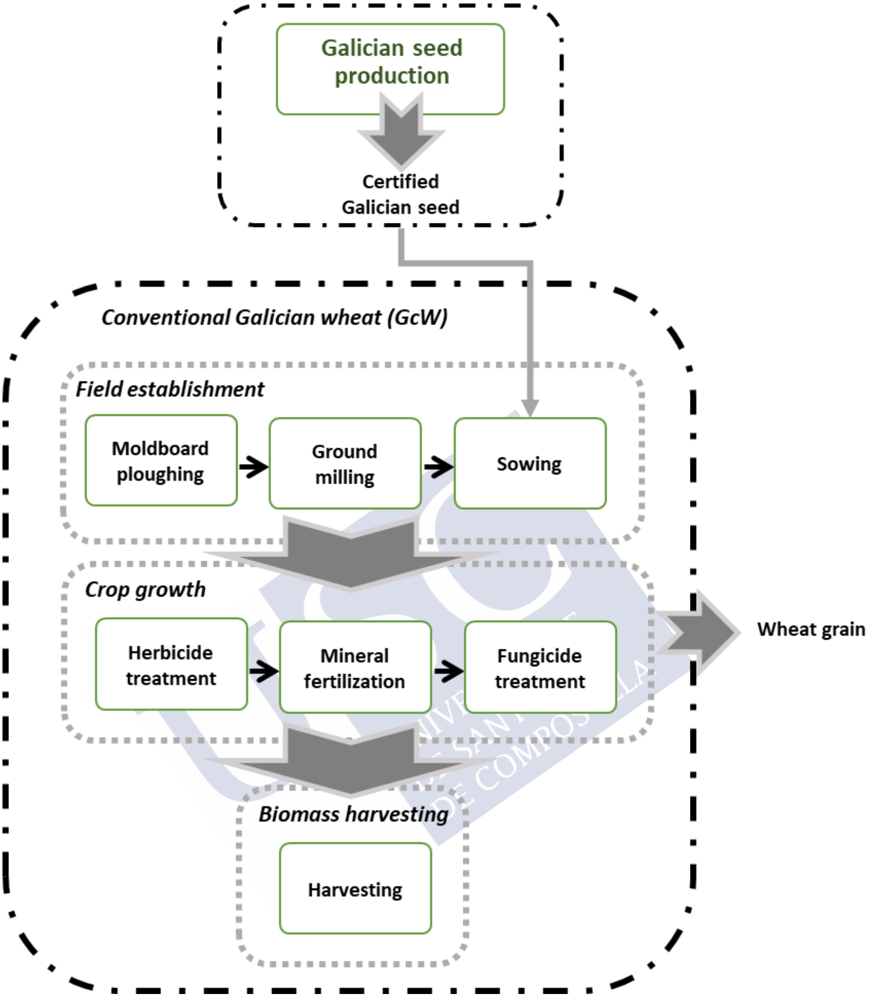

Figure 4.4. Description of conventional Galician wheat cultivation (GcW) system.

4.2.2 Inventory data

Data on agricultural activities in the three farming systems were gathered through interviews at the farmer´s cooperative. The life cycle inventory was collected for the three-year potato-wheat cropping system in the region of Galicia, taking into account the sequence of three cropping systems: 1) potatoes (cP); 2) commercial wheat (cW) and 3) Galician wheat (GcW). Background processes are derived from the Ecoinvent v3.5® database (Wernet et al., 2016) but adapted to the operating hours and fuel demands of each farming activity. Tables 4.2 and 4.3 summarize the inventory data of the 3 farming systems with special attention to these mentioned parameters. The background processes used from the Ecoinvent v3.5® database are listed in the Table 4.4.

Table 4.2. Sequence of standard field operations and inventory data (per ha) for cultivation of conventional potato cultivation (cP).

	Tractor (A)	**Implement (B)**	**A+B**			
Operation	**Weight & Power**	**Tillage item**	**Weight (kg)**	**Effective work capacity (h·ha^{-1})**	**Fuel diesel (L·ha^{-1})**	**Input rates**
Mouldboard ploughing	7000 kg 96.9 kW	Mouldboard plough	2600	0.90	18	--
Chisel ploughing	7000 kg 96.9 kW	Chisel plough	1500	0.50	12	
Mineral fertilisation	7000 kg 96.9 kW	Centrifugal fertiliser spreader	450	0.25	1.5	NPK 9-18-27 800 kg·ha^{-1}
Ground milling	7000 kg 96.9 kW	Milling machine	1300	0.75	14	-
Sowing	7000 kg 96.9 kW	Seed driller	1100	0.50	5	1200-1500 kg·ha^{-1}
Herbicide treatment	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Metribuzin 70% 750 g·ha^{-1}

	Tractor (A)	**Implement (B)**	**A+B**			
Operation	**Weight & Power**	**Tillage item**	**Weight (kg)**	**Effective work capacity ($h\cdot ha^{-1}$)**	**Fuel diesel ($L\cdot ha^{-1}$)**	**Input rates**
Herbicide treatment	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Bentazon 48% 2 $L\cdot ha^{-1}$
Insecticide treatment	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Lambda Cyhalothrin 10% 0.75 $L\cdot ha^{-1}$
Mineral fertilisation	7000 kg 96.9 kW	Centrifugal fertiliser spreader	450	0.25	1.5	CAN 27% 250 $kg\cdot ha^{-1}$
Fungicide treatment	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Metalaxyl 1.2 $kg\cdot ha^{-1}$
Insecticide treatment	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Cypermethrin 10% 0.2 $L\cdot ha^{-1}$
Fungicide treatment	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Benalaxyl 6% + Cymoxanil 3.2% + Mancozeb 40% 3 $kg\cdot ha^{-1}$
Fungicide treatment	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Chlorothalonil 39.95% + Dimetomorf 7.99% 2.5 $kg\cdot ha^{-1}$

	Tractor (A)	**Implement (B)**	**A+B**			
Operation	**Weight & Power**	**Tillage item**	**Weight (kg)**	**Effective work capacity (h·ha^{-1})**	**Fuel diesel (L·ha^{-1})**	**Input rates**
Harvesting	15000 kg 260 kW	Harvester	--	1.00	15	10% residual potatoes to animal feed 35 t·ha^{-1}
Insecticide treatment	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Lambda Cyhalothrin 10% 0.75 L·ha^{-1}
Mineral fertilisation	7000 kg 96.9 kW	Centrifugal fertiliser spreader	450	0.25	1.5	CAN 27% 250 kg·ha^{-1}

Table 4.3. Sequence of standard field operations and inventory data (per ha) of conventional commercial wheat (cW) and Galician (GcW) wheat cultivation.

	Tractor (A)	**Implement (B)**	**A+B**			
Operation	**Weight & Power**	**Tillage item**	**Weight (kg)**	**Effective work capacity (h·ha^{-1})**	**Fuel diesel (L·ha^{-1})**	**Input rates**
Mouldboard ploughing	7000 kg 96.9 kW	Mouldboard plough	2600	0.90	18	--
Mineral fertilisation+	7000 kg 96.9 kW	Centrifugal fertiliser spreader	450	0.25	1.5	NPK 8-15-15 400 kg·ha^{-1}
Ground milling	7000 kg 96.9 kW	Milling machine	1300	0.75	14	-
Sowing	7000 kg 96.9 kW	Seed driller	1100	0.50	5	200 kg·ha^{-1} + 150 kg·ha^{-1} ++
Herbicide treatment	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Chlorotoluron + Diflufenican 2.50 L·ha^{-1}
Herbicide treatment+	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Tribenuron-methyl 40 g·ha^{-1} Pinoxaden 6% 0.75L·ha^{-1}
Mineral fertilisation	7000 kg 96.9 kW	Centrifugal fertiliser spreader	450	0.25	1.5	CAN 27% 200 kg·ha^{-1} + 150 kg·ha^{-1} ++
Fungicide treatment	7000 kg 96.9 kW	Hydraulic sprayer	2000	0.15	1.5	Epoxiconazole 1 L·ha^{-1} + Teboconazole 25% 1 L·ha^{-1} ++

	Tractor (A)	**Implement (B)**	**A+B**			
Operation	**Weight & Power**	**Tillage item**	**Weight (kg)**	**Effective work capacity (h·ha^{-1})**	**Fuel diesel (L·ha^{-1})**	**Input rates**
Harvesting	15000 kg 260 kW	Harvester	--	1.00	15	--
Baling+	7000 kg 96.9 kW	Baler	1700	1.00	10	85% of straw residue is baled to animal feed
Seed selector machine++	80 kW	-	-	-	-	2000 kg seed selected per hour

+ It is applied in the conventional commercial wheat system (cW).

++ It is applied in the conventional Galician wheat system (cGW).

Table 4.4. Processes considered in the Ecoinvent® database v3.6 for the agricultural crops cP, cW and GcW.

Process name	Unit
Inputs	
Occupation, annual crop	ha·year^{-1}
Ammonium nitrate, as N {GLO}| market for | Cut-off, U	kg
Nitrogen fertiliser, as N {GLO}| market for | Cut-off, U	kg
Phosphate fertiliser, as P2O5 {GLO}| market for | Cut-off, U	kg
Potassium fertiliser, as K2O {GLO}| market for | Cut-off, U	kg
Pesticide, unspecified {GLO}| market for | Cut-off, U	kg
Nitrogen fertiliser, as N {GLO}| market for | Cut-off, U	kg
Phosphate fertiliser, as P2O5 {GLO}| market for | Cut-off, U	kg
Potassium fertiliser, as K2O {GLO}| market for | Cut-off, U	kg
Potato seed, for setting {GLO}| market for | Cut-off, U	kg
Wheat seed, for sowing {GLO}| market for | Cut-off, U	kg
Chlorotoluron {GLO}| market for | Cut-off, U	kg
Outputs to environment (water, air and/or soil)	
Dinitrogen monoxide (air)	kg
Nitrogen dioxide (air)	kg
Ammonia (air)	kg
Chlortoluron (air, water and soil)	kg
Diflufenican (air, water and soil)	kg
Tebuconazole (air, water and soil)	kg
Tribenuron-methyl (air, water and soil)	kg
Clethodim (air, water and soil)	kg
Epoxiconazole (air, water and soil)	kg
Metribuzin (air, water and soil)	kg
Bentazone (air, water and soil)	kg
Lambda-cyhalothrin (air, water and soil)	kg
Metalaxil (air, water and soil)	kg
Cypermethrin (air, water and soil)	kg
Benalaxyl-M (air, water and soil)	kg
Cymoxanil (air, water and soil)	kg
Mancozeb (air, water and soil)	kg
Chlorothalonil (air, water and soil)	kg
Dimethomorph (air, water and soil)	kg
Nitrate (groundwater)	kg
Phosphorus (groundwater)	kg
Phosphorus (river)	kg

Field emissions due to the application of agrochemicals were included in this study. Nitrous oxides (N_2O) emissions were estimated according to the Intergovernmental Panel on Climate Change (IPCC, 2019). Nitrogen dioxides Tier 1 (NO_x) and ammonia Tier 2 (NH_3) emissions were calculated as proposed by the European Environmental Agency and European Monitoring and Evaluation Programme (EMEP/EEA, 2019). Nitrate (NO_3^-) leaching (Faist-Emmenegger et al., 2009), phosphorus (P) leaching and runoff (Prasuhn, 2006) were also taken into consideration. Pesticides emissions to air, water and soil were estimated according to Product environmental footprint category rule PEFCR (European Commission, 2017). CO_2 emissions resulting from land use change have not been assessed, as the study area has been dedicated to agriculture over the past 20 years. In addition, as this study deals with crop rotation systems, the nutrients from the residues left in the field from the previous harvest were considered for the calculation of nutrient inputs for the next harvest. Emissions generated by crop residues (e.g., N_2O emissions) were also considered.

This study is an attributional LCA of 3 agriculture systems undergoing a 3-year rotation period. The agricultural inputs and outputs are considered in terms of average values. The yields of wheat and potato crops, for example, are expressed in terms of average values of the last years. Due to the complexity of the relationship between climate events and agriculture, this study has not considered the dynamics of yield variation. However, identifying the correlation between climate and crop yield is important for the adoption of measures for the resilience of agriculture to climatic phenomena (Leng and Huang, 2017).

4.2.3 Allocation

Wheat straw and non-standard potatoes are by-products generated by commercial wheat (cW) and potato (cP) cultivation systems. Allocation is not necessary when the FU is assessed in terms of hectare and year

($ha^{-1}·year^{-1}$) as well as per income (Euros $€^{-1}$) since wheat straw and non-standard potatoes residues are an integral part of the system. The allocation is also not performed when the FU is for energetic value (MJ^{-1}) because it has a nutritional perspective for the consumer and the by-products are not intended for human consumption. However, when the FU has a productive function (e.g., kg^{-1}), allocation is needed in the LCA analysis. Since these by-products have an economic value, economic allocation was chosen in this study, in agreement with other reports (Nemecek et al., 2011a). The product and residues prices were gathered from interviews and are depicted in Table 4.1. There is no need for allocation in the conventional Galician wheat system (cGW) as the straw is left in the field.

4.2.4 Life cycle impact assessment

Assigning input and output flows to impact categories is an important step in LCA to make the figures more understandable. The Recipe 1.12 hierarchist method (Goedkoop et al., 2009) at midpoint level was chosen to assess the environmental impacts in this study. The chosen impact categories are Climate Change - CC (CO_2 eq), Particulate Matter – PM (kg PM2.5 eq), Terrestrial Acidification – TA (kg SO_2 eq), Freshwater Eutrophication – FE (kg P eq), Marine Eutrophication – ME (kg N eq), Human Toxicity – HT (kg 1,4-DCB), Land Use – LU (m^2a crop eq) and Fossil Depletion – FD (kg oil eq).

4.3 RESULTS AND DISCUSSION

4.3.1 Environmental impacts – land management function

The environmental results of the cropping system when using a land management function are depicted in Table 4.5. The environmental outcomes show that, except for LU, GcW has the best environmental performance among the three farming systems and cP shows the worst profile. cP presents remarkably better results for LU due to the very low land occupation from sowing the seed to harvesting of potato (only 4 months), compared to 10 months for wheat cultivation. cP cultivation requires much more agrochemicals and agricultural machinery than the wheat crops (cW and cGW) analysed. The cW system also requires more agricultural inputs than cGW, since it needs more fertilisation, pesticides and a baling process because 85% of the wheat straw is sold for animal feed, while all straw in GcW is left in the field.

Table 4.5. Environmental impact results of wheat-potato crop rotation system. FU: per land management. Acronym: cP –potato; cW – commercial wheat; GcW – Galician wheat; CC – Climate Change; PM – Particulate Matter; TA – Terrestrial Acidification; FE – Freshwater Eutrophication; ME – Marine Eutrophication; HT – Human carcinogenic Toxicity; LU – Land Use; FD – Fossil Depletion.

	Units	**cP**	**cW**	**GcW**	**Total**
FU		**$ha^{-1}·year^{-1}$**	**$ha^{-1}·year^{-1}$**	**$ha^{-1}·year^{-1}$**	**rotation 3 years (ha)**
CC	**kg CO_2 eq**	1298	741	392	2431
PM	**kg PM2.5 eq**	2.82	1.43	0.57	4.82
TA	**kg SO_2 eq**	10.62	5.23	1.56	17.41
FE	**kg P eq**	0.46	0.33	0.14	0.93
ME	**kg N eq**	4.13	1.84	1.38	7.35
HT	**kg 1,4-DCB**	33.10	17.66	8.27	59.03
LU	**m^2a crop eq**	1230	2731	2646	6607
FD	**kg oil eq**	222	120	58	400

Figure 4.5 shows the contribution of each agricultural activity to the total environmental impacts. Hotspot's analysis offers a great opportunity to identify the processes that most contribute to environmental impacts and to adopt measures. As shown in Figure 4.5, field emissions, fertilisers application and field operation contribute significantly to CC, PM, TA and FE. As regards ME, field emissions are by far the main contributor. Field operation and fertilisers application have a large influence on HT and FD. Finally, direct land occupation is the main contributor to LU. The process "avoided fertilisers application" has a negative number, as it represents the nutrient in the crop residues of the previous crop, which reduces the need for additional fertilisers application. With regards to the "field operation process", of the machines used in the three agricultural systems, harvesting, mouldboard ploughing, and ground milling are the operations that contribute most to all impact categories. These three agricultural machines are very heavy and consume a considerably high

amount of diesel (see Tables 4.2 and 4.3) in their operations. Therefore, reducing soil tillage would benefit the sustainability of this crop rotation. The use of more efficient machines, with less weight and consumption of diesel are measures that could reduce the global environmental burden.

In this study, nitrous oxides N_2O and carbon dioxide CO_2 are the substances that contribute most to CC. In terms of the "field emission" process, fertiliser application is the largest contributor to direct N_2O emissions. CO_2 emissions are mainly derived from background processes due to the production of fertilisers and agricultural machinery. Emissions of SO_2, NH_3, Particulates < 2.5 um and NO_x are the most influential in the PM impact category, with NH_3 and NO_x directly released during fertiliser application, and the other pollutants occur mainly from background processes in the production of fertilisers and machinery. SO_2, NH_3 and NO_x pollutants also contribute to TA. Phosphate PO_4^{-3} and nitrate NO_3^- emissions due to fertilisers application have a large impact on FE and ME, respectively. Chromium into water is the main responsible to HT and crude oil, gas natural and hard coal to FD.

Chemical nitrogen fertilisation shows a strong influence on almost all environmental indicators, due to direct emissions linked to the application of fertilisers, which entails energy-intensive background processes of the nitrogen fertiliser process. The negative environmental impact of nitrogen fertilisation is an important issue in agricultural LCA studies (MacWilliam et al., 2014; Nemecek et al., 2015; Wang et al., 2014). Hence, the use of organic fertilisers could significantly contribute to reducing the environmental impacts related to the background processes of inorganic fertiliser production. In addition, the introduction of catch crops inhibits nitrogen leaching in water bodies and the use of legumes can reduce the need for nitrogen fertilisation, as they have the potential to fix nitrogen from the air and transfer nutrients for the next crops. Moreover, cover crops are also important to protect the soil, preventing soil erosion. Many LCA studies have reported the benefits of introducing catch or cover crops in crop rotation systems (Hayer et al., 2009; Kim and Dale, 2005; MacWilliam et al., 2014; Nemecek et al., 2015, 2011b, 2011a; Tidåker et al., 2014).

Due to the peculiarity of each crop rotation system and the few LCA studies in this topic, the comparison of the outcomes from this study with other literature is not straightforward. To date, and to the knowledge of the authors, there are no LCA studies that specifically investigate these three sequences of crops. However, the comparison with other LCA studies on crop rotation can be evaluated, even though different assumptions, agricultural management and crops have been used. In this chapter, as shown in Table 4.5, wheat-potato crop rotation releases 2431 kg CO_2-eq ha^{-1} in a 3-year period. A study performed by Hayer et al. (2009) presented the results of 12 crop rotations in France using combinations of rapeseed, winter wheat, winter and spring barley, winter and spring peas, sunflower and catch crop. The CC results of the aforementioned crop combinations were between 2057 kg and 2756 kg CO_2-eq ha^{-1} in a 6- and 7-year period. Nemecek et al. (2015a) investigated 64 crop combinations with the same crops, except for sunflower, and the same region as the above-mentioned study, and reported an average of approximately 2800 kg CO_2-eq ha^{-1} in a 4, 5, 6 and 7-year period. This shows that the CC outcome of the present work are in the range of previous LCA studies on crop rotation.

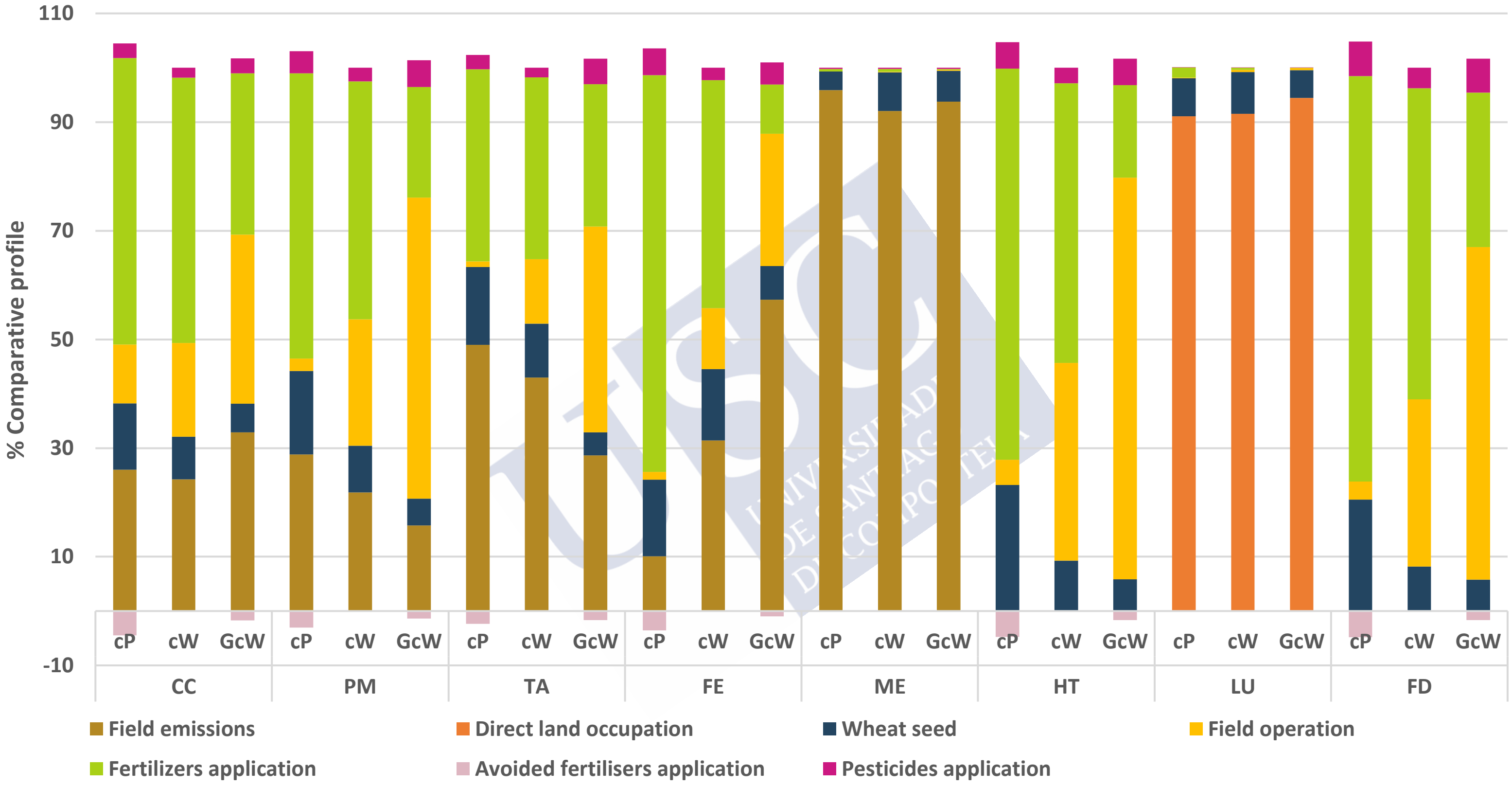

Figure 4.5. Contribution analysis of wheat-potato crop rotation system per crop cultivation. FU: ha-1·year-1. Acronym: cP – potato; cW – commercial wheat; GcW – Galician wheat; CC – Climate Change; PM – Particulate Matter; TA – Terrestrial Acidification; FE – Freshwater Eutrophication; ME – Marine Eutrophication; HT – Human carcinogenic Toxicity; LU – Land Use; FD – Fossil Depletion.

4.3.2 Environmental impacts – productive and energetic functions

When a productive function is applied in terms of kg of product, the figures show a significant change (Table 4.6). Now cP contributes the least to global environmental impacts. This is mainly due to the considerable difference in yield between the three farming systems. As already mentioned, and shown in Table 4.1, the yield of the cP harvest is about 6 and 11 times higher than the cW and cGW systems, respectively. Goglio et al. (2012) showed attention to carefully choose the functional unit when using high-yielding crops. For instance, in this present study, the cP system shows the best environmental profile, although it consumes more materials and energy than cW and cGW per hectare. The use of economic allocation is also benefiting the results for cP and cW, as both produce valuable by-products as animal feed. No allocation was performed for GcW as the wheat straw is left completely in the field.

Table 4.6. Environmental impact results of wheat-potato crop rotation system. FU: per kg of fresh harvested crop. Acronym: cP – potato; cW – commercial wheat; GcW – Galician wheat; CC – Climate Change; PM – Particulate Matter; TA – Terrestrial Acidification; FE – Freshwater Eutrophication; ME – Marine Eutrophication; HT – Human carcinogenic Toxicity; LU – Land Use; FD – Fossil Depletion.

	Units	**cP**	**cW**	**GcW**
CC	**kg CO$_2$ eq**	0.12	0.35	0.42
PM	**kg PM2.5 eq**	$2.60\cdot10^{-4}$	$6.89\cdot10^{-4}$	$6.15\cdot10^{-4}$
TA	**kg SO$_2$ eq**	$9.78\cdot10^{-4}$	$2.52\cdot10^{-3}$	$1.68\cdot10^{-3}$
FE	**kg P eq**	$4.22\cdot10^{-5}$	$1.59\cdot10^{-4}$	$1.56\cdot10^{-4}$
ME	**kg N eq**	$3.80\cdot10^{-4}$	$8.87\cdot10^{-4}$	$1.48\cdot10^{-3}$
HT	**kg 1,4-DCB**	$3.04\cdot10^{-3}$	$8.51\cdot10^{-3}$	$8.86\cdot10^{-3}$
LU	**m^{2}a crop eq**	0.11	1.31	2.83
FD	**kg oil eq**	$2.04\cdot10^{-2}$	$5.78\cdot10^{-2}$	$6.19\cdot10^{-2}$

The previous Chapter 3 investigated wheat cultivation in the region of Galician was performed using kg^{-1} as functional unit. However, it is important to notice that different system boundaries, agricultural operations as well as types of fertilisers and pesticides were considered. This current Chapter 4 considered the effects of the previous crop on the later one, such as the nutrients from agricultural residues left in the field. In addition, this chapter has as its main crop the potato while the previous one is wheat. This chapter also considers only wheat crops that undergo crop rotation, while Chapter 3 also involves monoculture farming systems. When Galician wheat in a crop rotation system was analysed in the previous chapter, the life cycle assessment of other rotating crops combined with wheat was not carried out. The comparison of monoculture with crop rotation that took place in the previous chapter considered the differences in inputs and agricultural operations between these two systems.

Figure 4.6 shows the environmental comparison of this chapter with the previous per kg of wheat grain. It can be observed that, compared to the previous chapter, this chapter shows a considerable reduction, particularly for the CC impact category. From the global figures, it can be seen that wheat cultivation under crop rotation has better environmental profile than under a monoculture system.

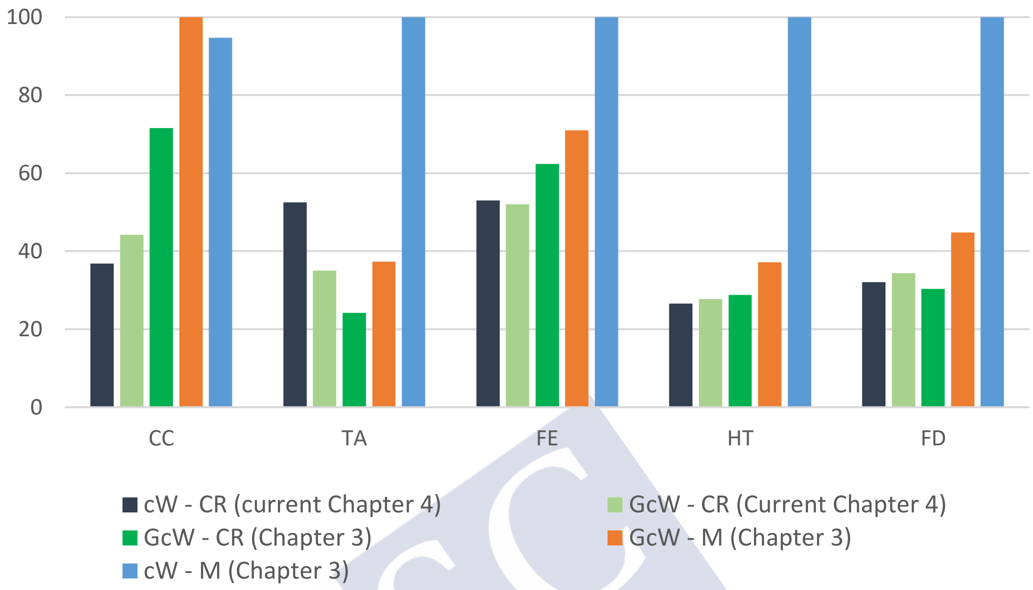

Figure 4.6. Comparison wheat cultivation from present chapter with previous. FU: kg of wheat grain. Acronym: CR – Crop rotation; cW – commercial wheat; M – Monoculture; GcW – Galician wheat; CC - Climate Change; TA – Terrestrial Acidification; FE – Freshwater Eutrophication; HT – Human carcinogenic Toxicity; FD – Fossil Depletion.

Due to the different moisture content and energetic value of these crops, another functional unit per MJ was analysed (Figure 4.7). Now the numbers have changed considerably, and the cultivation of cP potatoes shows again the worst environmental profile. This is because potatoes have high moisture content (80%) compared to wheat grain (12%) and low gross caloric value (3.14 MJ per dry matter) compared to wheat grain (15.9 MJ per dry matter).

The work of MacWilliam et al. (2014) sought to analyse the environmental impact of a crop rotation system (pulse and wheat grain), according to its energetic value. However, these authors investigated only the protein content. For this study, we believe that wheat and potatoes have not only protein, but also carbohydrate importance. Therefore, it was decided to use the gross calorific value, as this method considers the caloric value of protein, carbohydrate and lipids.

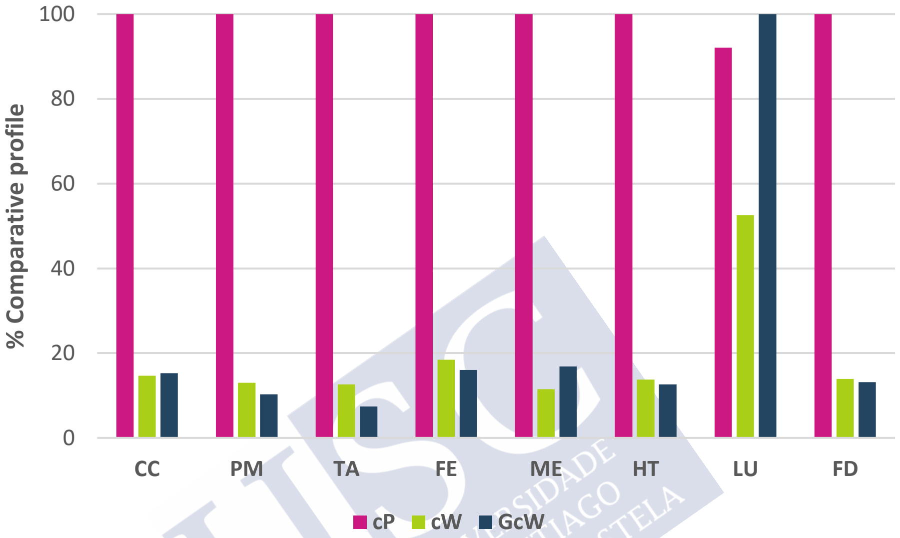

Figure 4.7. Comparative profile of wheat-potato crop rotation system. FU: per MJ. Acronym: cP – potato; cW – commercial wheat; GcW – Galician wheat; CC – Climate Change; PM – Particulate Matter; TA – Terrestrial Acidification; FE – Freshwater Eutrophication; ME – Marine Eutrophication; HT – Human carcinogenic Toxicity; LU – Land Use; FD – Fossil Depletion.

4.3.3 Environmental impacts – income function

The results of this section show the environmental impacts from the perspective of farmers' income (€) from sales. For this evaluation, the economic value of gross grain per hectare was calculated, as exemplified below:

- cW: yield (5.5 t) x price (0.18 $€\cdot kg^{-1}$) = 990 € gross grain
- GcW: yield (2.8 t) x price (0.40 $€\cdot kg^{-1}$) = 1120 € gross grain
- cP: yield (31.5 t) x price (0.16 $€\cdot kg^{-1}$) = 5040 € gross grain

Therefore, the total value of gross grain of this potato-wheat cropping system per ha is 7150 €.

Table 4.7 shows the environmental results per income. When considering the CC impact category, for every euro gained in agriculture, the GHG emissions are 0.34 kg CO^2 eq. As depicted, GcW agricultural system presents the best profile in all impact categories, except for LU, while cP shows the worst figures. The results can be explained by the fact that the price of GcW is more than double that of other crops, since it is an indigenous wheat grain that is appreciated for its nutritional value and flavour in the region. In addition, this crop uses less agrochemicals and machinery.

Table 4.7. Environmental impact results of wheat-potato crop rotation system. FU: per income. Acronym: cP – potato; cW – commercial wheat; GcW – Galician wheat; CC – Climate Change; PM – Particulate Matter; TA – Terrestrial Acidification; FE – Freshwater Eutrophication; ME – Marine Eutrophication; HT – Human carcinogenic Toxicity; LU – Land Use; FD – Fossil Depletion.

	Unit	**cP**	**cW**	**GcW**	**Profile per € of rotation)**
CC	**kg CO_2 eq**	0.54	0.31	0.16	0.34
PM	**kg PM2.5 eq**	$1.19\cdot10^{-3}$	$6\cdot10^{-4}$	$2.41\cdot10^{-4}$	$6.74\cdot10^{-4}$
TA	**kg SO_2 eq**	$4.46\cdot10^{-3}$	$2.19\cdot10^{-3}$	$6.58\cdot10^{-4}$	$2.43\cdot10^{-3}$
FE	**kg P eq**	$1.93\cdot10^{-4}$	$1.38\cdot10^{-4}$	$6.10\cdot10^{-5}$	$1.30\cdot10^{-4}$
ME	**kg N eq**	$1.73\cdot10^{-3}$	$7.72\cdot10^{-4}$	$5.79\cdot10^{-4}$	$1.02\cdot10^{-3}$
HT	**kg 1,4-DCB**	$1.39\cdot10^{-2}$	$7.41\cdot10^{-3}$	$3.47\cdot10^{-3}$	$8.25\cdot10^{-3}$
LU	**m^2a crop eq**	0.51	1.14	1.11	0.92
FD	**kg oil eq**	$9.30\cdot10^{-2}$	$5.04\cdot10^{-2}$	$2.42\cdot10^{-2}$	$5.60\cdot10^{-2}$

Some LCA studies (Hayer et al., 2009; Nemecek et al., 2015) have also included the functional unit of Euro $€^{-1}$. However, comparison with different LCA studies was not performed due to the different crops used, yield, prices and rotation periods. The results of this present research will be interesting to compare with future studies in Galicia, whose main objective is the cultivation of potato and wheat in a scheme of rotation of other crops such as legumes.

4.4 CONCLUSIONS

This chapter evaluated the environmental burdens of a conventional crop rotation system in the Galician region, Spain, using a three-year rotation period, in which the first year is composed of potato crop, followed by commercial wheat in the second year and finally native wheat grain in the third year. Although there are a variety of crop combinations in this region, this cropping system was chosen because it is one of the most preferred crop rotation systems for farmers when it comes to potato production.

The use of LCA methodology proved to be an interesting tool to evaluate the environmental impacts of this crop rotation system and the results showed different insights depending on the choice of allocation. The environmental results of the 3-year potato-wheat cropping system in the region of Galicia (Spain) shows an impact of about 2431 kg CO_2 eq for CC and 400 kg oil eq for FD per ha (about 810 kg CO_2 eq and 133 kg oil eq ha^{-1}·year^{-1}). When comparing the three agricultural cultivation systems, the production of native wheat in Galicia (GcW) shows the best possible profile when using the functional units ha^{-1}·year^{-1}, MJ^{-1} and Euro €$^{-1}$. However, due to its low yield, it presents the worst profile when the results are reported in terms of kg^{-1}. In addition, compared to the previous chapter on wheat production in Galicia, the environmental profile of this work shows a significant environmental improvement, especially in the CC impact category. It also showed that wheat under rotational cultivation has a better environmental profile than the monoculture of wheat.

This study provides a comprehensive analysis of LCA of a crop rotation system in Galicia, which can be used by many stakeholders: farmers to learn about their environmental impacts and seek ways to improve their agricultural systems; LCA professionals to extend the scope of research on agricultural LCA and crop rotation; and consumers to raise awareness about local and sustainable consumption. It also provides information for a more in-depth assessment of the entire sustainability aspect of these agricultural systems, including the social and economic assessment, which can be assessed through social LCA and life cycle costing. Potato and wheat are both very important staple crops in this region. Galicia is one of the most important potato producing regions in Spain. In addition, the native wheat grain produced in this region is extremely valued for local society, as its flour provides flavour and texture to the Galician bread. Research into the food heritage should be encouraged, as it is a huge but underestimated resource.

REFERENCES

Achten, W.M.J., Van Acker, K., 2016. EU-Average Impacts of Wheat Production: A Meta-Analysis of Life Cycle Assessments. J. Ind. Ecol. 20, 132–144. https://doi.org/10.1111/jiec.12278

Ankathi, S.K., Long, D.S., Gollany, H.T., Das, P., Shonnard, D., 2019. Life cycle assessment of oilseed crops produced in rotation with dryland cereals in the inland Pacific Northwest. Int. J. Life Cycle Assess. 24, 627–641. https://doi.org/10.1007/s11367-018-1488-y

Brandão, M., Clift, R., Milà, L.C., Basson, L., 2010. A life-cycle approach to characterising environmental and economic impacts of multifunctional land-use systems: An integrated assessment in the UK. Sustainability 2, 3747–3776. https://doi.org/10.3390/su2123747

Brankatschk, G., Finkbeiner, M., 2015. Modeling crop rotation in agricultural LCAs - Challenges and potential solutions. Agric. Syst. 138, 66–76. https://doi.org/10.1016/j.agsy.2015.05.008

Brankatschk, G., Finkbeiner, M., 2014. Application of the Cereal Unit in a new allocation procedure for agricultural life cycle assessments. J. Clean. Prod. 73, 72–79. https://doi.org/10.1016/ j.jclepro.2014.02.005

Deytieux, V., Nemecek, T., Freiermuth Knuchel, R., Gaillard, G., Munier-Jolain, N.M., 2012. Is Integrated Weed Management efficient for reducing environmental impacts of cropping systems? A case study based on life cycle assessment. Eur. J. Agron. 36, 55–65. https://doi.org/10.1016/j.eja.2011.08.004

EIP - AGRI, 2019. Workshop Cropping for the future : networking for crop rotation and crop diversification FINAL REPORT [WWW Document]. Final Rep. https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/ eip-agri_ws_cropping_for_the_future_final_report_2019_en.pdf

EMEP/EEA, 2019. Crop production and agricultural soils, in: Air

Pollutant Emission Inventory Guidebook 2019. pp. 1–35. https://doi.org/10.1016/b978-159749152-5/50001-2

EPA, 2020. Global Greenhouse Gas Emissions Data [WWW Document]. URL https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (accessed 5.26.20).

Estatista, 2020. Producción de patatas en españa por comunidad autónoma [WWW Document]. URL https://es.statista.com/estadisticas/ 510906/produccion-de-patatas-en-espana-por-comunidad-autonoma/ (accessed 11.25.20).

European Commission, 2019a. Agri-environmental indicator - greenhouse gas emissions [WWW Document]. https://ec.europa.eu/eurostat/ statistics-explained/pdfscache/16817.pdf

European Commission, 2019b. The Common Agricultural Policy: Separating Fact from Fiction, Agriculture and Rural Development.

European Commission, 2017. PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3.

Faist-Emmenegger, M., Reinhard, J., Zah, R., 2009. Sustainability Quick Check for Biofuels. Intermediate background report. Dübendorf.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., Zelm, R. Van, 2009. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. https://doi.org/10.029/2003JD004283

Hayer, F., Bonnin, Emmanuel Carrouée, B., Gaillard, G., Nemecek, T., Schneider, A., Vivier, C., 2009. Designing sustainable crop rotations using Life Cycle Assessment of crop combinationsTitle, in: 9th European IFSA Symposium, 4-7 July 2009, Vienna (Austria) 2.

IPCC, 2019. N2O Emissions From Managed Soils, and Co2 Emissions From Lime and Urea Application, in: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. pp. 1–48.

ISO 14040, 2006. Environmental Management-Life Cycle Assessment-Principles and Framework, Geneve, Switzerland.

ISO 14044, 2006. Environmental management — Life cycle assessment — Requirements and guidelines [WWW Document]. Int. Organ. Stand. URL https://www.iso.org/standard/38498.html (accessed 2.15.21).

Jeswani, H.K., Espinoza-Orias, N., Croker, T., Azapagic, A., 2018. Life cycle greenhouse gas emissions from integrated organic farming: A systems approach considering rotation cycles. Sustain. Prod. Consum. 13, 60–79. https://doi.org/10.1016/j.spc.2017.12.003

Kim, S., Dale, B.E., 2005. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. Biomass and Bioenergy 29, 426–439. https://doi.org/10.1016/j.biombioe.2005.06.004

Knudsen, M.T., Meyer-Aurich, A., Olesen, J.E., Chirinda, N., Hermansen, J.E., 2014. Carbon footprints of crops from organic and conventional arable crop rotations - Using a life cycle assessment approach. J. Clean. Prod. 64, 609–618. https://doi.org/10.1016/j.jclepro.2013.07.009

Leng, G., Huang, M., 2017. Crop yield response to climate change varies with crop spatial distribution pattern. Sci. Rep. 7, 1463. https://doi.org/10.1038/ s41598-017-01599-2

MacWilliam, S., Wismer, M., Kulshreshtha, S., 2014. Life cycle and economic assessment of Western Canadian pulse systems: The inclusion of pulses in crop rotations. Agric. Syst. 123, 43–53. https://doi.org/10.1016/j.agsy.2013.08.009

Mancuso, T., Verduna, T., Blanc, S., Di Vita, G., Brun, F., 2019. Environmental sustainability and economic matters of commercial types of common wheat. Agric. Econ. 65, 194–202. https://doi.org/10.17221/172/2018-agricecon

Mousavi, S.R., Eskandari, H., 2014. A General Overview on Intercropping and Its Advantages in Sustainable Agriculture. J. Appl. Environ. Biol. Sci. 1, 482–486.

Nemecek, T., Dubois, D., Huguenin-Elie, O., Gaillard, G., 2011a. Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. Agric. Syst. 104, 217–232. https://doi.org/10.1016/ j.agsy.2010.10.002

Nemecek, T., Hayer, F., Bonnin, E., Carrouée, B., Schneider, A., Vivier, C., 2015. Designing eco-efficient crop rotations using life cycle assessment of crop combinations. Eur. J. Agron. 65, 40–51. https://doi.org/10.1016/j.eja.2015.01.005

Nemecek, T., Huguenin-Elie, O., Dubois, D., Gaillard, G., Schaller, B., Chervet, A., 2011b. Life cycle assessment of Swiss farming systems: II. Extensive and intensive production. Agric. Syst. 104, 233–245. https://doi.org/10.1016/ j.agsy.2010.07.007

Noya, I., González-García, S., Bacenetti, J., Arroja, L., Moreira, M.T., 2015. Comparative life cycle assessment of three representative feed cereals production in the Po Valley (Italy). J. Clean. Prod. 99, 250–265. https://doi.org/10.1016/ j.jclepro.2015.03.001

Prasuhn, V., 2006. Erfassung der PO4 -Austräge für die Ökobilanzierung. SALCA-Phosphor.

Selim, M.M., 2019. A Review of Advantages, Disadvantages and Challenges of Crop Rotations. Egypt. J. Agron. 41, 1–10. https://doi.org/10.21608/agro.2019.6606.1139

Tamburini, E., Pedrini, P., Marchetti, M.G., Fano, E.A., Castaldelli, G., 2015. Life cycle based evaluation of environmental and economic impacts of agricultural productions in the Mediterranean area. Sustain. 7, 2915–2935. https://doi.org/10.3390/su7032915

Tenuta, M., Amiro, B.D., Gao, X., Wagner-Riddle, C., Gervais, M.,

2019. Agricultural management practices and environmental drivers of nitrous oxide emissions over a decade for an annual and an annual-perennial crop rotation. Agric. For. Meteorol. 276–277. https://doi.org/10.1016/j.agrformet.2019.107636

Tidåker, P., Sundberg, C., Öborn, I., Kätterer, T., Bergkvist, G., 2014. Rotational grass/clover for biogas integrated with grain production - A life cycle perspective. Agric. Syst. 129, 133–141. https://doi.org/10.1016/ j.agsy.2014.05.015

Traba, J., Morales, M.B., 2019. The decline of farmland birds in Spain is strongly associated to the loss of fallowland. Sci. Rep. 9, 1–6. https://doi.org/10.1038/s41598-019-45854-0

Volanti, M., Savarino, F.O., Passarini, F., Vassura, I., Grosso, S.A., 2021. Environmental analysis of crop rotations through the application of the Cereal Unit approach. Ecol. Indic. 121, 107199. https://doi.org/10.1016/j.ecolind.2020.107199

Wang, C., Li, X., Gong, T., Zhang, H., 2014. Life cycle assessment of wheat-maize rotation system emphasizing high crop yield and high resource use efficiency in Quzhou County. J. Clean. Prod. 68, 56–63. https://doi.org/10.1016/ j.jclepro.2014.01.018

Yang, X., Sui, P., Zhang, X., Dai, H., Yan, P., Li, C., Wang, X., Chen, Y., 2019. Environmental and economic consequences analysis of cropping systems from fragmented to concentrated farmland in the North China Plain based on a joint use of life cycle assessment, emergy and economic analysis. J. Environ. Manage. 251. https://doi.org/10.1016/ j.jenvman.2019.109588

CHAPTER 5: ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF MAIZE STOVER AND BEET PULP LIGNOCELLULOSIC FEEDSTOCKS[3]

SUMMARY

The shift from a fossil to bio-based economy has encouraged the appraisal of renewable biomass in biorefineries. Residues from agricultural activities and by-products from industrial processing are potential renewable feedstocks. This chapter explores the environmental and economic profile of maize stover and sugar beet pulp as possible lignocellulosic biomass to be valued in a biorefinery. Four scenarios were considered in this chapter: beet pulp in France (BP–FR) and the United Kingdom (BP–UK); and maize stover in Italy (MS–IT) and Belgium (MS–BE).

Life cycle assessment (LCA) was applied considering 1 GJ of lignocellulosic biomass and functional unit and the chosen impact categories are climate change (CC), terrestrial acidification (TA); freshwater eutrophication (FE); marine eutrophication (ME); human toxicity (HT); photochemical oxidant formation (POF); particulate matter formation (PM); and fossil depletion (FD). The economic

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[3] Chapter based on the publication:

Iana Câmara-Salim[a], Pablo Conde[a], Gumersindo Feijoo[a] and Maria Teresa Moreira[a]. The use of maize stover and sugar beet pulp as feedstocks in industrial fermentation plants – An economic and environmental perspective, Cleaner Environmental Systems, Volume 2, 2021, 100005, ISSN 2666-7894, https://doi.org/10.1016/j.cesys.2020.100005.

[a] CRETUS Research Center. Department of Chemical Engineering, School of Engineering, Universidade de Santiago de Compostela, Rúa Lope Gómez de Marzoa, s/n, 15782 Santiago de Compostela, Spain

analysis assessed the internal and external cost indicators. The results show that maize stover would reduce the total environmental burdens and production costs. The outcomes show total costs ranging from 22 € (MS–IT) to 174 € (BP–UK) per FU. The environmental results show that BP–UK scenario also represents the worst case. For CC, for instance, in the MS–IT scenario, the impact dropped by more than 80%, compared to BP–UK. Additionally, sensitivity analysis was performed considering changes in the stover removal rate from 30% to 50% and uncertainty analysis was evaluated to assess robustness of the environmental results.

5.1 INTRODUCTION

Biomass has by tradition been used to offer shelter and energy ever since the start of human civilization. Nevertheless, this reliance on biomass has reduced significantly with the introduction of fossil fuels. In the past few decades, negative environmental consequences associated with fossil resources have triggered a paradigm shift, where biomass is regarded as innovative and as a substitute to fossil fuels. The move from a fossil to a bio-based economy will entail an efficient and sustainable use of renewable biomass to avoid issues such as land use change, biodiversity loss and food shortage (Cutz et al., 2017).

As mentioned in Chapter 1, bio-commodities can be produced from edible crops, such as starch (e.g. maize and wheat), sugar (e.g. sugar cane and beet) (Muñoz et al., 2014) and oil crops (e.g. palm oil and rapeseed) (Uusitalo et al., 2014), which are also classified as 1G feedstocks. However, population growth puts pressure on food demand and the use of edible crops for the production of bioproducts may put food security at risk in the near future, unless they are made from non-food crops (Thompson and Meyer, 2013). Therefore, the use of lignocellulosic agricultural residues or by-products, e.g. wheat straw, sugarcane straw and maize stover (Hernández et al., 2019; Sampaio et al., 2019), as well as industrial process residues (e.g. cane bagasse and beet pulp) (Bezerra and Ragauskas, 2016; Joanna et al., 2018) for the production of biofuels or bioproducts has been promoted over the last decade. Yet, the transformation of lignocellulosic biomass into valuable products has many technological constraints, far behind the technology to process 1G raw materials (Joelsson et al., 2016).

Maize stover and sugar beet pulp (SBP) are potential biomass for use in industrial fermentation processes. The former is a by-product from maize grain production, while the latter from the manufacture of sugar. Both are feedstocks that do not compete with food and are rich in cellulose and hemicellulose, which can be further processed into a variety of final products. Overall, the main factors for exploiting maize stover and beet pulp in this study are to avoid the use of 1G feedstocks that compromise food demand and decrease pressure on fossil fuels.

Stover is what remains of the maize plant in the soil after harvesting the grain, which comprise the stalks, cob and leaves. Given that maize is one of the most cultivated crops in the world, with around 1 billion tonnes in 2019 (FAOSTAT, 2019), and considering that about 1 kg of maize grain generates 1 kg of stover on a dry basis (Murphy and Kendall, 2013), there is enormous potential for valorisation of this residue. The authors (Wietschel et al., 2019) also predict a growth in Europe of lignocellulose residues, with maize stover being the largest increase, up to 20% from 2017 to 2030. Stover can be left in the field as a soil conditioner or removed partially or totally for animal feed and forage, as well as for the production of biofuels and bioproducts (Ruan et al., 2019). It is necessary to consider a sustainable harvest of stover, as repeated stover removal can compromise soil quality (Murphy and Kendall, 2013). Current research has stressed the prospects for valuing stover as a raw material for the production of bio-commodities (Humbird et al., 2011; Wang et al., 2012).

Sugar beet is an important crop in Europe, with a production of around 120 million tonnes in 2019, representing almost 45% of the world's beet production. (FAOSTAT, 2019). This culture is traditionally grown to produce sucrose. About 30% of world sugar production comes from sugar beet (Zicari et al., 2019). The beet sugar industry is well developed in Europe and its production generates by-products such as beet pulp, which has long been used as a low-value animal feed. In addition, there is a high energy expenditure (about 33% of the plant's total energy) in the drying process to produce the pulp in the form of pellets and to be marketed for animal feed (Mujumdar, 2014). Therefore, research has been looking for opportunities to use raw beet pulp as a raw material in industrial fermentation processes (Díaz et al., 2017).

In this regard, an environmental assessment of maize stover and beet pulp was performed through life cycle assessment (LCA) method. In addition, an economic evaluation considering operational costs (OPEX) and also the costs associated with environmental pollution was conducted (De Bruyn et al., 2018). The integration of environmental assessment with economic assessment considering internal and external costs, in a context of a life cycle approach, has recently gained attention in research (Özkan et al., 2016; Tamburini et al., 2015). Studies have investigated the environmental (Kim et al., 2009; Murphy and Kendall, 2013; Whitman et al., 2011) and economic (Wendt et al., 2018) profile of stover as potential feedstock for biorefineries (Kim et al., 2009; Murphy and Kendall, 2013; Whitman et al., 2011). As regards beet pulp, environmental and economic studies that consider beet pulp are those whose main objective is to investigate the production of beet sucrose, the pulp being considered a by-product for animal feed and not as a raw material for industrial fermentation (Klenk et al., 2012; Maravíc et al., 2015; Renouf et al., 2008).

The main objective of this chapter is to evaluate the environmental and economic impacts of these lignocellulosic-rich biomass as upstream inputs of industrial fermentation processes, taking into consideration the external costs that pollution entails. Two scenarios for beet pulp and two for maize stover production in a European context were evaluated in this study. Although maize stover and beet pulp were considered to be used in industrial fermentation processes, this chapter is located in section I because maize stover and beet pulp can also be used in animal feed, for example.

5.2 MATERIALS AND METHODS

5.2.1 Goal and scope definition

This chapter aims to evaluate the key environmental and economic factors associated with the life cycle of lignocellulosic raw materials from maize stover and beet pulp. The functional unit (FU) of the evaluation is 1 GJ of feedstock. This FU was chosen because it is intended for biorefinery purposes (for example, biofuels). A cradle-to gate LCA was evaluated, and the system description is shown in Figure 5.1.

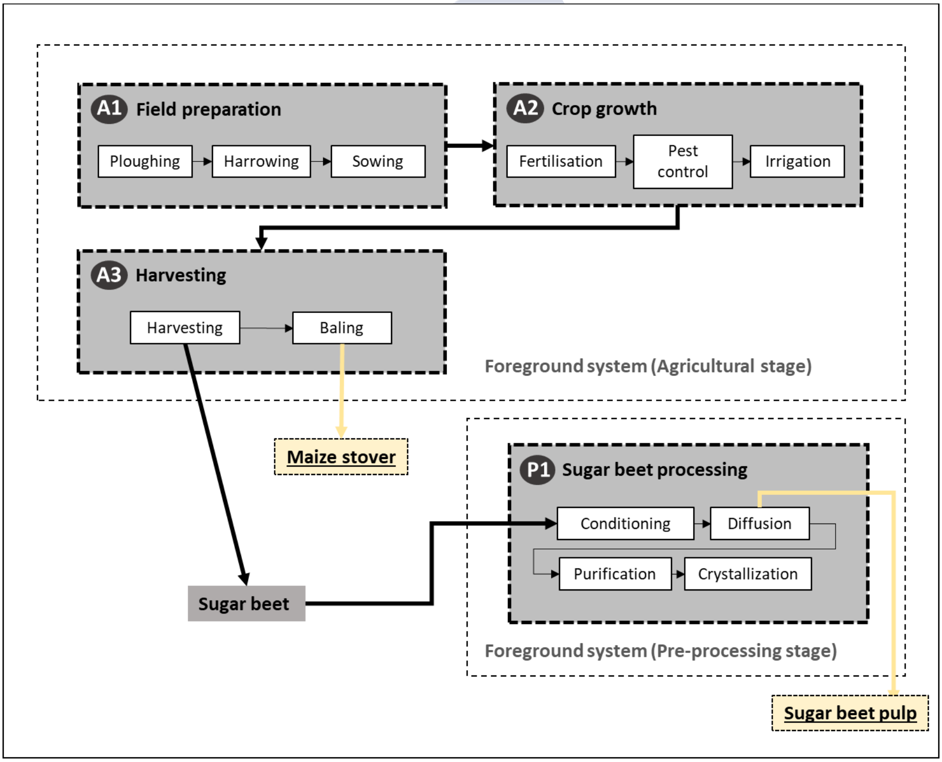

Figure 5.1. Flowchart of agricultural activities for maize stover and sugar beet and pre-processing activities of sugar beet pulp production.

Agricultural maize production involves the application of agricultural materials and operations for soil preparation, plant growth and harvesting. Part of the stover is left in the field and the rest is collected through a baling process. On average, about 1 kg of stover is produced for every kg of grain (Prasad et al., 2016). In this study, it was considered that 30% of the stover would be harvested as it is a recommended harvest rate. Certification programs, such as the Working Landscapes Certificate (WLC), which has as focus sustainable agricultural production for biorefinery purpose, uses as criteria that no more than 30% of crop residues are removed from the field (IATP, 2012). However, there is considerable difference in the rates of stover removal in the literature (Simon et al., 2010). Therefore, a sensitivity analysis will be performed considering a 50% removal rate.

As for the sugar beet pulp, first the beet cultivation must take place, from the preparation of the field, the growth of the crop until the harvest of the beet root. The harvested beet root is transported from the agricultural fields to the factory. In the conditioning phase, impurities, such as stones and sand, are removed and washed. The root is cut into small strips called “cosettes” and a diffusion process takes place using hot water and chemicals, such as sulphuric acid. This phase works like a “tea preparation”, allowing the sugar to be diluted in the hot water. The SBP is exactly what is left from the diffusion process (the “tea bag”) and the diluted water with sugar is called “raw juice”.

Other stages of the sucrose production include *purification*, which involves the use of lime and CO_2 to purify the raw juice, removing the non-sugar compounds. Calcium carbonate is a by-product of the purification process. However, it was excluded in this assessment since the FU of this study is energy-based and calcium carbonate has no calorific value. Finally, *crystallization* occurs by centrifugation, producing sucrose (the crystallised sugar) and molasses (the non-crystallised sugar). The drying process of beet pulp was not taken into consideration, because the biorefineries plants uses wet pulp in the process. This saves considerable energy as approximately 33% of the energy in a sugar factory is used in the drying process of beet pulp (Mujumdar, 2014).

Four scenarios from a European context were evaluated: 1) beet pulp produced in France (BP – FR); beet pulp in United Kingdom (BP – UK); 3) stover in Italy (MS - IT) and 4) Belgium (MS – BE). In general, the choice of these scenarios was motivated by the quantities of production, the type of agricultural management and the availability of data in the European region. France and United Kingdom are important producers of sugar beet root and beet sugar in Europe (Muñoz et al., 2014; Renouf et al., 2008). Italy is an important maize producer in Europe (FAOSTAT, 2019). The scenario in Belgium was chosen owing to data availability. Moreover, the study is limited to Europe as a geographical representation, since the methodology for calculating external costs focuses on European prices.

5.2.2 Inventory data

Table 5.1 summarizes the inventory data for agricultural activities in the different scenarios. The quantities of inputs and agricultural operations are presented per hectare. The data for maize and sugar beet crops were gathered from bibliography (Boone et al., 2016; Muñoz et al., 2014; Noya et al., 2015; Renouf et al., 2008). The main agricultural data were selected as the foreground system: seeds, fertilisers and pesticides, diesel used for agricultural machinery, and quantities of machinery used. Background system were assessed through the Ecoinvent v3.5® database (Wernet et al., 2016) and includes the production of the agricultural inputs (e.g., fertilisers) and operations (e.g., machinery) and their transportation to the foreground system. As the data used for agricultural activities were used from different bibliographic sources, field emissions were reassessed using the same methods for all scenarios with the aim to provide a fair comparison of the scenarios. Table 5.2 summarizes the data sources used to calculate field emissions, whose references are recommended by agricultural methodological guidelines (Nemecek et al., 2015).

Table 5.1. Life cycle inventory data of the different scenarios for agricultural activities. Acronyms: BP – Beet pulp; MS – Maize stover; FR – France; UK – United Kingdom; IT – Italy and BE – Belgium.

Scenarios	**BP - FR**[a]	**BP - UK**[b]	**MS - IT**[c]	**MS - BE**[d]
Yield sugar beet ($t{\cdot}ha^{-1}$)	84.6	50	–	–
Yield maize grain ($t{\cdot}ha^{-1}$)			14.9	10.3
Yield maize stover ($t{\cdot}ha^{-1}$)	–	–	5.3	3.1
Agricultural inputs				
Seeds ($kg{\cdot}ha^{-1}$)	2	1.1	24	27.6
N Fertiliser ($kg{\cdot}ha^{-1}$)	103	112	60	35
P_2O_5 Fertiliser ($kg{\cdot}ha^{-1}$)	67	41	–	17.6
K_2O Fertiliser ($kg{\cdot}ha^{-1}$)	146	61	–	90
Slurry ($m^3{\cdot}ha^{-1}$)	–	–	–	18
Digestate ($t{\cdot}ha^{-1}$)	–	–	85	–
Pesticides ($kg{\cdot}ha^{-1}$)	3	8.6	6	1.6
Agricultural operations				
Diesel ($kg{\cdot}ha^{-1}$)	160	194	162	64
Tractor ($kg{\cdot}ha^{-1}$)	11.8	14.4	8.9	2.9
Agricultural machinery ($kg{\cdot}ha^{-1}$)	16	19.5	15.5	7.1
Harvester ($kg{\cdot}ha^{-1}$)	–	–	6.6	6.6
Labour ($h{\cdot}ha^{-1}$)	27	33	21	7.7

a. (Muñoz et al., 2014)
b. (Renouf et al., 2008)
c. (Noya et al., 2015)
d. (Boone et al., 2016)

Table 5.2. Type of field emissions from agricultural activities and sources.

Emissions	Sources
N_2O (to air)	(IPCC, 2019)
NO_2 and NH_3 (to air)	(EMEP/EEA, 2019)
NO_3^- and P (to ground and surface water)	(Faist-Emmenegger et al., 2009)
Heavy metals (to water and soil)	(Durlinger et al., 2017)
Pesticides (to air, water and soil)	(European Commission, 2017)

The costs associated with the agricultural inputs and operations in the different scenarios are presented in Table 5.3. As regards beet pulp processing, the materials and energy required for sugar beet processing and related costs are shown in Table 5.4 (Maravíc et al., 2015). This inventory data is used for both scenarios (BP – FR and BP – UK).

Table 5.3. Life cycle cost inventory data of the different scenarios for agricultural activities. Acronyms: BP – Beet pulp; MS – Maize stover; FR – France; UK – United Kingdom; IT – Italy and BE – Belgium.

Crops	**BP - FR**	**BP - UK**	**MS - IT**	**MS - BE**
		Agricultural inputs		
Seeds (€·kg^{-1})[a]	0.028	0.033	0.20	0.15
N Fertiliser (€·kg^{-1})	0.69[b]	0.90[c]	0.85[d]	0.65[f]
P_2O_5 Fertiliser (€·kg^{-1})	0.55[b]	0.63[c]	_	0.66[f]
K_2O Fertiliser (€·kg^{-1})	0.45[b]	0.47[c]	_	0.30[f]
Slurry (€·m^{-3})	_	_	_	5.2[g]
Digestate (€·t^{-1})	_	_	4[e]	_
Pesticides (€·kg^{-1})	21.6[h]	21.6[h]	24.1[i]	24.1[i]
		Agricultural operations		
Diesel (€·kg^{-1})[j]	1.69	1.69	1.72	1.72
Tractor (€·kg^{-1})[k]	26.51	26.51	26.51	26.51
Agricultural machinery (€·kg^{-1})[k]	38.71	38.71	35.20	33.50
Harvester (€·kg^{-1})[k]	_	_	16.29	16.29
Labour costs (€·h^{-1})[l]	13.5	13	9	12

[a] Food and Agriculture Organization Corporate Statistical Database (FAOSTAT, 2019)

[b] 27% ammonium nitrate (AN), triple super phosphate (TSP) and muriate of Potash (MOP) (TERRE-net, 2020)

[c] 34.5% ammonium nitrate (AN), super phosphate triple (TSP) and muriate of Potash (MOP) (AHDB, 2020) from

[d] 46% prilled urea (CLAL, 2020)

[e] Digestate is an organic fertiliser from the anaerobic digestion process (Noya et al., 2015)

[f] 46% prilled urea, triple super phosphate (TSP) and kornkali 60% K_2O (Agrarheute, 2020)

[g] Pig slurry (Teagasc, 2017)

[h] Chlorpyrifos 15G, 15% active ingredient (Agricultural Chemical Solutions, 2020)
[i] Lumax, 43% active ingredient (Agricultural Chemical Solutions, 2020)
[j] (Datosmacro, 2020)
[k] (Unirioja, 2020)
[l] (European Commission, 2016)

Table 5.4. Life cycle inventory data of sugar beet processing (Maravíc et al., 2015).

Input	**Amount**	**Unit**	**Price (€/Unit)**
Sugar beet	7.84	kg	0.038
Natural gas	0.11	m^3	0.34
Coke	$2.38 \cdot 10^{-2}$	kg	0.24
Limestone	0.383	kg	0.011
H_2SO_4	$5.32 \cdot 10^{-3}$	kg	0.069
NaOH (50% in H_2O)	$4.05 \cdot 10^{-4}$	kg	0.48
NaOH (Flakes)	$1.39 \cdot 10^{-4}$	kg	0.54
Output	**Amount**	**Unit**	
Raw juice	1	kg	
Beet pulp (Wet basis)	1.5	kg	

5.2.3 Allocation

In this assessment, by-products of agricultural and industrial processing activities are produced. Therefore, allocation should be considered to address the issue of multifunctionality in life cycle assessment. As the objective of this study is the use of raw material in the industrial fermentation process, energy-based allocation is an appropriate allocation choice. This work considers the lower heating value (LHV) of the feedstocks. Maize grain and stover have a LHV of 16.3 MJ·kg^{-1} and 16.5 MJ·kg^{-1} on a dry basis, respectively (Murphy and Kendall, 2013). Sugar beet root and beet pulp have LHV of 3.78 MJ·kg^{-1} (Wernet et al., 2016) and 3,4 MJ·kg^{-1} (Durlinger et al., 2017) on a wet basis, respectively. Beet sugar has LHV of 16.92 MJ·kg^{-1} on a dry basis (Klenk et al., 2012).

5.2.4 Sensitivity and uncertainty analysis

With the aim of assessing the effect of changing variables on the environmental LCA results, a sensitivity analysis was assessed considering changes in the stover removal rate from 30% to 50%. As more stover is removed, more fertiliser and energy for the baling process is applied. There is approximately 0.45 kg N, 0.15 kg P_2O_5 and 0.41 kg K_2O per GJ of dry stover (David, 2013). Moreover, additional operation was used for the baling process, which was gathered from the Ecoinvent process named “baling [unit]”. Uncertainty analysis was evaluated to assess robustness of the environmental results. Monte Carlo simulation in SimaPro 9.1 software and 1000 simulations were applied with a 95% confidence.

5.2.5 Life cycle impact assessment

This chapter has a twofold perspective to consider the environmental and economic impacts of maize stover and beet pulp production, which will be further detailed.

5.2.5.1 Environmental assessment

To assess the environmental impacts, this works applies a cradle-to-gate LCA. Only the classification and characterization steps are considered in this LCA. The ReCiPe methodology at mid-point level (Goedkoop et al., 2009) and SimaPro 9.1 software are used in this chapter. The impact categories chosen are climate change (CC - kg CO_2-eq), terrestrial acidification (TA - kg SO_2 eq), freshwater eutrophication (FE - kg P eq), marine eutrophication (ME – kg N eq); human toxicity (HT - kg

1,4-DB eq), photochemical oxidant formation (POF - kg NMVOC), particulate matter formation (PM - kg PM10 eq) and fossil depletion (FD - kg oil eq).

5.2.5.2 Economic assessment

A true economic evaluation must consider internal and external costs. As for the analysis of internal costs, operating costs (OPEX) were considered and for external costs, the environmental costs of pollution were considered using the Environmental Price Handbooks method (De Bruyn et al., 2018). Total costs are the sum of OPEX and environmental costs (Özkan et al., 2016). OPEX considers production and labour costs in the investigated scenarios. Due to lack of data, it only covers the operational cost of the processes, not considering any fixed costs, maintenance or other expenses associated with the installation.

With relation to external costs, the environmental costs are considered as externalities, hidden costs that society is paying for (e.g., human health) but which are not included in the price of the product. This is the name given to the economic value assigned to the negative effects of a productive activity on society (pollution, loss of soil fertility, etc.). The external costs are measured in terms of price per impact category. For instance, for CC impact category, the external cost is 0.05 € per kg of CO_2-eq. Detailed cost values can be assessed in the manual (De Bruyn et al., 2018). The Environmental Price Handbooks considers average prices for 2015 per kg of emissions in a European context and uses the ReCiPe midpoint method.

5.3 RESULTS AND DISCUSSION

The economic and environmental results of the 4 scenarios for stover and beet pulp are described in Section 5.3.1 and Section 5.3.2, respectively.

5.3.1 Economic analysis

Table 5.5 depicts the monetary values per FU taking into consideration agricultural and processing activities for the scenarios BP -FR; BP – UK; MS – IT and MS – BE.

Table 5.5. Operational and environmental costs of the different feedstocks. Unit: € / GJ of lignocellulosic feedstock. Acronyms: BP – Beet pulp; MA – Maize stover; FR – France; UK – United Kingdom; IT – Italy and BE – Belgium; CC - climate change (kg CO_2-eq); TA - terrestrial acidification (kg SO_2 eq); FE - freshwater eutrophication (kg P eq); ME – Marine eutrophication (kg N eq); HT - human toxicity (kg 1,4-DB eq); POF - photochemical oxidant formation (kg NMVOC); PM - particulate matter formation (kg PM10 eq).

Economic indicator (€/FU)	**BP - FR**	**BP - UK**	**MS - IT**	**MS - BE**
Total operational costs (agriculture)	44.61	93.35	21.68	16.26
Total operational costs (beet processing)	68.56	68.56	–	–
Total operational costs	113.17	161.91	21.68	16.26
Environmental costs per impact category:				
CC	1.02	2.76	0.33	0.43
TA	0.37	1.18	1.26	2.35
FE	$4.08\cdot10^{-3}$	0.011	$1.05\cdot10^{-3}$	$1.46\cdot10^{-3}$
ME	0.017	0.27	0.02	0.32
HT	0.218	1.16	0.01	-0.02
POF	0.115	0.39	0.098	0.09
PM	1.49	6.30	2.16	3.30
Total Environmental costs (€/FU)	3.25	12.10	3.91	6.5
Total costs (€/FU)	116.41	174.01	25.59	22.76

The results of the cost analysis show that the use of maize stover in Italy (MS – IT), as raw material for fermentation, would reduce total costs. As shown in Table 5.5, the total costs range from a minimum of 22 € (MS - IT) to a maximum of 174 (BP - UK) € per FU. Figure 5.2 helps to better visualise the comparative cost profile of the different feedstocks.

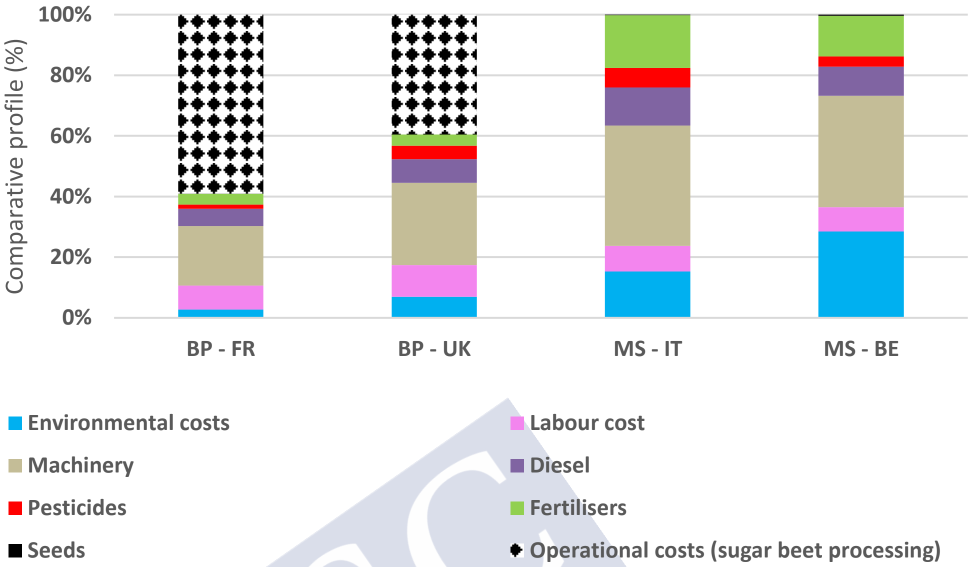

Figure 5.2. Cost comparative profile (%) of the different feedstock scenarios per FU. Acronyms: BP-FR (beet pulp-France), BP-UK (beet pulp-United Kingdom), MS-IT (Maize stover-Italy), MS-BE (Maize stover-Belgium).

As noted, for beet pulp scenarios (BP -FR and BP -UK), the main contributor is the processing stage (40-60%), followed by machinery costs (19-27%). The total cost is higher for BP-UK than for BP-FR, mainly due to the lower yield (50 t) in the UK scenario compared to the FR scenario (84 t) per hectare. Overall, environmental costs have little influence in the total costs results for both beet pulp scenarios. When analysing only the external costs, due to the high direct ammonia emissions from the field in the BP-UK scenario, which directly influences the formation of PM, the PM environmental cost is very high and contributes about 50% of the total environmental costs. Moreover, PM has the highest characterization factor (around 39 €/kg $PM_{10\text{-eq}}$) of the analysed impact categories.

With respect to the maize stover, for both MS-IT and MS-BE, the main contributor to total costs is the machinery use (36-39%), followed by environmental costs (15-28%) and fertiliser (13-17%). Unlike the beet case studies, environmental costs make a significant contribution to the total costs of the stover scenarios. For all evaluated scenarios, seed production and labour have little influence on the overall cost analysis.

5.3.2 Environmental analysis

Table 5.6 shows the environmental profile of beet pulp and maize stover scenarios. The global LCA results shows that the BP - UK scenario represents the worst-case, followed by BP-FR. The MS-IT scenario causes the lowest environmental impacts. For CC, for instance, scenario MS-IT has an impact reduction of more than 80%, compared to BP-UK. The environmental results show a similar trend to the assessment of environmental costs, where maize stover performs better than beet pulp.

Table 5.6. Environmental profile of the different feedstocks per FU. Acronym: CC - climate change; TA - terrestrial acidification; FE - freshwater eutrophication; ME – Marine eutrophication; HT - human toxicity; POF - photochemical oxidant formation; PM - particulate matter formation; and FD - fossil depletion.

Impact category	**Units**	**BP - FR**	**BP - UK**	**MS - IT**	**MS - BE**
CC	kg CO_2-eq	18.13	48.87	6.00	7.67
TA	kg SO_2 eq	$4.62 \cdot 10^{-2}$	0.146	0.155	0.289
FE	kg P eq	$2.15 \cdot 10^{-3}$	$5.94 \cdot 10^{-3}$	$5.54 \cdot 10^{-4}$	$7.67 \cdot 10^{-4}$
ME	kg N eq	$5.53 \cdot 10^{-3}$	$8.81 \cdot 10^{-2}$	$9.48 \cdot 10^{-3}$	0.104
HT	kg 1,4-DB eq	1.38	7.40	0.081	-0.133
POF	kg NMVOC	$5.49 \cdot 10^{-2}$	0.186	$4.70 \cdot 10^{-2}$	$4.62 \cdot 10^{-2}$
PM	kg PM10 eq	$2.17 \cdot 10^{-2}$	$9.14 \cdot 10^{-2}$	$3.14 \cdot 10^{-2}$	$4.79 \cdot 10^{-2}$
FD	kg oil eq	3.75	10.79	1.74	1.31

In the beet pulp scenarios, most of the environmental emissions come from the agricultural phase, as observed in Figure 5.3a and 5.3b. For instances, the agricultural phase contributes 67% and 89% of the total CO_2 emissions to the beet pulp scenarios in FR and UK, respectively. These high impacts on the environmental performance of beet pulp in the UK are also due to the low yield of sugar beet in agricultural activities as well as direct emissions in the field. Moreover, the sugar beet processing uses raw beet root as feedstocks. Therefore, sugar beet root has very low LHV, compared to maize stover, which is used in the dry form. Hence, the choice of a high yield and the LHV biomass will considerably decrease the environmental burdens of production.

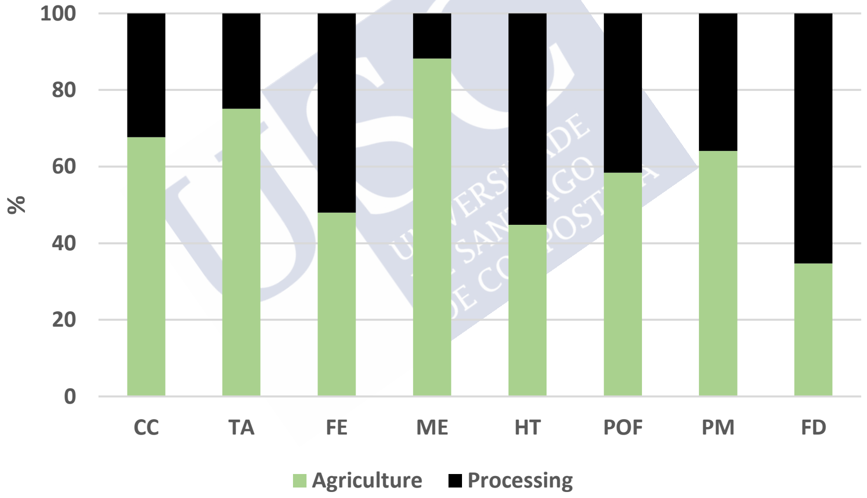

Figure 5.3a. Contribution analysis of beet pulp production for BP -FR scenario per FU. Acronyms: CC - climate change; TA - terrestrial acidification; FE - freshwater eutrophication; ME – Marine eutrophication; HT - human toxicity; POF - photochemical oxidant formation; PM - particulate matter formation; and FD - fossil depletion.

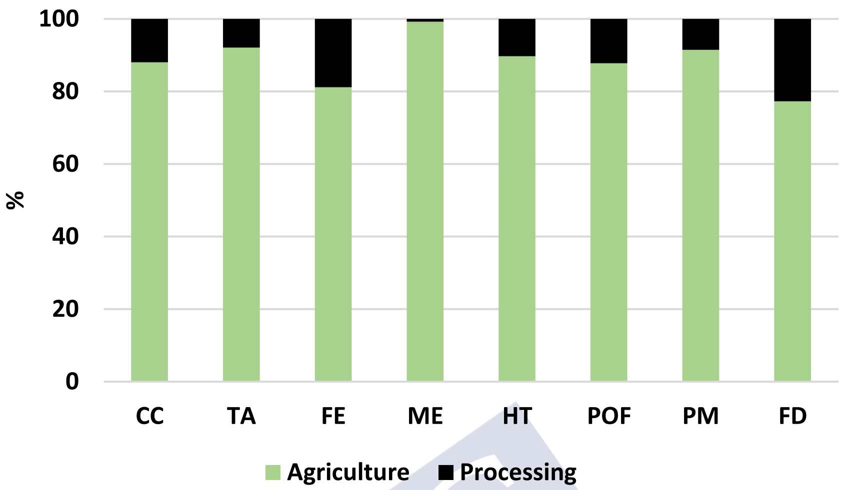

Figure 5.3b. Contribution analysis of beet pulp production for BP - UK scenario. Acronyms: CC - climate change; TA - terrestrial acidification; FE - freshwater eutrophication; ME – Marine eutrophication; HT - human toxicity; POF - photochemical oxidant formation; PM - particulate matter formation; and FD - fossil depletion.

5.3.3 Sensitivity and uncertainty analysis

A sensitivity analysis for the case study MS–BE was performed considering an increase of 30% to 50% in the removal of stover. The environmental outcomes are presented in Figure 5.4. The results show a slight increase in the environmental impacts when the removal rate is increased by 20%, with less than 10% increase in the environmental indicators.

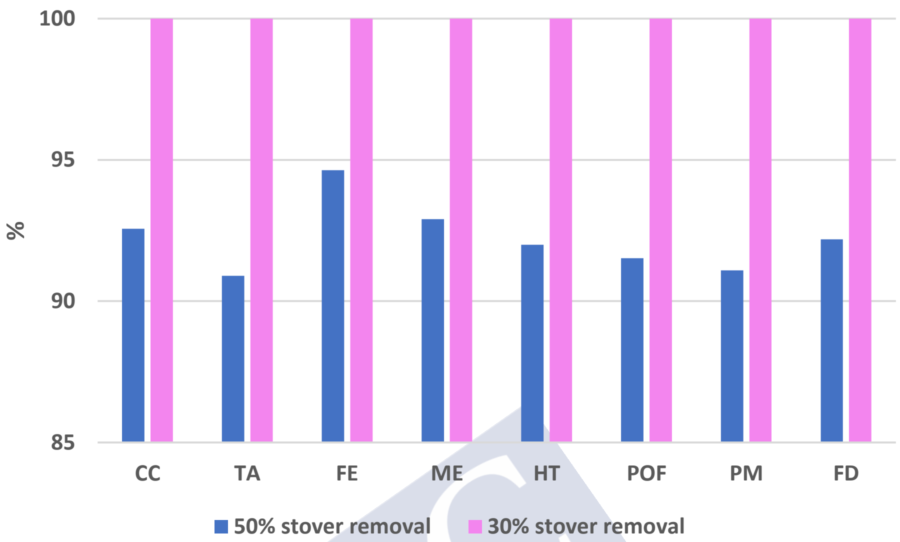

Figure 5.4. Sensitivity analysis for stover removal in MS - BE scenario. Acronyms: CC - climate change; TA - terrestrial acidification; FE - freshwater eutrophication; ME – Marine eutrophication; HT - human toxicity; POF - photochemical oxidant formation; PM - particulate matter formation; and (FD - fossil depletion.

Regarding the uncertainty analysis, the results are presented in Figure 5.5, showing the different coefficient of variations (CV) for each impact category. The complete data source considering the mean, median and standard deviation of the uncertainty analysis is presented in Tables 5.7, 5.8, 5.9 and 5.10. The HT impact category has not been evaluated, as there are great uncertainties related to this indicator, as literature show, hindering a clear interpretation (Alyaseri and Zhou, 2019).

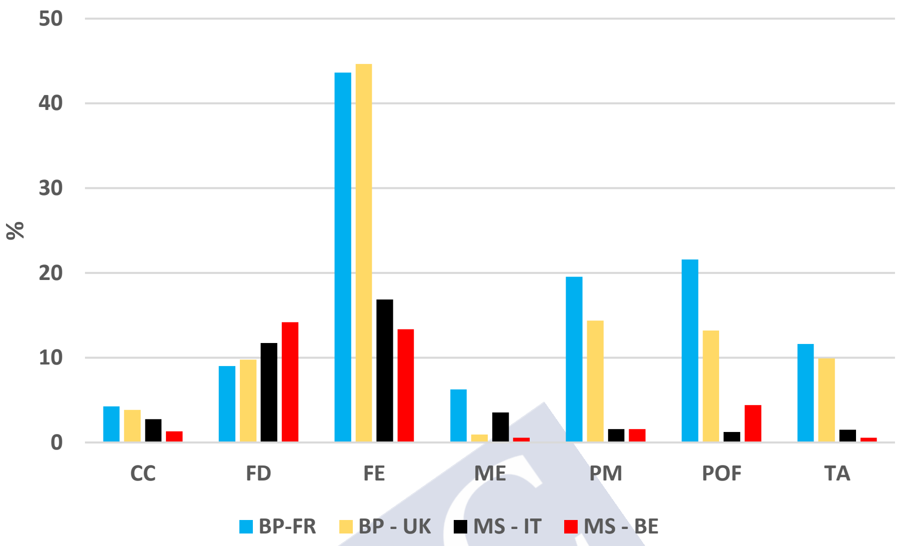

Figure 5.5. Uncertainty analysis - Coefficient of variation of the different scenarios. Acronyms: CC - climate change; TA - terrestrial acidification; FE - freshwater eutrophication; ME – Marine eutrophication; POF - photochemical oxidant formation; PM - particulate matter formation; and FD - fossil depletion.

As observed in Figure 5.5, apart from FE for the beet pulp scenarios, all impact categories present a CV less than 30%. Regarding the FE impact category for the BP - FR and BP - UK scenarios, it shows a relatively high variation of around 43-44%. This occurs due to background processes, which present great uncertainty, mainly for the production of energy that affects the eutrophication of fresh water. Therefore, it can be concluded that the uncertainty analysis show robustness of the environmental results.

Table 5.7. Uncertainty analysis in the SimaPro 9.1 software and 1000 simulations. Scenario BP – FR. Acronyms: SD – standard deviation; CV – coefficient of variation; SEM - standard error of the mean; CC - climate change; FD - fossil depletion; FE - freshwater eutrophication; ME – Marine eutrophication; PM - particulate matter formation; POF - photochemical oxidant formation; and TA - terrestrial acidification.

Impact category	**Unit**	**Mean**	**Median**	**SD**	**CV**	**2.50%**	**97.50%**	**SEM**
CC	**kg CO_2 eq**	18.17	18.13	0.777	4.27	16.78	19.83	$2.46\cdot10^{-2}$
FD	**kg oil eq**	3.76	3.74	0.339	9.00	3.14	4.49	$1.07\cdot10^{-2}$
FE	**kg P eq**	$2.14\cdot10^{-3}$	$1.89\cdot10^{-3}$	$9.33\cdot10^{-4}$	43.64	$1.12\cdot10^{-3}$	$4.48\cdot10^{-3}$	$2.95\cdot10^{-5}$
ME	**kg N eq**	$5.51\cdot10^{-3}$	$5.45\cdot10^{-3}$	$3.45\cdot10^{-4}$	6.25	$5.01\cdot10^{-3}$	$6.33\cdot10^{-3}$	$1.09\cdot10^{-5}$
PM	**kg PM10eq**	$2.17\cdot10^{-2}$	$2.09\cdot10^{-2}$	$4.24\cdot10^{-3}$	19.55	$1.64\cdot10^{-2}$	$3.34\cdot10^{-2}$	$1.34\cdot10^{-4}$
POF	**kg NMVOC**	$5.45\cdot10^{-2}$	$5.21\cdot10^{-2}$	$1.18\cdot10^{-2}$	21.57	$3.92\cdot10^{-2}$	$8.12\cdot10^{-2}$	$3.72\cdot10^{-4}$
TA	**kg SO_2 eq**	0.045	0.0454	$5.35\cdot10^{-3}$	11.63	0.037	0.057	$1.69\cdot10^{-4}$

Table 5.8. Uncertainty analysis in SimaPro 9.1 software and 1000 simulations. Scenario BP – UK. Acronyms: SD – standard deviation; CV – coefficient of variation; SEM - standard error of the mean; CC - climate change; FD - fossil depletion; FE - freshwater eutrophication; ME – Marine eutrophication; PM - particulate matter formation; POF - photochemical oxidant formation; and TA - terrestrial acidification.

Impact category	**Unit**	**Mean**	**Median**	**SD**	**CV**	**2.50%**	**97.50%**	**SEM**
CC	**kg CO_2 eq**	48.94	48.81	1.88	3.84	46.14	52.26	0.059
FD	**kg oil eq**	10.81	10.72	1.05	9.75	8.96	13.18	0.033
FE	**kg P eq**	$5.79\cdot10^{-3}$	$5.12\cdot10^{-3}$	$2.59\cdot10^{-3}$	44.67	$2.69\cdot10^{-3}$	0.012	$8.17\cdot10^{-5}$
ME	**kg N eq**	0.088	0.087	$8.13\cdot10^{-4}$	0.923	0.086	0.090	$2.57\cdot10^{-5}$
PM	**kg PM10eq**	0.091	0.088	0.013	14.38	0.073	0.126	$4.16\cdot10^{-4}$
POF	**kg NMVOC**	0.186	0.182	0.024	13.20	0.148	0.247	$7.77\cdot10^{-4}$
TA	**kg SO_2 eq**	0.145	0.144	0.014	9.90	0.124	0.180	$4.57\cdot10^{-4}$

Table 5.9. Uncertainty analysis in SimaPro 9.1 software and 1000 simulations. Scenario MS – IT. Acronyms: SD – standard deviation; CV – coefficient of variation; SEM - standard error of the mean; CC - climate change; FD - fossil depletion; FE - freshwater eutrophication; ME – Marine eutrophication; PM - particulate matter formation; POF - photochemical oxidant formation; and TA - terrestrial acidification.

Impact category	**Unit**	**Mean**	**Median**	**SD**	**CV**	**2.50%**	**97.50%**	**SEM**
CC	**kg CO$_2$ eq**	5.99	5.98	0.164	2.74	5.70	6.34	$5.21\cdot10^{-3}$
FD	**kg oil eq**	1.74	1.74	0.205	11.72	1.36	2.19	$6.49\cdot10^{-3}$
FE	**kg P eq**	$5.57\cdot10^{-4}$	$5.38\cdot10^{-4}$	$9.38\cdot10^{-5}$	16.85	$4.44\cdot10^{-4}$	$8.01\cdot10^{-4}$	$2.97\cdot10^{-6}$
ME	**kg N eq**	$9.47\cdot10^{-3}$	$9.44\cdot10^{-3}$	$3.36\cdot10^{-4}$	3.54	$8.89\cdot10^{-3}$	0.010	$1.06\cdot10^{-5}$
PM	**kg PM10eq**	0.031	0.031	$4.96\cdot10^{-4}$	1.57	0.030	0.032	$1.57\cdot10^{-5}$
POF	**kg NMVOC**	0.046	0.046	$5.73\cdot10^{-4}$	1.22	0.045	0.048	$1.81\cdot10^{-5}$
TA	**kg SO$_2$ eq**	0.155	0.155	$2.34\cdot10^{-3}$	1.50	0.15	0.159	$7.39\cdot10^{-5}$

Table 5.10. Uncertainty analysis in SimaPro 9.1 software and 1000 simulations. Scenario MS – BE. Acronyms: SD – standard deviation; CV – coefficient of variation; SEM - standard error of the mean; CC - climate change; FD - fossil depletion; FE - freshwater eutrophication; ME – Marine eutrophication; PM - particulate matter formation; POF - photochemical oxidant formation; and TA - terrestrial acidification.

Impact category	**Unit**	**Mean**	**Median**	**SD**	**CV**	**2.50%**	**97.50%**	**SEM**
CC	**kg CO$_2$ eq**	7.67	7.67	0.100	1.31	7.48	7.89	$3.18\cdot10^{-3}$
FD	**kg oil eq**	1.31	1.28	0.185	14.18	1.00	1.75	$5.88\cdot10^{-3}$
FE	**kg P eq**	$7.65\cdot10^{-4}$	$7.44\cdot10^{-4}$	$1.02\cdot10^{-4}$	13.36	$6.31\cdot10^{-4}$	$1.03\cdot10^{-3}$	$3.23\cdot10^{-6}$
ME	**kg N eq**	0.104	0.104	$5.70\cdot10^{-4}$	0.544	0.103	0.106	$1.80\cdot10^{-5}$
PM	**kg PM10eq**	0.047	0.047	$7.65\cdot10^{-4}$	1.59	0.046	0.049	$2.42\cdot10^{-5}$
POF	**kg NMVOC**	0.046	0.045	$2.04\cdot10^{-3}$	4.41	0.042	0.050	$6.44\cdot10^{-5}$
TA	**kg SO$_2$ eq**	0.289	0.289	$1.67\cdot10^{-3}$	0.576	0.286	0.293	$5.28\cdot10^{-5}$

5.3.4 Comparison with other studies

An economic comparison with other studies is difficult since, as far as known, there are no studies that combine the internal and external costs of producing lignocellulosic feedstocks for industrial fermentation processes, using the same methods. Tamburini et al. (2015) carried out an economic LCA considering the internal and external costs for agricultural crops in the Mediterranean, including wheat. Although the crops are intended for food and the analysis used very different indicators, a comparison of this chapter was made with wheat grain, as this raw material is also an important starch crop that can be valued in biorefineries. Considering that the LHV for wheat grain is in the order of 17 $MJ \cdot kg^{-1}$ (Niebel et al., 2012), it is possible to transform the units to compare with the functional unit of this present work. The total costs (internal + external) of wheat grain production are 25 € per GJ, while the environmental impact for CC is 8.67 kg CO_2 eq per GJ. This shows not much difference with the maize stover scenarios (MS–IT and MS–BE) of this current work.

Another study (Parajuli et al., 2017) performed an environmental LCA comparing different feedstocks for biorefinery systems, using also energy-based FU. The environmental results show that 5, 6 and 18 kg CO_2 eq per GJ for willow, alfalfa and straw from spring barley, respectively. This shows again that the results of the present study (for maize stover) do not present a large discrepancy with other studies, except for the beet pulp scenarios (BP–FR and BP–UK).

5.4 CONCLUSIONS

This chapter applied a cradle-to-gate LCA to assess the environmental burdens of the different fermentable feedstock scenarios. In addition, a cost assessment was carried out considering the internal and external costs. The application of these methodologies proved to be useful in evaluating the environmental and cost profile of maize stover and beet pulp, as well as powerful tools in the decision-making process for the selection of raw materials in industrial fermentation processes.

The results of economic and environmental assessment of this work show that maize stover has less impact than beet pulp. Maize stover goes through only one agricultural process to be produced, while beet pulp needs an additional pre-processing stage. Moreover, maize stover has a much higher calorific value, compared to sugar beet pulp.

This study represents a starting point towards effective sustainability in agricultural production and processing of lignocellulosic materials. This chapter innovates in the sense that it seeks to integrate economic aspects, internal and external, in the evaluation of the life cycle of a feedstock. It also allows future research to consider important aspects of the analysis of bio-commodities, such as the consequential LCA, to understand the variations of avoiding the production of 1G raw materials.

In addition, although the environmental impacts of these lignocellulosic feedstocks appear to be clearly assessed, understanding the cost associated with pollution remains a difficult task, due to the high subjectivity involved. The integration of environmental prices into LCA is a relatively new issue. Therefore, it is important to strengthen research in environmental economics for a more robust future assessment.

REFERENCES

Agrarheute, 2020. Erzeugerpreise für Düngemittel [WWW Document]. URL https://markt.agrarheute.com/duengemittel/ (accessed 4.9.20).

Agricultural Chemical Solutions, 2020. Pesticides Price List [WWW Document]. URL http://www.agchemicalsolutions.com/pesticides (accessed 4.9.20).

AHDB, 2020. GB fertiliser prices [WWW Document]. Agric. Hortic. Dev. Board. URL https://ahdb.org.uk/GB-fertiliser-prices (accessed 4.9.20).

Alyaseri, I., Zhou, J., 2019. Handling uncertainties inherited in life cycle inventory and life cycle impact assessment method for improved life cycle assessment of wastewater sludge treatment. Heliyon 5, e02793. https://doi.org/10.1016/j.heliyon.2019.e02793

Bezerra, T.L., Ragauskas, A.J., 2016. A review of sugarcane bagasse for second-generation bioethanol and biopower production. Biofuels, Bioprod. Biorefining 10, 634–647. https://doi.org/10.1002/bbb.1662

Boone, L., Van, V., Meester, S. De, Vandecasteele, B., Muylle, H., Roldán-ruiz, I., Nemecek, T., Dewulf, J., 2016. Environmental life cycle assessment of grain maize production : An analysis of factors causing variability. Sci. Total Environ. 553, 551–564. https://doi.org/10.1016/j.scitotenv.2016.02.089

CLAL, 2020. Italy: Prices of mineral fertilizers [WWW Document]. URL https://www.clal.it/en/?section=concimi (accessed 4.9.20).

Cutz, L., Masera, O., Santana, D., Faaij, A.P.C., 2017. Switching to efficient technologies in traditional biomass intensive countries : The resultant change in emissions. Energy 126, 513–526. https://doi.org/10.1016/ j.energy.2017.03.025

Datosmacro, 2020. Precios de los derivados del petróleo [WWW Document]. Expansión. URL https://datosmacro.expansion.com/

energia/precios-gasolina-diesel-calefaccion/espana (accessed 4.9.20).

David, E., 2013. Sustainable Corn Stover Harvest. Iowa.

De Bruyn, S., Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., Vergeer, R., Ahdour, S., 2018. Environmental Prices Handbook EU28 Version. Methods and numbers for valuation of environmental impacts. CE Delft 175.

Díaz, A.B., Marzo, C., Caro, I., de Ory, I., Blandino, A., 2017. Valorization of exhausted sugar beet cossettes by successive hydrolysis and two fermentations for the production of bio-products. Bioresour. Technol. 225, 225–233. https://doi.org/10.1016/j.biortech.2016.11.024

Durlinger, B., Koukouna, E., Broekema, R., Van Paassen, M., Scholten, J., 2017. Agri-footprint 4.0. Gouda.

EMEP/EEA, 2019. Crop production and agricultural soils, in: Air Pollutant Emission Inventory Guidebook 2019. pp. 1–35. https://doi.org/10.1016/b978-159749152-5/50001-2

European Commission, 2017. PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3.

European Commission, 2016. EU Farm Economics Overview. Eur. Comm. Dev. Dir. Agric. Rural Dev. 2015, 82.

Faist-Emmenegger, M., Reinhard, J., Zah, R., 2009. Sustainability Quick Check for Biofuels. Intermediate background report. Dübendorf.

FAOSTAT, 2019. Crop statistics [WWW Document]. URL http://www.fao.org/faostat/en/#data (accessed 1.10.19).

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., Zelm, R. Van, 2009. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level.

https://doi.org/10.029/2003JD004283

Hernández, C., Escamilla-Alvarado, C., Sánchez, A., Alarcón, E., Ziarelli, F., Musule, R., Valdez-Vazquez, I., 2019. Wheat straw, corn stover, sugarcane, and Agave biomasses: chemical properties, availability, and cellulosic-bioethanol production potential in Mexico. Biofuels, Bioprod. Biorefining 13, 1143–1159. https://doi.org/10.1002/ bbb.2017

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D., Dudgeon, D., 2011. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol. Renew. Energy 303, 147. https://doi.org/10.2172/ 1013269

IATP, 2012. 2012 Working Landscapes Certificate Informatio [WWW Document]. Inst. Agric. Trade Policy. URL https://www.iatp.org/documents/2012-working-landscapes-certificate-information (accessed 11.30.20).

IPCC, 2019. N2O Emissions From Managed Soils, and Co2 Emissions From Lime and Urea Application, in: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. pp. 1–48.

Joanna, B., Michal, B., Piotr, D., Agnieszka, W., Dorota, K., Izabela, W., 2018. Sugar Beet Pulp as a Source of Valuable Biotechnological Products, in: Advances in Biotechnology for Food Industry. Elsevier Inc., pp. 359–392. https://doi.org/10.1016/B978-0-12-811443-8/00013-X

Joelsson, E., Erdei, B., Galbe, M., Wallberg, O., 2016. Techno-economic evaluation of integrated first- and second-generation ethanol production from grain and straw. Biotechnol. Biofuels 9, 1–16. https://doi.org/10.1186/s13068-015-0423-8

Kim, S., Dale, B.E., Jenkins, R., 2009. Life cycle assessment of corn grain and corn stover in the United States. Int. J. Life Cycle Assess. 14, 160–174. https://doi.org/10.1007/s11367-008-0054-4

Klenk, I., Landquist, B., de Imana, O.R., 2012. The Product Carbon Footprint of EU beet sugar. Sugar Ind. J. 137, 169–177.

Maravíc, N., Kiss, F., Seres, L., Bogdanovic, Branislav, Bogdanovic, Biljana, Seres, Z., 2015. Economic analysis and LCA of an advanced industrial-scale raw sugar juice purification procedure. Food Bioprod. Process. 5, 19–26. https://doi.org/10.1016/j.fbp.2015.02.004

Mujumdar, A.S., 2014. Superheated Stream Drying, in: Handbook of Industrial Drying. pp. 421–432.

Muñoz, I., Flury, K., Jungbluth, N., Rigarlsford, G., I Canals, L.M., King, H., 2014. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int. J. Life Cycle Assess. 19, 109–119. https://doi.org/10.1007/s11367-013-0613-1

Murphy, C.W., Kendall, A., 2013. Life cycle inventory development for corn and stover production systems under different allocation methods. Biomass and Bioenergy 58, 67–75. https://doi.org/10.1016/ j.biombioe.2013.08.008

Nemecek, T., Bengoa, X., Lansche, J., Mouron, P., Riedener, E., Rossi, V., Humbert, S., 2015. Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 3.0. Lausanne and Zurich.

Niebel, A., Balcazar, H., Reisch, T., Lappas, A., Michailof, C., 2012. Feedstock selection, Characterization and Preparation.

Noya, I., González-García, S., Bacenetti, J., Arroja, L., Moreira, M.T., 2015. Comparative life cycle assessment of three representative feed cereals production in the Po Valley (Italy). J. Clean. Prod. 99, 250–265. https://doi.org/10.1016/j.jclepro.2015.03.001

Özkan, A., Günkaya, Z., Tok, G., Karacasulu, L., Metesoy, M., Banar, M., Kara, A., 2016. Life cycle assessment and life cycle cost analysis of magnesia spinel brick production. Sustain. 8, 1–13. https://doi.org/10.3390/ su8070662

Parajuli, R., Trydeman, M., Njakou, S., Corona, A., Birkved, M., Dalgaard, T., 2017. Environmental life cycle assessment of producing willow , alfalfa and straw from spring barley as feedstocks for bioenergy or biorefinery systems. Sci. Total Environ. 586, 226–240. https://doi.org/10.1016/j.scitotenv.2017.01.207

Prasad, A., Sotenko, M., Blenkinsopp, T., Coles, S.R., 2016. Life cycle assessment of lignocellulosic biomass pretreatment methods in biofuel production. Int. J. Life Cycle Assess. 21, 44–50. https://doi.org/10.1007/s11367-015-0985-5

Renouf, M.A., Wegener, M.K., Nielsen, L.K., 2008. An environmental life cycle assessment comparing Australian sugarcane with US corn and UK sugar beet as producers of sugars for fermentation. Biomass and Bioenergy 32, 1144–1155. https://doi.org/10.1016/j.biombioe.2008.02.012

Ruan, Z., Wang, X., Liu, Y., Liao, W., 2019. Corn, in: Integrated Processing Technologies for Food and Agricultural By-Products. Elsevier Inc., pp. 59–72. https://doi.org/10.1016/B978-0-12-814138-0.00003-4

Sampaio, I.L.M., Cardoso, T.F., Souza, N.R.D., Watanabe, M.D.B., Carvalho, D.J., Bonomi, A., Junqueira, T.L., 2019. Electricity Production from Sugarcane Straw Recovered Through Bale System : Assessment of Retrofit Projects. BioEnergy Res. 12, 865–877. https://doi.org/10.1007/s12155-019-10014-9 Electricity

Simon, D., Tyner, W.E., Jacquet, F., 2010. Economic Analysis of the Potential of Cellulosic Biomass Available in France from Agricultural Residue and Energy Crops. Bioenerg. Res. 3, 183–193. https://doi.org/10.1007/s12155-009-9061-y

Tamburini, E., Pedrini, P., Marchetti, M.G., Fano, E.A., Castaldelli, G., 2015. Life cycle based evaluation of environmental and economic impacts of agricultural productions in the Mediterranean area. Sustain. 7, 2915–2935. https://doi.org/10.3390/su7032915

Teagasc, 2017. Available Nutrient Content & Guide Value (€) of Organic Fertilizers 2017 [WWW Document]. Agric. Food Devepoment Auth. URL https://www.teagasc.ie/crops/soil--soil-fertility (accessed 4.9.20).

TERRE-net, 2020. Cotations des engrais [WWW Document]. URL https://www.terre-net.fr/marche-agricole/ammonitrate-27/engrais (accessed 4.9.20).

Thompson, W., Meyer, S., 2013. Second generation biofuels and food crops : Co-products or competitors ? Glob. Food Sec. 2, 89–96. https://doi.org/10.1016/j.gfs.2013.03.001

Unirioja, 2020. Cálculo de costes de maquinaria. Método combinado [WWW Document]. URL https://acmag.unirioja.es/ (accessed 4.9.20).

Uusitalo, V., Väisänen, S., Havukainen, J., Havukainen, M., Soukka, R., Luoranen, M., 2014. Carbon footprint of renewable diesel from palm oil , jatropha oil and rapeseed oil. Renew. Energy 69, 103–113. https://doi.org/10.1016/j.renene.2014.03.020

Wang, M., Han, J., Dunn, J.B., Cai, H., Elgowainy, A., 2012. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environ. Res. Lett. 7. https://doi.org/10.1088/1748-9326/7/4/045905

Wendt, L.M., Smith, W.A., Hartley, D.S., Wendt, D.S., Ross, J.A., Sexton, D.M., Lukas, J.C., Nguyen, Q.A., Murphy, J.A., Kenney, K.L., 2018. Techno-Economic Assessment of a Chopped Feedstock Logistics Supply Chain for Corn Stover. Front. Energy Res. 6, 1–14. https://doi.org/10.3389/fenrg.2018.00090

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Whitman, T., Yanni, S.F., Whalen, J.K., 2011. Life cycle assessment of corn stover production for cellulosic ethanol in Quebec. Can. J.

Soil Sci. 91, 997?1012. https://doi.org/10.4141/CJSS2011-011

Wietschel, L., Thorenz, A., Tuma, A., 2019. Spatially explicit forecast of feedstock potentials for second generation bioconversion industry from the EU agricultural sector until the year 2030. J. Clean. Prod. 209, 1533–1544. https://doi.org/10.1016/j.jclepro.2018.11.072

Zicari, S., Zhang, R., Kaffka, S., 2019. Sugar beet, in: Integrated Processing Technologies for Food and Agricultural By-Products. pp. 331–351.

SECTION III

AGRICULTURE AND BIO-BASED CONTEXT

CHAPTER 6: ENVIRONMENTAL ASSESSMENT OF WHEAT-BASED GLUCOSE PRODUCTION[4]

SUMMARY

In recent years, the need to substitute fossil fuels with renewable biomass has been a key driver in the development of the biorefinery concept. One of the possible routes towards the production of bio-based products under this scheme is through a sugar intermediate. Sugars, such as glucose, can be produced through starch crops, for instance wheat. While there are many environmental assessment studies that consider sugar as a platform for biofuel production, the main focus is on the end product of the value chain (typically bioethanol), but not on sugars as the basic feedstock. Taking the bottom-up perspective as a roadmap, the assessment of technological, economic and environmental barriers in the biorefinery scheme must take into account the sustainability of sugar production with the aim of improving its current framework or finding novel technologies.

This chapter investigates the environmental sustainability of wheat cultivation and grain processing in different European countries by applying the life cycle assessment (LCA) methodology with a cradle-to-gate approach. Moreover, 1 kg of wheat grain and 1 kg of glucose at

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[4] Chapter based on publication:

Iana Câmara-Salim[a], Sara González-García[a], Gumersindo Feijoo[a], Maria Teresa Moreira[a]. Assessing the environmental sustainability of glucose from wheat as a fermentation feedstock, Journal of Environmental Management, Volume 247, 2019, Pages 323-332, ISSN 0301-4797, https://doi.org/10.1016/ j.jenvman.2019.06.016

[a] Department of Chemical Engineering, University of Santiago de Compostela, Santiago de Compostela, 15782, Spain

the factory gate have been considered as functional units for reporting the environmental results. The chosen impact categories are climate change (CC), particular matter (PM), human toxicity (HT), freshwater eutrophication (FE), terrestrial eutrophication (TE), acidification (AC) and abiotic depletion (AD). Mass and economic allocations are evaluated as the processing of grain wheat generates different valuable by-products, namely wheat bran, gluten meal and gluten feed. The results show that agricultural activities play an important role in the environmental impacts, predominantly due to the production of agrochemicals and field emissions derived from fertilisation. Compared to mass allocation, the use of economic allocation shows a slight increase in the environmental results.

6.1 INTRODUCTION

As mentioned earlier in Chapter 3, for millennia, wheat cultivation has developed with the world's leading civilizations and still remains one of the most important domestic crops today (Curtis et al., 2002). Wheat can be used for a wide range of products, from food/feed to biofuels, biochemicals, pharmaceuticals and bioplastics. Given the high starch content of wheat, this polysaccharide can serve as a source of glucose and undergo further processing through different routes, such as fermentation (Deloitte, 2014; E4tech et al., 2015).

In the growing context of bioeconomy, interest in the application of LCA in biorefineries systems has increased (Vaskan et al., 2017). Most of LCA studies emphasize the final product, such as the production of ethanol from fermentable sugars (Bernesson et al., 2006; Gnansounou et al., 2008; Muñoz et al., 2014). To a lesser extent, studies focusing on the environmental sustainability of fermentable sugars as an intermediate platform for the production of bioproducts or biofuels have been gaining interest in recent years and most of them have investigated glucose production mainly from maize grain (Moncada et al., 2018; Renouf et al., 2008; Tsiropoulos et al., 2013).

However, it should be borne in mind that the cultivation of maize in Europe represents only 6% of world production, while wheat is 20%. (FAOSTAT, 2019), so the study of this production route is considered to arise special interest. The authors Vercalsteren and Boonen (2015) performed an LCA of starch and glucose from wheat, maize and potato. However, the results are presented in an aggregated form, considering the production of starch and glucose from the mixture of the three raw materials, which makes it difficult to identify the environmental impacts associated only with the production of glucose from wheat.

Due to technological and economic restrictions, the upstream processes of bio-based products are considered, until now, as bottlenecks in the direction of the downstream phases. Tsiropoulos et al. (2013) analysed the environmental profile of maize glucose production in a European context and stated the need to apply more LCAs on this topic. Taking into consideration that wheat is an important crop in Europe, assessing the environmental sustainability of wheat-based glucose in this region is interesting to understand its environmental profile, as well as finding new and more efficient ways to reach the sugar platform, on the way to bioeconomy.

6.2 MATERIALS AND METHODS

This study has twofold perspectives. The first one is to analyse the environmental sustainability of wheat cultivation in Europe from 15 agricultural systems representing farming activities in 9 countries. For this research, the agricultural stages were identified based on the work of Achten and Van Acker (2016). The second perspective is to perform an LCA on the production of glucose from wheat. To this end, the results of wheat cultivation in Europe will be linked to the glucose production process to consider the environmental impact of the production of glucose from different European countries.

6.2.1 Goal and scope definition

This study aims to conduct an LCA to assess the environmental profile of different European wheat producing countries and to further analyse the environmental profile of wheat-based glucose. The chosen functional units are 1 kg of wheat grain and 1 kg of glucose at the factory gate. This monosaccharide is specified as glucose syrup, with 95 dextrose equivalent (DE), which is the type of substrate used in industrial fermentation processes (Wood and Rourke, 1995). The harvested wheat grain is assumed to have 13.5% moisture content (MC), which is a standard established by the market to evaluate the quality and price of wheat (Sadaka et al., 2014). It was assumed that wheat straw was left completely in the field as soil amendment. As shown in Figure 6.1, the analysed system has a cradle-to-gate perspective, ranging from agricultural activities to glucose production.

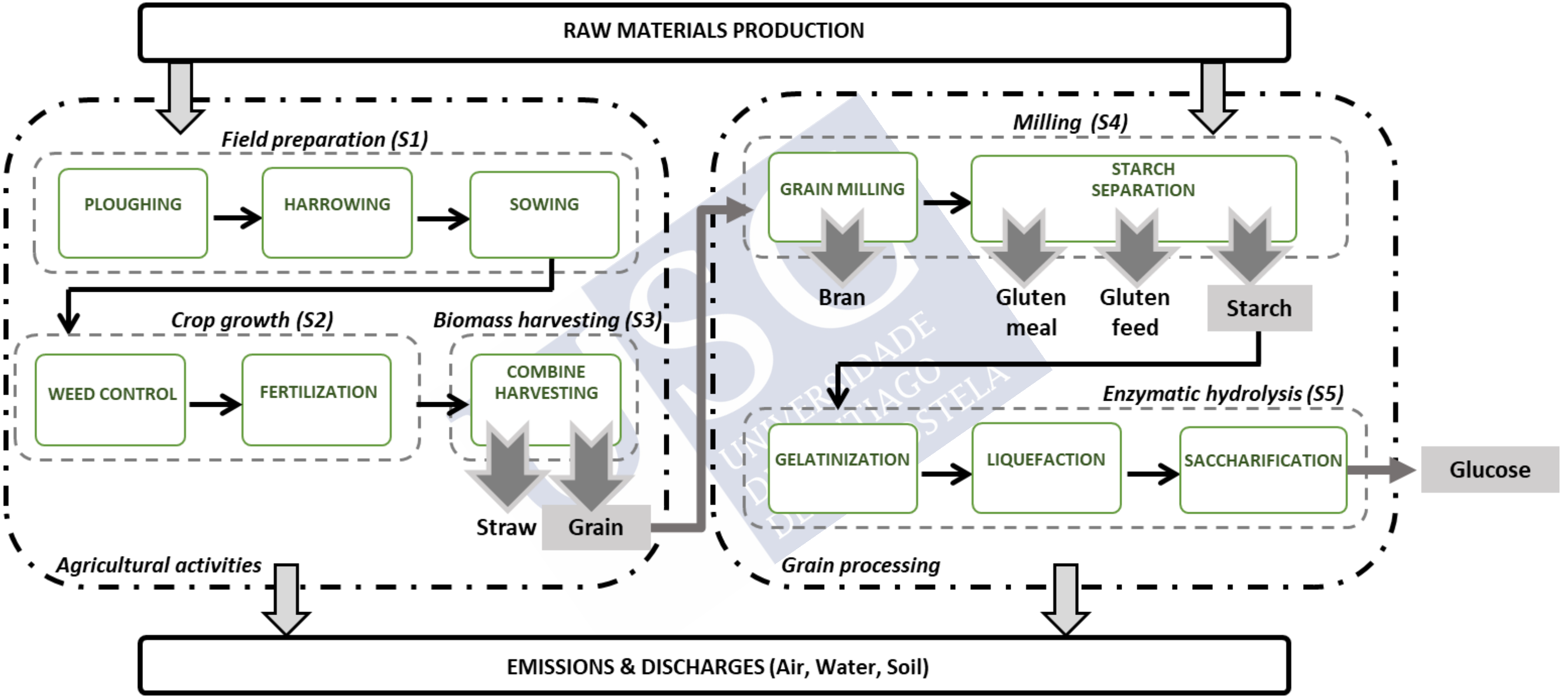

Figure 6.1. System boundaries considered to produce glucose from wheat.

6.2.1.1 Agricultural system (S1, S2 and S3)

The agricultural system under this study is established in several subsystems: field preparation (S1), crop growth (S2) and biomass harvesting (S3). Although there are a variety of agricultural practices in wheat cultivation, the system boundaries, considered for the 15 cases in the study of Achten and Van Acker (2016), cover the most common agricultural processes, such as tillage, sowing, fertilisation, plant protection and combine harvesting (Figure 6.1).

The background processes comprise the production of machinery and infrastructure, fossil fuel extraction, refining and electricity generation. In this study, transport from the farm to the manufacturing plants was not considered, as it is assumed that they are all located side by side, according to a biorefinery approach. The grain processing phase, from wheat grain to glucose production, is specified below and divided in two main subsystems: Milling (S4) and Enzymatic hydrolysis (S5).

Chapters 3 and 4 also assessed the environmental sustainability of wheat cultivation, with a focus on local agriculture and traditional food, using mostly primary data from in situ interviews, while this chapter emphasizes an overview by country using secondary data from the literature.

6.2.1.2 Milling (S4)

Once the wheat has been stored and transported to the factory, it must be processed into starch. First, the wheat is cleaned to remove impurities. After the separation of the grain according to its size, shape and weight, the wheat grain is milled; initially, through a dry milling stage with the objective of separating the bran from the kernel, by continuous arrangements of breaking, grinding and separation stages. A subsequent wet milling process takes on, in which the grain is soaked with water for approximately 24-48 h to raise the moisture content of the grain. The soaking process requires a relatively long time to soften the wheat grain and, depending on the wet milling facility, can take up to a week (Papageorgiou and Skendi, 2018a). The soft grain is then crushed, generating a starch fraction and a protein fraction. This process generates important by-products, namely bran, gluten meal and gluten feed (OECD, 2003). After milling, the starch goes through an enzymatic hydrolysis stage.

6.2.1.3 Enzymatic hydrolysis (S5)

Starch hydrolyses may take an acidic or enzymatic route. To date, the most common process of glucose production from starch (starch hydrolysis) undergoes initial washing, gelatinization, liquefaction and saccharification (Arifeen et al., 2009; Du et al., 2008; Elliott et al., 2002). Gelatinization and Liquefaction occur when water and heat break starch molecules, dissolving starch granules in water. With the addition of alpha-amylase enzymes, sodium hydroxide (NaOH) and calcium chloride ($CaCl_2$), starch is transformed into soluble dextrin. In this process, the milled wheat grain is soaked with water to obtain a slurry which is heated twice inside a cooker. The liquefied solution will then be slowly cooled. Finally, saccharification takes place and the sugar, which is mainly composed of dextrin, is further cooled and hydrolysed with the addition of glucoamylase enzyme and H_2SO_4, converting dextrin into glucose. The purification process, which is normally used in the starch food industry, was not taken into consideration, since fermentation processes do not use purified glucose, but starch hydrolysate or glucose syrup as substrate.

6.2.2 Life cycle inventory

As aforementioned, life cycle inventory (LCI) data were assessed for the wheat agricultural activities, taking into account 15 case studies from 9 countries (Achten and Van Acker, 2016). As shown in Table

6.1, the main material inputs and outputs were identified for the production of 1 kg of wheat with 13.5% MC for each European country. The input materials included in the system boundaries are those necessary for the production and use of fertilisers, pesticides, seeds, diesel, tractors, harvesters and agricultural machineries. Emissions to the atmosphere, water and soil derived from agricultural activities are also comprised in the system.

Table 6.1. Summarized Life Cycle Inventory data corresponding with European wheat production scenarios. Data displayed per kg wheat grain. Acronyms: SE-Sweden, DK – Denmark, CH – Switzerland, DE-Deutschland, UK – United Kingdom, IT – Italy, GR – Greece, NL – Netherlands, BE – Belgium, NOx - Nitrogen oxides, NMVOC - Non-methane volatile organic compounds, CO - Carbon monoxide, CO_2 – Carbon dioxide, SO_2 – Sulfur dioxide, N_2O – Dinitrogen monoxide, NH_3 – Ammonia, Zn – Zinc, K – Potassium; S – Sulfur, Cu – Copper, Fe – Iron.

	SE1[a]	**SE2[a]**	**SE3[a]**	**DK1**	**DK2**	**CH1**	**CH2**	**CH3**	**DE**	**UK1**	**UK2**	**IT**	**GR**	**NL**	**BE**
Inputs from the nature:															
Arable land (m^2·year/kg wheat)	1.8	1.4	1.6	1.6	1.40	1.7	1.5	1.8	1.7	1.3	1.4	1.4	3.2	1.3	1.2
Inputs from technosphere:															
Tractor (g)	1.18	0.99	1.00	1.01	0.86	1.10	1.01	1.16	1.16	0.79	0.96	0.85	1.99	0.79	0.75
Harvester (g)	1.13	0.88	1.01	1.01	0.88	1.07	0.95	1.13	1.07	0.82	0.88	0.88	2.02	0.82	0.76
Diesel (g)	18.0	13.3	15.5	15.6	13.3	17.1	15.5	17.9	17.0	12.2	14.1	13.8	30.9	12.3	11.5
Agricultural machinery (g)	1.85	1.38	1.61	1.63	1.39	1.81	1.68	1.86	1.78	1.27	1.54	1.69	3.20	1.27	1.20
N fertiliser (g)	21.8	22.0	20.0	29.2	22.4	22.0	21.2	21.6	26.7	30.0	29.3	25.7	33.5	25.3	21.7
P_2O_5 fertiliser (g)	9	3.4	6.6	9.4	7.1	8.4	8.4	6.2	8.4	7.5	5.7	12.8	4	-	5.5
K_2O fertiliser (g)	-	6.1	6.5	11.7	11.7	2	2	1.5	20	7.6	6.1	-	-	-	22
Pesticides (g)	-	-	0.50	-	-	0.50	-	-	-	1.50	1.30	0.20	0.50	1.50	0.30

a The abbreviations SE1, SE2 and SE3 represent different case studies of wheat production within the same country. In this case, three wheat agricultural systems in Sweden (SE). The same reasoning applies for the other scenarios.
b Due to lack of reliable data, emissions into water (phosphorus leaching and runoff) were not considered for some case studies.

Table 6.1. (Cont.) Summarized Life Cycle Inventory data corresponding with European wheat production scenarios. Data displayed per kg wheat grain. Acronyms: SE-Sweden, DK – Denmark, CH – Switzerland, DE-Deutschland, UK – United Kingdom, IT – Italy, GR – Greece, NL – Netherlands, BE – Belgium, NOx - Nitrogen oxides, NMVOC - Non-methane volatile organic compounds, CO - Carbon monoxide, CO2 – Carbon dioxide, SO2 – Sulfur dioxide, N2O – Dinitrogen monoxide, NH3 – Ammonia, Zn – Zinc, K – Potassium; S – Sulfur, Cu – Copper, Fe – Iron.

	Outputs to environment:	**SE1**[a]	**SE2**[a]	**SE3**[a]	**DK1**	**DK2**	**CH1**	**CH2**	**CH3**	**DE**	**UK1**	**UK2**	**IT**	**GR**	**NL**	**BE**
To air	NOx (g)	0.81	0.60	0.70	0.70	0.60	0.77	0.70	0.81	0.77	0.56	0.64	0.62	1.40	0.56	0.52
	NMVOC (mg)	55.9	41.9	48.6	48.9	42.2	53.7	48.6	56.5	53.6	38.8	44.4	44.7	97.2	38.8	36.4
	Particulates<2,5 µm (mg)	81.2	59.5	69.4	69.7	59.8	76.6	69.7	79.7	75.7	54.8	62.4	62.2	138.3	54.8	51.8
	CO (g)	0.13	0.10	0.11	0.11	0.10	0.12	0.11	0.13	0.12	0.09	0.10	0.10	0.23	0.09	0.09
	CO2 (g)	56.0	41.3	48.1	48.4	41.5	53.0	48.2	55.4	53.0	38.1	43.8	43.0	96.0	38.1	36.0
	SO2 (mg)	18.1	13.4	15.6	15.7	13.4	17.2	15.6	18.0	17.2	12.3	14.2	13.9	31.1	12.3	11.6
	N2O (mg)	2.60	1.93	2.25	2.26	1.94	2.46	2.22	2.55	2.46	1.78	2.03	2.00	4.49	1.78	1.67
	NH3 (g)	1.89	1.79	1.76	2.48	1.80	1.87	1.76	1.78	1.04	1.57	1.56	4.13	2.85	2.09	1.79
To water	Nitrogen (N) leaching (g)	6.14	6.20	5.64	11.6	8.91	12.0	11.8	11.8	4.60	4.31	4.19	7.24	9.45	7.13	6.18
	Phosphorus (P) runoff (g)	0.03	-	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	-	0.13	-	0.03
	Phosphorus (P) leaching (g)[b]	-	-	-	0.10	0.10	-	-	-	-	-	-	-	0.10	-	-
To soil	Zn (mg)	3.15	2.40	2.80	2.82	2.21	3.09	2.85	3.20	3.04	2.21	2.55	2.42	2.67	5.53	2.07
	K (mg)	0.97	0.80	0.90	1.13	0.86	0.98	0.91	0.94	1.10	1.12	1.11	1.05	1.46	0.91	0.82
	S (mg)	2.61	2.27	2.41	3.18	2.41	2.63	2.49	2.55	3.02	3.17	3.12	2.93	3.90	2.58	2.30
	Cu (mg)	1.22	1.20	1.11	1.62	1.25	1.23	1.19	1.19	1.49	1.66	1.60	1.46	1.82	1.35	1.21
	Glyphosate (mg)	3.60	1.30	3.37	3.83	1.39	3.14	3.16	3.47	3.57	3.34	3.46	3.44	4.48	2.80	1.32

Outputs to environment:	**SE1[a]**	**SE2[a]**	**SE3[a]**	**DK1**	**DK2**	**CH1**	**CH2**	**CH3**	**DE**	**UK1**	**UK2**	**IT**	**GR**	**NL**	**BE**
Oils (mg)	149	112	134	162	124	147	139	143	161	147	148	155	216	114	114
Fe (mg)	6.69	5.32	6.29	7.96	5.82	6.71	6.31	6.29	6.50	7.77	7.67	7.26	9.76	6.16	5.71

a The abbreviations SE1, SE2 and SE3 represent different case studies of wheat production within the same country. In this case, three wheat agricultural systems in Sweden (SE). The same reasoning applies for the other scenarios.

b Due to lack of reliable data, emissions into water (phosphorus leaching and runoff) were not considered for some case studies.

As noted, data can vary on a case-by-case basis and a plethora of materials is needed, from field preparation, plant development and harvesting. As far as the use of NPK (Nitrogen, as N; Phosphorus, as P_2O_5 and Potassium, as K_2O) fertilisers is concerned, nitrogen represents the main input. In the Netherlands, for instance, only nitrogen is used as a fertiliser. On the other hand, in countries such as Germany and Belgium, the addition of potassium nutrients has a considerable weight in NPK fertilisation. Apart from Greece, the size of arable land varies slightly from country to country with an average of 1.5 ± 0.19 m^2 year per kg of wheat. Furthermore, due to different agricultural practices, not all countries require the use of pesticides.

The emissions to the air, water and soil are displayed in Table 6.1. Background data were gathered from the Ecoinvent v3.2® database (Wernet et al., 2016). Many emissions were considered, such as nitrogen-derived substances (i.e., NO_x), non-methane volatile organic compounds (NMVOC), particulates < 2,5 µm and carbon monoxide (CO). In addition, emissions from nitrous oxide (N_2O) and carbon dioxide (CO_2), which are recognized GHG, occurs mainly due to field emissions from fertilisation and the burning of fuel in agricultural activities (e.g., diesel use in tractors). The use of nitrogenous and phosphorus substances in agricultural activities contributes to water emissions, such as nitrogen leaching into groundwater. As regards soil emissions, heavy metals, such as zinc (Zn), may be released as tire wear particles by tractors that remain on the ground. This substance can be assimilated in the food chain or by direct absorption in the soil (Wuana and Okieimen, 2014). Other soil emissions, such as oils, arise from the use of lubricant in agricultural machinery. The full inventory list is displayed in Table 6.1.

As regards LCI for the pre-processing phases (Table 6.2), data for wet milling were gathered from different sources (Moncada et al., 2018; Mustafa et al., 2007; Renouf et al., 2008; van Zeist et al., 2012;

Vercalsteren and Boonen, 2015). Material inputs from the starch enzymatic hydrolysis process were taken from a wheat biorefinery for ethanol production (Mustafa et al., 2007). As shown in Table 6.2, about 1.5 kg of wheat grain produces 1 kg of glucose.

Table 6.2. Life Cycle Inventory data corresponding with glucose production, regarding foreground system (Grain processing). Data displayed per kg of glucose.

	Amount	Unit
Milling (S4)		
Inputs from technosphere		
Wheat	1.51	kg
Electricity	0.93	MJ
Natural gas	2.18	MJ
Process water	3.10	kg
Outputs to technosphere		
By-products		
Wheat bran	0.26	kg
Wheat gluten feed	0.11	kg
Wheat gluten meal	0.14	kg
Enzymatic hydrolysis (S5)		
Inputs from technosphere		
Enzyme α-Amylase	1.00	g
Glucoamylase	2.00	g
NaOH	10	g
$CaCl_2$	2.00	g
H_2SO_4	3.00	g
Process water	2.78	kg
Steam	0.37	kg
Cooling water	4.27	kg
Electricity	$13 \cdot 10^{-3}$	MJ
Output to technosphere		
Glucose	1.00	kg
Waste to treatment from grain processing		
Wastewater	4.50	kg
Emissions to water from grain processing		
BOD_5	$0.2 \cdot 10^{-3}$	g

The uppermost goal of the wet milling process is to obtain the maximum amount of high-quality starch and separate it from gluten. The wheat milling process renders into valuable by-products, namely wheat bran, gluten feed and gluten meal. The bran, which represents the outer part of the wheat, is an abundant source of fibre. The germ was supposed to be added to the bran to supplement its nutritional value with lipids (Papageorgiou and Skendi, 2018b).

Wheat gluten feed has a low protein content (about 20%) and may include the combination of bran and evaporated steep water, while wheat gluten meal has a higher purity and protein content (about 80%). The composition of each by-product may vary according to the needs of the producer and consumer and types of processing. In fact, it is possible to assemble a variety of combinations of by-products with different protein, lipids and starch contents (EFISC, 2013). It was assumed that 97% of the starch stream is decomposed into glucose after enzymatic hydrolysis. This supposition is consistent with wet milling facilities that are capable of converting large amounts of starch into glucose (Moncada et al., 2018; Tsiropoulos et al., 2013).

Transport to the mill was not considered in this study as mill facilities were supposed to be located near the agricultural fields. Therefore, the contribution of transport would be minor to the overall environmental impacts. As for emissions to the environment, the majority are water emissions, that will be treated in a wastewater treatment plant. However, a small amount of biological oxygen demand (BOD_5) released untreated into waterbodies was assumed as in the work of Renouf et al. (2008) for wet milling process.

With respect to the data to account for the environmental impacts of the background processes, it was assessed through the Ecoinvent v3.2® database (Wernet et al., 2016). However, due to lack of reliable data for enzymes in this database, information on α-Amylase and Glucoamylase production was taken from the USDA Food Composition Database (Table 6.3).

Table 6.3. Description of the main Ecoinvent ® database version v3.2 (Wernet et al., 2016). Processes used for the accounting of background processes.

Input	Process description
Electricity	Electricity, medium voltage {[a]}| market group for | Alloc Rec, U
Natural gas	Heat, district or industrial, natural gas {CH}| market for heat, district or industrial, natural gas | Alloc Rec, U
Water	Tap water {CH}| market for | Alloc Rec, U
α-Amylase	Enzyme, Alpha-amylase, Novozyme Liquozyme/kg/RER
NaOH	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Rec, U
$CaCl_2$	Calcium chloride {GLO}| market for | Alloc Rec, U
Steam	Steam, in chemical industry {GLO}| market for | Alloc Rec, U
Cooling water	Water, cooling, unspecified natural origin
Glucoamylase	Enzyme, Glucoamylase, Novozyme Spirizyme/kg/RER
H_2SO_4	Sulfuric acid {GLO}| market for | Alloc Rec, U
Wastewater treatment	Wastewater, average {CH}| treatment of, capacity 1E9l/year | Alloc Rec, U

[a] The electricity choice is according to the electricity mix of the country under investigation

6.2.3 Allocation

Allocation should be carefully considered when performing LCA of starch-based products, since this industry generates a variety of complex and useful by-products. As the production of glucose involves additional valuable by-products (bran, gluten meal and gluten feed) from wet milling, it is difficult to apply a subdivision or system expansion as recommended by ISO 14040/44 (ISO14044, 2006) and the PEF guide (European Commission, 2017) due to the complexity of this allocation method. Therefore, mass and economic allocations were performed in this study (Table 6.4) as they are two of the main allocation methods used in LCA (Mackenzie et al., 2017; Urban and Bakshi, 2009). Furthermore, data on mass values and market prices were retrieved from databases (Durlinger et al., 2017). The price of glucose was assumed to be twice the price of starch (Porras et al., 2018). Energy-based allocation was disregarded since the product (glucose) and by-products (bran, wheat gluten feed and meal) of this study are not intended to be used for energy production (i.e., biofuels) but have a feed/food and/or bio-products purpose (e.g., glucose for bioplastic production).

Table 6.4. Wheat by-products mass and economic allocations.

	Mass (kg /kg wheat)	**Percentage (%)**	**Price (€/kg)**	**Percentage (%)**
Wheat bran[a]	0.18	17.5	0.12	5
Wheat gluten feed[a]	0.08	7.8	0.16	3
Wheat gluten meal[a]	0.10	9.7	0.78	18
Wheat glucose[a,b]	0.66	65.0	0.5	74

[a] Data from Agri-footprint database (Durlinger et al., 2017)

[b] The price is assumed to be twice the starch (dry basis)

6.2.4 Life cycle impact assessment

The life cycle inventory phase generates a long list of elementary flows that are difficult to interpret. However, this obstacle is reduced by the implementation of life cycle impact assessment (LCIA), which can associate a large amount of inventory data with selected environmental indicators. In this context, it is important to bear in mind that LCA results may have a different understanding, depending on the LCIA methods being used.

The environmental impact categories (Table 6.5) at midpoint level were chosen according to the recommendations of the International Reference Life Cycle Data System (ILCD) (Fazio et al., 2018), the Product Environmental Footprint (PEF) guide (European Commission, 2017) and also according to the work on starch and glucose production in Europe (Vercalsteren and Boonen, 2015). In addition, a review of different studies on the agricultural phase and glucose production shows that these selected impact categories are the most used in the literature on biorefinery systems (Moncada et al., 2018; Prasad et al., 2016; Renouf et al., 2008; Vercalsteren and Boonen, 2015).

Table 6.5. The chosen environmental impact categories.

Impact category	Unit	Model	Source
Climate change (CC)	kg CO_2 eq	IPCC GWP100	(IPCC, 2013)
Particulate matter (PM)	Disease incidence/kg PM2.5	UNEP recommended model	(Fantke et al., 2016)
Human toxicity (HT)	CTUh	USETox	(Rosenbaum et al., 2008)
Acidification (AC)	Mol H+ eq	Accumulated exceedance	(Posch et al., 2008; Seppälä et al., 2006)
Freshwater eutrophication (FE)	kg P eq	EUTREND as implemented in Recipe 2008	(Struijs et al., 2013)
Terrestrial eutrophication (TE)	Mol N eq	Accumulated exceedance	(Posch et al., 2008; Seppälä et al., 2006)
Abiotic depletion (Fossil fuels) (AD)	MJ	CML-IA baseline V3.03 / EU25	(Guinée et al., 2002; Van Oers et al., 2002)

6.3 RESULTS AND DISCUSSION

6.3.1 Environmental profile of wheat cultivation and grain processing phases

LCA results on wheat cultivation vary considerably between European countries, due to differences in geography, climate and agricultural management. The average values of the 15 case studies are assessed in Table 6.6 for each impact category. As shown, standard deviations are relatively high for each environmental indicator. This is mainly due to the difference in agricultural management and, to a lesser extent, to the electricity mix of each country. The results show a greater environmental impact for glucose when making an economic allocation.

Table 6.6. Absolute values and their respective standard deviations for all the 15 agricultural systems for 1 kg of wheat grain and 1 kg glucose production, including agriculture (A) and grain processing (GP) in the mass allocation (Mass alloc) and economic allocation (Eco alloc) scenarios.

Impact categories	A	A + GP (Mass alloc)	A + GP (Eco alloc)
CC (kg CO_2 eq)	0.68±0.14	0.95±0.17	1.09±0.20
PM (Disease incidence)	$(5.35±1.51)·10^{-8}$	$(5.97±1.58)·10^{-8}$	$(7.03±1.79)·10^{-8}$
HT (CTUh)	$(5.90±1.25)·10^{-9}$	$(7.35±1.36)·10^{-9}$	$(8.57±1.55)·10^{-9}$
AC (Mol H+ eq)	$(7.83±2.18)·10^{-3}$	$(8.92±2.37)·10^{-3}$	$(1.05±2.7)·10^{-2}$
FE (kg P eq)	$(1.51±0.87)·10^{-4}$	$(2.28±1.82)·10^{-4}$	$(3.09±2.07)·10^{-4}$
TE (Mol N eq)	$(3.16±0.95)·10^{-2}$	$(3.40±0.97)·10^{-2}$	$(4.03±1.11)·10^{-2}$
AD (MJ)	3.32±0.56	6.40±1.15	7.48±1.30

The study of Vercalsteren and Boonen (2015), which assessed four similar impact categories, shows that about 0.80 kg CO_2 eq (CC), $11.5 \cdot 10^{-3}$ mol H+ eq (AC), $0.3 \cdot 10^{-3}$ kg P eq (FE) and $4.8 \cdot 10^{-2}$ mol N eq (TE) per kg of glucose from a mix of maize, wheat and potato feedstocks. These results are in the range of the outcomes of the present study (Table 6.6). The authors of this study also indicated that cultivation is one of the phases with the greatest environmental impact on the glucose production process. An LCA study on maize-based glucose in Europe (Tsiropoulos et al., 2013), resulted in about 0.7-1.1 kg CO_2 eq and 6.8-9.3 MJ per kg of glucose, no showing considerable differences in results with this present study. The comparison with other studies will be better evaluated in the following Chapter 7, which studied the fermentable sugars of maize grain, stover and sugar beet pulp.

The comparative environmental profile (Figure 6.2) shows that Greece is the country that presents the worst results in terms of CC, HT, FE, and AD, while Italy performs worst in the indicators PM, AC and TE. Low yields, high land requirements, use of fertilisers and the use of fossil fuels in agricultural operations for wheat cultivation make Greece the country with the worst environmental profile among the rest of the European countries. In 2016, for instance, the average yield in Greece was 2.7 t per ha, meanwhile in Germany, one of the main wheat producers in Europe, the yield accounted for 7.6 t per ha (FAOSTAT, 2019). In all European countries, the agricultural activities that have the greatest impacts on the environment are field emissions due to fertilisation, fertiliser production and agricultural operations. The use of fertilisers leads to the release of substances that impact the environment, such as N_2O and NH_3. Moreover, agricultural activities require considerable use of fossil fuels for use in vehicles and machineries.

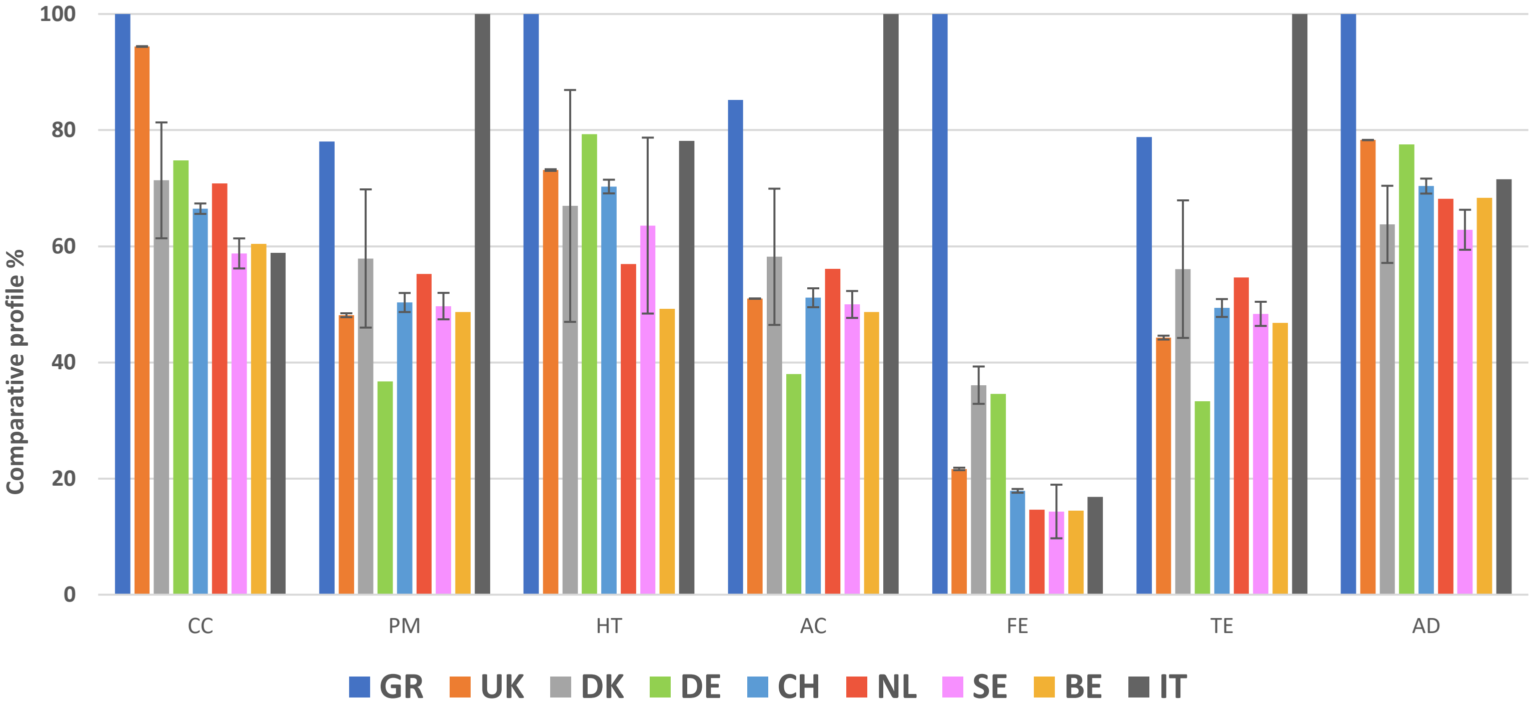

Figure 6.2. Environmental profile of wheat production in different European countries. Acronym: CC-Climate Change, PM-Particulate Matter, HT- Human Toxicity, AC – Acidification, FE – Freshwater Eutrophication, TE – Terrestrial Eutrophication, AD – Abiotic Depletion. GR – Greece, UK – United Kingdom, DK – Denmark, DE – Germany, CH – Switzerland, NL – The Netherlands, SE – Sweden, BE – Belgium, IT – Italy. The average value and error bars were assessed for the countries with more than one case study.

When the processing phase of wheat to produce glucose is included in the system boundary, the results obtained show a slight variation (Figure 6.3) of the comparative environmental profile of the different European countries. In general, it can be observed that agriculture remains the main contributor to almost all environmental impact categories, except for the AD impact category, where wheat processing activities play an important role. The following subsections describe the results of each impact category in more detail.

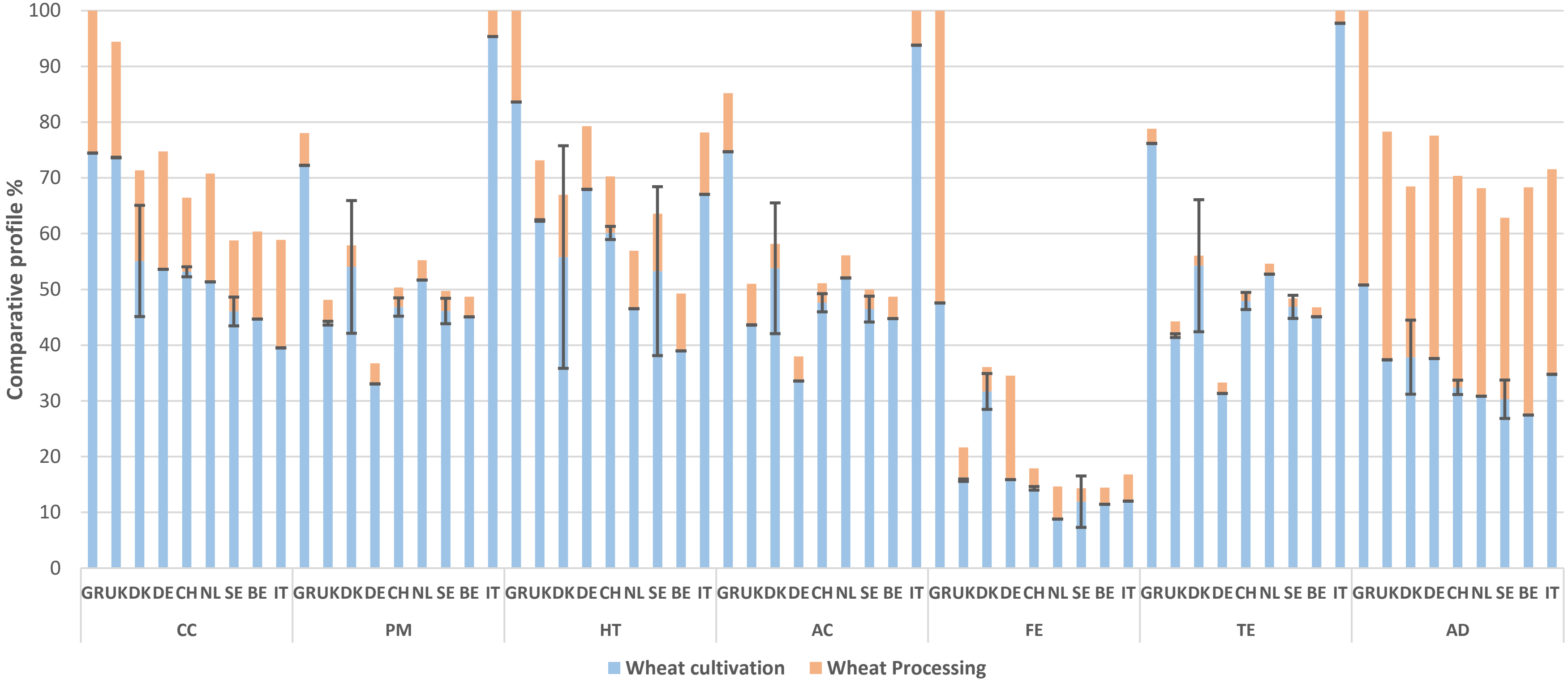

Figure 6.3. Environmental profile of glucose production from wheat in different European countries using mass allocation. Acronym: CC-Climate Change, PM-Partic
Human Toxicity, AC – Acidification, FE – Freshwater Eutrophication, TE – Terrestrial Eutrophication, AD – Abiotic Depletion. GR – Greece, UK – United Kingdom
DE – Germany, CH – Switzerland, NL – The Netherlands, SE – Sweden, BE – Belgium, IT – Italy. The average value and error bars were assessed for the countries w
case study.

6.3.1.1 Climate change (CC)

In this study, carbon dioxide (CO_2) and nitrous oxide (N_2O) are the major contributors to CC, due to field emissions related to fertiliser application and production, as well as the use of non-renewable fuels for agricultural management (i.e., diesel). Therefore, field emissions and fertilisation in agricultural activities are key factors for climate change. Other contributing factors, albeit to a lesser extent, are the use of electricity and heating in the processing phase. As observed in Figure 6.3, Greece is the major contributor to CC.

6.3.1.2 Particulate matter (PM)

The direct application of fertilisers and field operations entails the formation of ammonia (NH_3), particulates < 2.5 µm and sulphur dioxide (SO_2), responsible for PM formation, which may cause negative impacts on human health and the ecosystem (Fantke et al., 2016). Italy shows the worst results for PM, due to high NH_3 emissions derived from agricultural processes. For the production of 1 kg of glucose in the Italian case study, for example, up to 80% of the impacts are due to NH_3 emissions.

6.3.1.3 Human toxicity (HT)

In relation to this impact category, chromium released into the air, water and soil are the main substances contributing to TH, mainly due to the background processes in the production of nitrogen fertilisers and, to a lesser extent, to the use of agricultural machinery. Some heavy metals, such as Cr, are toxic substances that endanger human health and the ecosystem. Greece has the worst-case scenario, whose impact results are more than double, compared to Belgium.

6.3.1.4 Acidification (AC)

Agricultural processes are by far the main contributors to AC in the production of glucose. NH_3, SO_2 and nitrous oxide (N_2O) emissions are the most influential outflows into terrestrial and freshwater AC mainly due to field emissions from fertilisation. Italy shows the highest impacts for AC, since it is the country that most releases NH_3 into the atmosphere (see Table 6.1). Acidification is a major problem in agriculture worldwide, as it changes the pH of agricultural land and can lead to unproductive land, such as desertification (Peters et al., 2011).

6.3.1.5 Freshwater eutrophication (FE)

In general, agricultural activities contribute most to this impact category in most case studies, mainly due to the release of phosphorus into water bodies by mineral fertilisation in agriculture. However, depending on the type of electricity used in each country, the wet milling process of wheat may play a key role in this impact category. The wheat processing phase is responsible for a slightly higher impact than the agricultural stage for the FE impact category in Germany and Greece, due to their electricity mix profile. It is important to bear in mind that electricity-related emissions vary according to each country's electricity profile. The impact on FE due to the medium voltage electricity mix in Germany is up to 6 times greater than in Italy, for example. This is due to background processes, such as the intensive use of lignite in Germany, which releases a large amount of phosphates in mining operations (Atilgan and Azapagic, 2016).

6.3.1.6 Terrestrial eutrophication (TE)

Agricultural activities, mainly due to field emissions, are almost entirely responsible for TE in the glucose production process. Like the acidification impact category, NH_3 is also a great contributor to TE. In Italy, which represents the worst-case scenario, NH_3 and nitrogen oxides (NO_x) are responsible for about 90% and 10% of the impacts, respectively.

6.3.1.7 Abiotic depletion (AD)

In addition to the cultivation of wheat, the wheat processing phase also contributes considerably to AD. This is due to the use of natural gas for heating and crude oil for electricity generation. As far as agriculture is concerned, nitrogen fertilisation and the use of fossil fuels in agricultural machinery are the main critical points in AD. Once again, Greece has the greatest impact, up to twice as much as Sweden. As mentioned earlier, the type of fossil fuels, whether crude oil or natural gas, for example, which will contribute mostly to AD, will depend on the electricity mix of each country.

6.3.1.8 General findings

As it can be observed from the environmental profile of glucose production, fertilisation is an important contributor and nitrogenous fertiliser plays a key role in wheat cultivation as one of its main sources of nutrients. In this sense, agricultural management practices should focus on optimizing rather than reducing nitrogen inputs (Berthoud et al., 2012). By applying efficient nutrient management, the integration of crop systems and the use of advanced crops, nitrogen losses and GHG emissions may be reduced (Chen et al., 2014). Because each climate, soil and geography require different fertiliser dosage load, studies should focus also on localised agricultural systems. Another measure is to find more efficient ways in agricultural operations to reduce the use of fossil fuels and use cleaner energy systems (Cambria et al., 2016).

Almost all LCA studies of wheat crops indicate the production of mineral fertilisers and field emissions as main environmental burdens (Berthoud et al., 2012; Cambria et al., 2016; De Matos et al., 2015; Guo, 2012; Holka et al., 2016; Noya et al., 2015). Therefore, the production and application of fertilisers are determining elements in the environmental sustainability of this cultivation system. In addition, energy demand, climate change, eutrophication and acidification were the main environmental impacts considered in the studies evaluated. It is important to consider that this study only discusses the use of chemical fertilisation in all agricultural systems. The use of organic fertilisation, such as manure or slurry, could reduce the overall environmental impacts, since the process of fertilisers production has a large impact on the agricultural systems analysed (Fallahpour et al., 2012). In addition, the efficient use of electricity and heating in the wheat processing phase could reduce environmental impacts, as these processes represent a significant contribution to CC, FE and AD.

Although the technological pathway for converting starch crops (i.e., wheat) into glucose is well developed, there is growing concern about the use of first-generation feedstocks for bioproducts, due to competition with food/feed markets and land use. Therefore, second-generation feedstocks from agricultural residues (i.e., wheat straw) and forest wood are an abundant potential substitute that should also be considered in future research as biomass that does not jeopardize food supply. However, the use of these residues as biomass for the production of bio-products should be applied with care to avoid carbon loss and soil erosion.

6.3.2 Results for Italy and Germany

One of the targets of this study was to assess the effects on the environmental outcomes using two allocation methods. Figures 6.4a and 6.4b present the differences in shares obtained from wheat agricultural activities and glucose production through mass and economic allocation. As an illustrative example, Germany and Italy were chosen since these countries show relevant differences in the results of the impact categories among other countries. Absolute values are also presented in Table 6.7. As observed, the outcomes per functional unit of economic allocation are higher than those of mass allocation for glucose production. It is also clear that agricultural process has great contribution in the overall environmental impacts. However, for the impact category FE, the cultivation phase has less influence on the environmental performance than the grain processing phase in Germany than in Italy. This is due to the type of electricity mix in each country. Germany is known for its intensive electricity production from coal and lignite (Agora Energiewende and Sandbag, 2018).

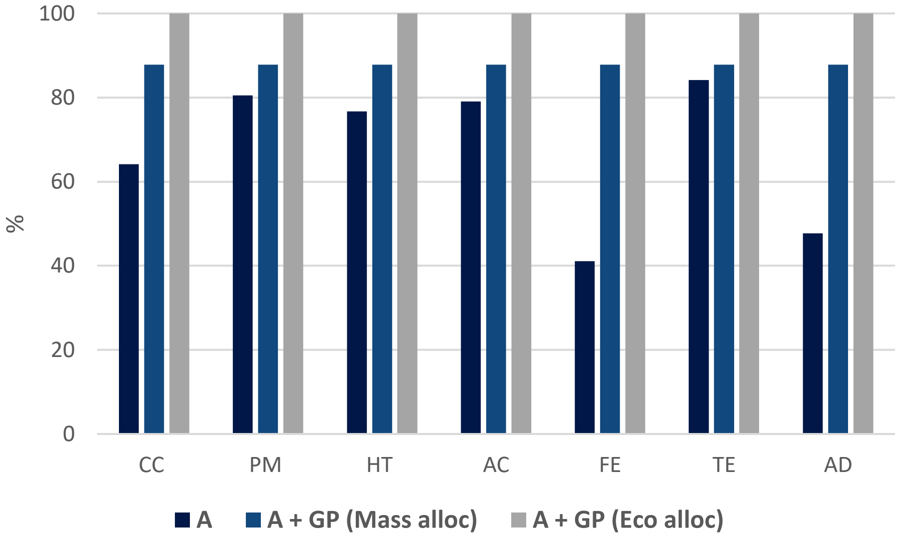

Figure 6.4a. Environmental impacts from agriculture production (A) for 1 kg of wheat grain and the different allocation methods used for the production of 1 kg glucose: Agriculture (A) + Grain Processing (GP) (A + GP) for mass allocation (Mass alloc) and economic allocation (Eco Alloc) for the country Germany.

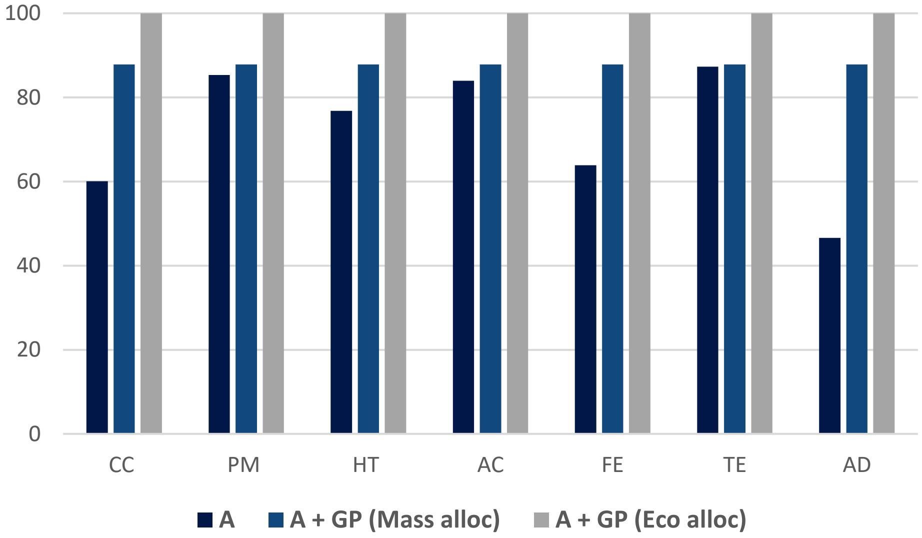

Figure 6.4b. Environmental impacts from agriculture production (A) for 1 kg of wheat grain and the different allocation methods used for the production of 1 kg glucose: Agriculture (A) + Grain Processing (GP) (A + GP) for mass allocation (Mass alloc) and economic allocation (Eco alloc) for the country Italy.

As noted, mass and economic allocations have a slight influence on the environmental results of glucose production. As depicted in Table 6.4, mass quantities and prices vary among the by-products. Wheat gluten meal, for example, is produced in low quantities, but has a high market price, increasing its allocation factor when making an economic allocation.

Economic allocation is one of the most common technique used to account for valuable by-products produced from unit processes (Mackenzie et al., 2017). However, it is important to consider that prices may vary due to changes in consumer demand, seasons, price dependence, etc (Moncada et al., 2018). In addition, changes in the market may affect the sugar prices in the future. Sugar from sugar beet, for instance, is already facing a challenge, due to the cheaper price of sugars from sugar cane, increased health awareness and growing preference for high fructose corn syrups (HFCS) (Tomaszewska et al., 2018).

Table 6.7. LCI of selected impact categories of agriculture production (A) for 1 kg of wheat grain and the different allocation methods used for the production of 1 kg glucose: Agriculture (A) + Grain Processing (GP) (A + GP) for mass allocation (Mass alloc) and economic allocation (Eco alloc) for Germany and Italy.

	Germany			**Italy**		
	A	**A + GP (Mass alloc)**	**A + GP (Eco Alloc)**	**A**	**A + GP (Mass alloc)**	**A + GP (Eco Alloc)**
CC (kg CO^2 eq)	0.67	0.91	1.04	0.49	0.72	0.82
PM (Disease incidence)	$3.43 \cdot 10^{-8}$	$3.74 \cdot 10^{-8}$	$4.26 \cdot 10^{-8}$	$9.9 \cdot 10^{-8}$	$1.02 \cdot 10^{-7}$	$1.16 \cdot 10^{-7}$
HT (CTUh)	$6.82 \cdot 10^{-9}$	$7.82 \cdot 10^{-9}$	$8.90\ 10^{-9}$	$6.73 \cdot 10^{-9}$	$7.71 \cdot 10^{-9}$	$8.77 \cdot 10^{-9}$
AC (Mol H+ eq)	$5.08 \cdot 10^{-3}$	$5.64 \cdot 10^{-3}$	$6.43 \cdot 10^{-3}$	$1.42 \cdot 10^{-2}$	$1.49 \cdot 10^{-2}$	$1.69 \cdot 10^{-2}$
FE (kg P eq)	$1.34 \cdot 10^{-4}$	$2.85 \cdot 10^{-4}$	$3.25 \cdot 10^{-4}$	$1.01 \cdot 10^{-4}$	$1.39 \cdot 10^{-4}$	$1.58 \cdot 10^{-4}$
TE (Mol N eq)	$1.91 \cdot 10^{-2}$	$1.99 \cdot 10^{-2}$	$2.27 \cdot 10^{-2}$	$5.95 \cdot 10^{-2}$	$5.99 \cdot 10^{-2}$	$6.82 \cdot 10^{-2}$
AD (MJ)	3.67	6.76	7.70	3.39	6.40	7.28

6.4 CONCLUSIONS

Interest in using sugars from renewable biomass for biobased products has increased. One pathway towards the biorefinery route is the production of glucose from starch crops (e.g., wheat). Therefore, LCA studies on the environmental sustainability of C6 sugars should be encouraged. Moreover, sugars for fermentation (e.g., glucose) are viewed as promising platforms for the production of more sustainable materials.

The results obtained from the LCA assessment provide relevant insights into the glucose production chain. The outcomes showed that the agricultural phase presents by far the uppermost environmental burden on glucose production. This is due to the direct application of synthetic fertiliser and the use of non-renewable fuels in field operations. Heating and electricity use in the grain processing phase also have a considerable influence on the environmental impact categories of CC, FE and AD. The result values of the environmental impacts vary from country to country, mainly due to nitrogen fertiliser load, land use field operations and electricity mix profile. The outcomes obtained from allocation showed that economic allocation has a greater impact than mass allocation for the main product, glucose. It is important to keep in mind that prices may fluctuate and be affected by changes in demand, location and resource dependency.

This chapter showed that there is much room for improvement. One of the measures is to find more efficient ways of nitrogen fertilisation and field operations. In addition, as wheat is an edible crop and to avoid its competition with food, future research should be carried out to consider residues from wheat cultivation, namely wheat straw, as a promising lignocellulosic crop for glucose production. However, since wheat straw is an important source of nutrients to soil, the optimal removal rate of these residues should be controlled to avoid undesirable side-effects, such as unnecessary additional fertilisation load and reduced soil quality.

REFERENCES

Achten, W.M.J., Van Acker, K., 2016. EU-Average Impacts of Wheat Production: A Meta-Analysis of Life Cycle Assessments. J. Ind. Ecol. 20, 132–144. https://doi.org/10.1111/jiec.12278

Agora Energiewende and Sandbag, 2018. The European Power Sector in 2017. State of Affairs and Review of Current Developments. https://doi.org/128/02-A-2018/EN

Arifeen, N., Kookos, I.K., Wang, R., Koutinas, A.A., Webb, C., 2009. Development of novel wheat biorefining: Effect of gluten extraction from wheat on bioethanol production. Biochem. Eng. J. 43, 113–121. https://doi.org/10.1016/ j.bej.2008.09.005

Atilgan, B., Azapagic, A., 2016. Assessing the environmental sustainability of electricity generation in Turkey on a life cycle basis. Energies 9. https://doi.org/10.3390/en9010031

Bernesson, S., Nilsson, D., Hansson, P.A., 2006. A limited LCA comparing large- and small-scale production of ethanol for heavy engines under Swedish conditions. Biomass and Bioenergy 30, 46–57. https://doi.org/10.1016/ j.biombioe.2005.10.002

Berthoud, A., Buet, A., Genter, T., Marquis, S., 2012. Comparison of the environmental impact of three forms of nitrogen fertilizer, Fertilizars Europe. Sustainable Agriculture in Europe.

Cambria, D., Vazquez-Rowe, I., Gonzalez-Garcia, S., Teresa Moreira, M., Feijoo, G., Pierangeli, D., 2016. Comparative life cycle assessment study of three winter wheat production systems in the European Union. Environ. Eng. Manag. J. 15, 1755–1766.

Curtis, B.., Rajaram, S., Macpherson, H.., 2002. BREAD WHEAT. Improvement and Production, in: Plant Production and Protection Series. Rome, pp. 1–18.

De Matos, C.T., Garcia, J.C., Aurambout, J.-P., Kavalov, B., Manfredi, S., 2015. Environmental Sustainability Assessment of Bioeconomy Products and Processes – Progress Report 1.

https://doi.org/10.2788/708144

Deloitte, 2014. Opportunities for the fermentation-based chemical industry. An analysis of the market potential and competitiveness of North-West Europe 1–50. https://doi.org/10.2767/39856

Du, C., Lin, S.K.C., Koutinas, A., Wang, R., Dorado, P., Webb, C., 2008. A wheat biorefining strategy based on solid-state fermentation for fermentative production of succinic acid. Bioresour. Technol. 99, 8310–8315. https://doi.org/10.1016/j.biortech.2008.03.019

Durlinger, B., Koukouna, E., Broekema, R., Van Paassen, M., Scholten, J., 2017. Agri-footprint 4.0. Gouda.

E4tech, Re-Cord, Wur, 2015. From the Sugar Platform to biofuels and biochemicals, Final report for the European Commission Directorate-General Energy. https://doi.org/contract No. ENER/C2/423-2012/SI2.673791

EFISC, 2013. European Guide to good practice for the industrial manufacture of safe feed materials. Sector reference document on the manufacturing of safe feed materials from starch processing.

Elliott, D.C., Orth, R.J., Gao, J., Werpy, T.A., Eakin, D.E., Schmidt, A.J., Neuenschwander, G.G., Flagg, A.J., Murry, J., Lahman, L., Lin, C.J., Mennel, D.L., Landucci, R., 2002. Biorefinery Concept Development Based on Wheat Flour Milling. Fuel Chem. Div. Prepr. 47, 361–362.

European Commission, 2017. PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3.

Fallahpour, F., Aminghafouri, A., Ghalegolab Behbahani, A., Bannayan, M., 2012. The environmental impact assessment of wheat and barley production by using life cycle assessment (LCA) methodology. Environ. Dev. Sustain. 14, 979–992. https://doi.org/10.1007/s10668-012-9367-3

Fantke, P., Evans, J., Hodas, N., Joshua, A., Jantunen, M., Jolliet, O., Mckone, T.E., 2016. Health impacts of fine particulate matter, in: Global Guidance for Life Cycle Impact Assessment Indicators. p. 166.

FAOSTAT, 2019. Crop statistics [WWW Document]. URL http://www.fao.org/ faostat/en/#data (accessed 1.10.19).

Fazio, S., Castellani, V., Sala, S., Schau, E., Secchi, M., Zampori, L., Diaconu, E., 2018. Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment method New models and differences with ILCD. https://doi.org/10.2760/671368

Gnansounou, E., Dauriat, A., Panichelli, L., Villegas, J., 2008. Energy and greenhouse gas balances of biofuels: Biases induced by LCA modelling choices. J. Sci. Ind. Res. (India). 67, 885–897. https://doi.org/NA

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.., De Bruijn, J.A., Van Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards.

Guo, M., 2012. LCA of Wheat Agro-Eco-System, in: Life Cycle Assessment (LCA) of Light-Weight Eco-Composites. https://doi.org/10.1007/978-3-642-35037-5

Holka, M., JAnkowiak, J., Bieńkowski, J.F., Dabrowicz, R., 2016. Life Cycle Assessment (LCA) of Winter Wheat in an Intensive Crop Production System in Wielkopolska Region (Poland). Appl. Ecol. Environ. Res. 14, 535–545.

IPCC, 2013. Anthropogenic and natural radiative forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/ CBO9781107415324.018

ISO14044, 2006. ISO 14044, Environmental management — Life cycle assessment — Requirements and guidelines 2006, 54.

Mackenzie, S.G., Leinonen, I., Kyriazakis, I., 2017. The need for co-product allocation in the life cycle assessment of agricultural systems—is "biophysical" allocation progress? Int. J. Life Cycle Assess. 22, 128–137. https://doi.org/10.1007/ s11367-016-1161-2

Moncada, J., Vural Gursel, I., Huijgen, W.J.J., Dijkstra, J.W., Ramírez, A., 2018. Techno-economic and ex-ante environmental assessment of C6 sugars production from spruce and corn. Comparison of organosolv and wet milling technologies. J. Clean. Prod. 170, 610–624. https://doi.org/10.1016/j.jclepro.2017.09.195

Muñoz, I., Flury, K., Jungbluth, N., Rigarlsford, G., I Canals, L.M., King, H., 2014. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int. J. Life Cycle Assess. 19, 109–119. https://doi.org/10.1007/s11367-013-0613-1

Mustafa, M., Misailidis, N., Mateos-Salvador, F., Du, C., Sadhukhan, J., Campbell, G., 2007. Feasibility of co-producing arabinoxylans and ethanol in a wheat biorefinery. Manchester.

Noya, I., González-García, S., Bacenetti, J., Arroja, L., Moreira, M.T., 2015. Comparative life cycle assessment of three representative feed cereals production in the Po Valley (Italy). J. Clean. Prod. 99, 250–265. https://doi.org/10.1016/ j.jclepro.2015.03.001

OECD, 2003. Consensus Document on Compositional Considerations for New Varieties of Bread Wheat OF BREAD WHEAT (Triticum aestivum): Key Food and Feed Nutrients, Anti-Nutrients and Toxicants, in: Series on the Safety of Novel Foods and Feeds.

Papageorgiou, M., Skendi, A., 2018a. Introduction to cereal processing and by-products, in: Sustainable Recovery and Reutilization of Cereal Processing By-Products. pp. 1–25. https://doi.org/10.1016/B978-0-08-102162-0.00001-0.

Papageorgiou, M., Skendi, A., 2018b. Introduction to cereal processing and by-products. Sustain. Recover. Reutil. Cereal Process. By-

Products 1–25. https://doi.org/10.1016/B978-0-08-102162-0.00001-0

Peters, G.M., Wiedemann, S., Rowley, H. V, Tucker, R., Feitz, A.J., Schulz, M., 2011. Assessing agricultural soil acidification and nutrient management in life cycle assessment. Int J Life Cycle Assess 16, 431–441. https://doi.org/10.1007/ s11367-011-0279-5

Porras, M.A., Ramos, F.D., Diaz, M.S., Cubitto, M.A., Villar, M.A., 2018. Modeling the bioconversion of starch to P(HB-co-HV) optimized by experimental design using Bacillus megaterium BBST4 strain. Environ. Technol. (United Kingdom) 3330, 1–18. https://doi.org/10.1080/09593330.2017.1418436

Posch, M., Seppälä, J., Hettelingh, J.P., Johansson, M., Margni, M., Jolliet, O., 2008. The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. Int. J. Life Cycle Assess. 13, 477–486. https://doi.org/10.1007/s11367-008-0025-9

Prasad, A., Sotenko, M., Blenkinsopp, T., Coles, S.R., 2016. Life cycle assessment of lignocellulosic biomass pretreatment methods in biofuel production. Int. J. Life Cycle Assess. 21, 44–50. https://doi.org/10.1007/s11367-015-0985-5

Renouf, M.A., Wegener, M.K., Nielsen, L.K., 2008. An environmental life cycle assessment comparing Australian sugarcane with US corn and UK sugar beet as producers of sugars for fermentation. Biomass and Bioenergy 32, 1144–1155. https://doi.org/10.1016/ j.biombioe.2008.02.012

Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A.J., Jolliet, O., Juraske, R., Koehler, A., Larsen, H.F., MacLeod, M., Margni, M., Mackone, T.E., Payet, J., Schuhmacher, M., Van De Meent, D., Hauschild, M.Z., 2008. USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int. J. Life Cycle Assess. 13, 532–546.

https://doi.org/10.1007/s11367-008-0038-4

Sadaka, S., Atungulu, G., Osborn, S., 2014. On - Farm Wheat Drying and Storage, in: Arkansas Wheat Production Handbook.

Seppälä, J., Posch, M., Johansson, M., Hettelingh, J.P., 2006. Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. Int. J. Life Cycle Assess. 11, 403–416. https://doi.org/10.1065/lca2005.06.215

Struijs, J., Beusen, A., van Jaarsveld, H., Huijbregts, M.A.., 2013. Eutrophication, in: ReCiPe 2008. A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and Endpoint Level. pp. 58–66. https://doi.org/10.2307/40184439

Tomaszewska, J., Bieliński, D., Binczarski, M., Berlowska, J., Dziugan, P., Piotrowski, J., Stanishevsky, A., Witońska, I.A., 2018. Products of sugar beet processing as raw materials for chemicals and biodegradable polymers. RSC Adv. 8, 3161–3177. https://doi.org/10.1039/C7RA12782K

Tsiropoulos, I., Cok, B., Patel, M.K., 2013. Energy and greenhouse gas assessment of European glucose production from corn-a multiple allocation approach for a key ingredient of the bio-based economy. J. Clean. Prod. 43, 182–190. https://doi.org/10.1016/j.jclepro.2012.12.035

Urban, R.A., Bakshi, B.R., 2009. 1,3-Propanediol from Fossils versus Biomass : A Life Cycle Evaluation of Emissions and Ecological Resources. Ind. Eng. Chem 48, 8068–8082.

Van Oers, L., De Koning, A., Guinée, J.B., Huppes, G., 2002. Abiotic resource depletion in LCA. Improving characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA handbook., Aviation Week and Space Technology (New York). Delft, The Netherlands.

van Zeist, W.., Marinussen, M., Broekema, R., Groen, E., Kool, A., Dolman, M., Blonk, H., 2012. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization. Wet Milling Industry.

Vaskan, P., Ruiz Pachón, E., Gnansounou, E., 2017. Life Cycle Assessment of Sugar Crops and Starch-Based Integrated Biorefineries, in: Life-Cycle Assessment of Biorefineries. pp. 97–146.

Vercalsteren, A., Boonen, K., 2015. Life Cycle Assessment study of starch products for the European starch industry association (AAF): sector study.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Wood, D., Rourke, T.O., 1995. Glucose syrups in the fermentation industries, in: Handbook of Starch Hydrolysis Products and Their Derivatives. pp. 230–244. https://doi.org/10.1007/978-1-4615-2159-4_8

Wuana, R.A., Okieimen, F.E., 2014. Heavy metals in contaminated soils: A review of sources, chemistry, risks, and best available strategies for remediation. Int. Sch. Res. Not. ISRN Ecol. 2011, 1–20. https://doi.org/10.1201/b16566

CHAPTER 7: ENVIRONMENTAL ASSESSMENT OF FERMENTABLE SUGARS

SUMMARY

This chapter investigates the environmental impacts of feedstock production and upstream processing within the framework of the STAR-ProBio project (grant agreement No 727740). The feedstocks considered are fermentable sugars from sugar beet pulp, maize grain and maize stover. Fermentable sugars are essential in the biotechnological production of a variety of bioproducts, such as polylactic acid (PLA) and polybutylene succinate (PBS). The maize grain, which is a starch-rich crop, must go through milling and enzymatic hydrolysis steps to produce glucose. On the other hand, sugar beet pulp and maize stover, which are rich in ligno-hemicellulose, can be transformed into different types of sugars by first carrying out a pre-treatment process and then, enzymatic hydrolysis.

This study applied LCA to assess the related environmental impacts of a selection of feedstocks: maize grain, stover and sugar beet pulp as a source of fermentable sugars. As these processes generate by-products of economic value, an economic allocation was made to distribute the environmental impacts. Twenty fermentable sugars scenarios in six different countries were carried out. In addition, a sensitivity analysis was performed comparing the mass and economic allocation methods.

With regard only to agriculture, the results show that field emissions, chemical fertilisation, field operations and transport are critical factors for environmental impacts. For the production of fermentable sugars, the contribution analysis indicates that agricultural activities have a key responsibility for the overall environmental burden of glucose from maize grain. On the other hand, in the production of fermentable sugars

from stover and beet pulp, agriculture has a lower contribution when economic allocation is applied, especially for beet pulp, due to its low market value. In this upstream LCA, the outcomes showed that the use of fermentable sugars from beet pulp has less impact than maize grain and stover, consequently reducing the global environmental impacts of the STAR-ProBio case studies. Sensitivity analysis comparing economic and mass allocation of fermentable sugars indicates that the figures for maize grain do not vary as much compared to stover or beet pulp.

7.1 INTRODUCTION

In Europe, total annual biomass production in land is about 1500 Mt (dry matter), of which 65% comes from agriculture and 35% from forestry. These numbers correspond not only to the biomass that is harvested with economic value, but also to that biomass that is essential for sustaining the ecosystem, such as agricultural residues that remain in the field. In Europe, most of the biomass corresponds to sugar and starch (carbohydrates) and lignocellulosic raw materials, with Germany and France being the largest producers of agricultural biomass in Europe. Regarding biomass use in Europe, it is estimated that they are used in the food and feed industry (+60%), followed by the sectors of biofuels (about 19%) and bio-based products (about 19%). However, it should be noted that there is great uncertainty related to the biomass used for the production of biofuels and bio-based products (Camia et al., 2018).

The sustainable bioeconomy aims at the adequate use of biomass for bioproducts and also for soil conditioning, without compromising food security and environmental damage related to the production and harvest of biomass. In this context, the use of renewable biomass in industrial fermentation processes, such as carbohydrate-rich feedstocks, has raised attention. As aforementioned in Chapter 1, they may comprise first-generation (1G) feedstocks that compete directly with food/feed markets and second generation (2G) feedstocks, which are residues from agricultural or industrial processing activities.

As mentioned in Chapter 2 and 6, there are many LCA studies related to the production of food, biofuels and, to a lesser extent, bio-based products. In the past decade, there has been a growing interest in researching upstream processes due to their important environmental contribution. Some LCA studies emphasize fermentable sugar alternatives because, when deciding which one has the best environmental data, it is feasible to improve the environmental profile of a bio-based product. Table 7.1 depicts the studies that performed LCA of fermentable sugars. As noted, the studies used different raw materials and impact categories and they all used a mass-based functional unit.

Table 7.1 LCA of fermentable sugars. Acronyms: CC - Climate Change, AC – Acidification, EP – Eutrophication, WD – Water Depletion, OD – Ozone Depletion, ET – Ecotoxicity, PM – Particulate Matter, IR – Ionizing Radiation; POF – Photochemical Oxidant Formation; HT- Human Toxicity, CED – Cumulative Energy Demand; ALOP – Agricultural Land Occupation, NREU - Non-Renewable Energy Use, and FD – Fossil Depletion. Source: updated from (Camara-Salim et al., 2020).

Feedstocks	**Functional unit**	**Impact categories**	**Source**
Sugarcane Sugar beet Maize	1 t of saccharide	CC, AC, EP, WD, and FD	(Renouf et al., 2008)
Hardwood mill residuals Low value hardwood	1 kg fermentable sugar	CC, WD and FD	(Thomas et al., 2012)
Poplar	1 kg of sugars	CC and FD	(Tao et al., 2014)
Maize stover Switchgrass Poplar Miscanthus	1 kg fermentable sugar	CC and FD	(Adom et al., 2014)
Wheat, maize and potato	1 kg of starch and 1 kg of glucose	CC, AC, WD, OD, PM, IR, POF	(Vercalsteren and Boonen, 2015)
Maize stover	1 kg of fermentable sugars	CC, AC, EP, and WD	(Prasad et al., 2016)
Softwood harvest residues	1 kg dry mass sugar	CC, AC, EP, OD, ET, PM, POF, HT	(Nwaneshiudu et al., 2016)
Softwood harvest residues	1 kg of glucose	CED	(Morales et al., 2016)
Sugar beet	1 kg of hexose equivalent	CC	(Vargas-Ramirez et al., 2017)
Spruce Maize	1 kg C6 sugars	CC, WD, HT, ALOP, NREU	(Moncada et al., 2018)
Energy cane	1 t of fermentable	CC, EP and FD	(Ortiz-reyes and

Feedstocks	Functional unit	Impact categories	Source
Sweet sorghum Sugarcane Maize Sugar beet	carbohydrates		Anex, 2019)
Maize Starch Woody Biomass Residues	1 kg of glucose	CC, AC, OD, PM, HT, and FD	(Blanco et al., 2020)

The aim of this chapter is to carry out an LCA of the upstream processing of bio-based products, within the framework of STAR-ProBio project. Namely, this work assesses the environmental profile of fermentable sugars from maize grain, maize stover and sugar beet pulp. This feedstock selection was made based on the carbohydrate content and their availability in the world, mainly in Europe. Chapter 5 evaluated the environmental profile of maize stover and beet pulp, without considering the stage of processing the raw material into sugars. In addition, Chapter 6 performed LCA of fermentable sugars based on wheat. This chapter goes further by adding another 1G (maize grain) and two 2G raw materials (beet pulp and maize stover).

7.2 OVERVIEW OF STAR-ProBio PROJECT

STAR-ProBio is a 3-year Horizon 2020 project, funded by the European Commission, which main objective "*is to cover gaps in the existing framework for sustainability assessment of bio-based products and improve consumer acceptance for bio-based products by identifying the critical sustainability issues in their value chains.*" (see http://www.star-probio.eu/). 15 partners from all over Europe were involved, including the University of Santiago de Compostela (USC), whose role was a piece of the puzzle to fulfil the project's objectives.

USC was the leader of one of the work packages responsible for the upstream environmental assessment of selected bio-based case studies. These case studies were polylactic acid (PLA) and polybutylene succinate (PBS) and they are the products from the downstream processing phase, whose LCA is analysed by another STAR-ProBio partner. The upstream processes analysed are the production of fermentable sugars from maize grain, stover and sugar beet pulp. These fermentable sugars are the input stream to produce PLA and PBS. In Annex A (Figure A1), a generic system description is depicted for the production of fermentable sugars from the three feedstocks.

In the processing routes of PBS and PLA production, three intermediates biochemicals are required: lactic acid (LA), 1.4 butanediol (1.4 BDO) and succinic acid (SA). About 1.5 kg, 2.1 kg and 5.1 kg of maize grain, stover and beet pulp are used to produce 1 kg of fermentable sugars. It is necessary approximately 1.1 kg, 2.8 kg and 1.3 kg of fermentable sugars to produce 1 kg of LA, 1.4 BDO and SA, respectively. Moreover, it is required the amount of 1.3 kg of LA to produce 1 kg of PLA. To produce 1 kg of PBS, it is needed about 0.7 kg of SA and 0.7 kg of 1.4 BDO (see Annex A - Figure A.2).

7.3 MATERIALS AND METHODS

7.3.1 Goal and scope definition

The objective of this chapter is to model, by means of LCA, the production of fermentable sugars as valuable renewable raw materials to be used in the biotechnological production of bio-based products. Maize grain, maize stover and sugar beet pulp are the raw materials chosen to be processed into fermentable sugars and, eventually, into PBS and PLA. They were selected for their significant carbohydrate content and their availability in the world, especially Europe.

Fermentable sugars from maize grain are constituted of glucose syrup, with 95 dextrose equivalent (DE), which is common in fermentation processes (Wood and Rourke, 1995). Maize stover and sugar beet pulp, which are raw materials rich in lignocellulose, provide a combination of fermentable sugars after a hydrolysis process. In the case of maize stover, it represents glucose (59%), xylose (33%) and other sugars (8%) while for sugar beet pulp: arabinose (41%), glucose (37%), galactose (10%), xylose (9%) and mannose (3%).

The functional unit (FU) chosen in this study is 1 kg of fermentable sugars from maize grain, maize stover and sugar beet pulp. An additional functional unit was selected to investigate only the environmental loads of agricultural activities: 1 kg of maize grain, stover and sugar beet production in 6 different agricultural systems located in Italy, Belgium and the United States (for the maize case studies) and Germany, France and the United Kingdom (for the sugar beet case studies).

7.3.2 System boundaries

The processes involved in the production of fermentable sugars from maize grain and stover are depicted in Figure 7.1. Firstly, the maize grain is cultivated. Agricultural activities are divided into field preparation (S1), where tillage process starts, usually with the help of machineries, for instance ploughs and harrows, to prepare the soil for sowing. In the following step, in crop growth (S2), pesticides and fertilisers are added. In some cases, irrigation occurs depending on the climate conditions of the place (Kathage et al., 2016; Rüdelsheim and Smets, 2011). Finally, the biomass is harvested and transported to the pre-processing facility (S3). The harvesting process uses a combine harvester, which is able to separate the maize kernel from the stover.

Maize stover is composed of leaves, stems and cobs and its yield varies according to geoclimatic conditions and grain genotypes. However, in average, about 1 kg of stover is produced for each kg of grain (Prasad et al., 2016). As stated in Chapter 5, it is important to emphasize that stover is a soil amendment and that its removal can compromise the quality of the soil. Agricultural waste also protects the soil from erosion and other climatic adversities. Therefore, windy areas, with low soil fertility, high rainfall and slope should be more careful when removing stover.

Like wheat-based glucose evaluated in Chapter 6, maize-based glucose production involves wet milling and enzymatic hydrolysis processing activities (S4). During the wet milling phase, the impurities contained in the grain are cleaned (e.g., stones) and then the grain goes through a separation phase according to its size, shape and weight. A grinding process takes place to separate the endosperm (where the starch is located) from the germ and bran. The refined grain is saturated in water to make it softer and allow the separation of starch and gluten. There is not much waste in the production of maize starch, as it generates valuable by-products, namely maize oil (produced from the maize germ), gluten feed and gluten meal. Gluten feed and meal are protein-rich biomass generally used in the feed industry (Papageorgiou and Skendi, 2018). Finally, enzymatic hydrolysis takes place. First, there is the liquefaction step, in which the starch molecules are first dissolved in water with the aid of enzymes alpha-amylase and sodium hydroxide to transform the starch into small oligosaccharides. Second, the liquefied solution goes through a saccharification step, in which enzymes glucoamylase and sulphuric acid will transform it to glucose.

Regarding the processing of stover (S5), after it is harvested, the stover is transported to the processing unit and a pre-treatment process occurs. At first, the stover is crushed and a chemical hydrolysis takes place, with the aid of heat and sulfuric acid, converting xylan (a group of hemicelluloses) into xylose, achieving about 100% conversion. However, this pre-treatment step does not effectively transform cellulose into glucose. Therefore, enzymatic hydrolysis is carried out, with the addition of enzymes cellulase, converting cellulose into glucose at a conversion rate of about 90%. The stover processing (S5) was simulated by our STAR-ProBio partners. Stover has a high carbohydrate content, which is composed of cellulose (~38%), hemicellulose (~26%) and lignin (~19%)(Prasad et al., 2016). It is important to note that, unlike 1G raw materials, the conversion of lignocellulose to fermentable sugars has been limited by technological and economic barriers.

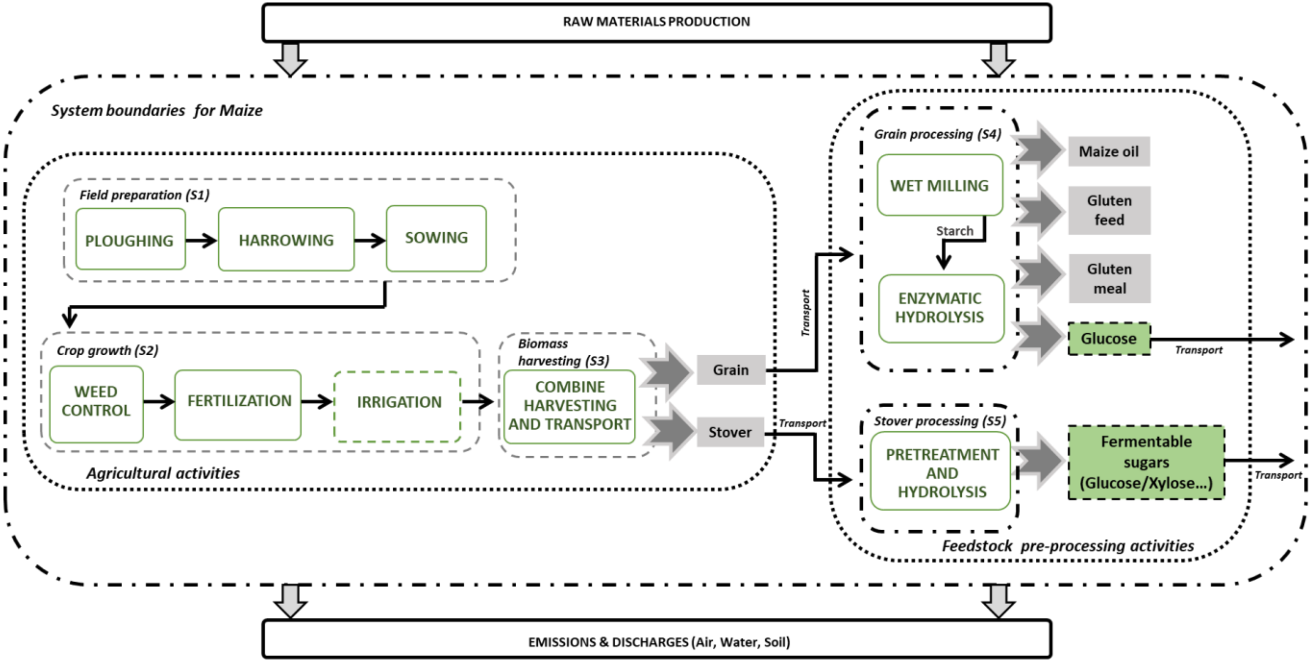

Figure 7.1. System description - fermentable sugars from maize grain and stover.

The processes involved in the production of fermentable sugars from sugar beet pulp are shown in Figure 7.2. Initially, the sugar beet is cultivated. In the cultivation of sugar beet, the first step is the preparation of the soil (S1), where ploughing and harrowing are carried out with the aim to make ready the soil for sowing. Pesticides and fertilisers are used to grow the crop (S2), as well as irrigation or rainwater, depending on the geoclimatic circumstances. Finally, harvesting with the use of a combine harvester and transport to the pre-processing unit takes places (S3). Sugar beet harvesting machines removes part of the soil contained in the crop and also cuts its leaves and roots all together. The leaves weight is about 50% of the sugar beet. Sugar beet leaves are also rich in lignocellulose with about 15% cellulose, 14% hemicellulose, 16% pectin and 5% lignin (Modelska et al., 2017) and can also be used as feedstock for fermentation process. However, in this study, it was assumed that the leaves are left in the field. Sugar beets store sugars in its roots due to photosynthesis. On average, sugar beet root contains about ~14% sucrose, ~6% pulp, ~4% molasses on a wet basis (FAO, 2009).

In the processing unit (S4), the transported beet root is at first washed to remove the impurities left behind and cut them into small strips called *cosettes*. The cosettes go through a diffusion process, adding hot water and sulphuric acid, diluting the sugar into the water. This process is similar to that of tea: the diluted sugar is the raw juice (the tea to drink) and the sugar beet pulp is the by-product (the tea bag). The raw juice undergoes a purification process, adding lime and carbon dioxide to remove the non-sugar compounds from the juice. Finally, crystallization is carried out by centrifugation, producing sucrose (the main product) and molasses (the by-product). Molasses is also a potential feedstock for fermentation and has been used mainly for feed/food and biofuels industries (Duraisam et al., 2017). Sucrose can also be used as fermentation biomass. However, it has a high market value compared to glucose from starch cultures. In the future, however, it is possible that this scenario will alter, due to changes in the diet and also by new market policies that are facilitating the entry of sugarcane into Europe, which may reduce the prices of sugar beet sucrose (Tomaszewska et al., 2018).

The processing stage of beet pulp (S5) is carried out first by means of chemical hydrolysis and then enzymatic hydrolysis to convert beet pulp into fermentable sugars. The pre-treatment step takes place through chemical hydrolysis, with the use of heat and sulphuric acid, converting most of the hemicellulose into sugars (xylose, arabinose, galactose…). Additionally, enzymatic hydrolysis using enzymes cellulase will transform cellulose into glucose. The beet pulp processing (S5) was simulated by our STAR-ProBio partners. The sugar beet pulp has been used until now mainly for animal feed. Still, it is an interesting raw material to be used in industrial fermentation processes, due to its high cellulose (~23%), and hemicellulose (~30%) content. Moreover, it is rich in pectin (~20%) and has low lignin content (~6%) (Tomaszewska et al., 2018).

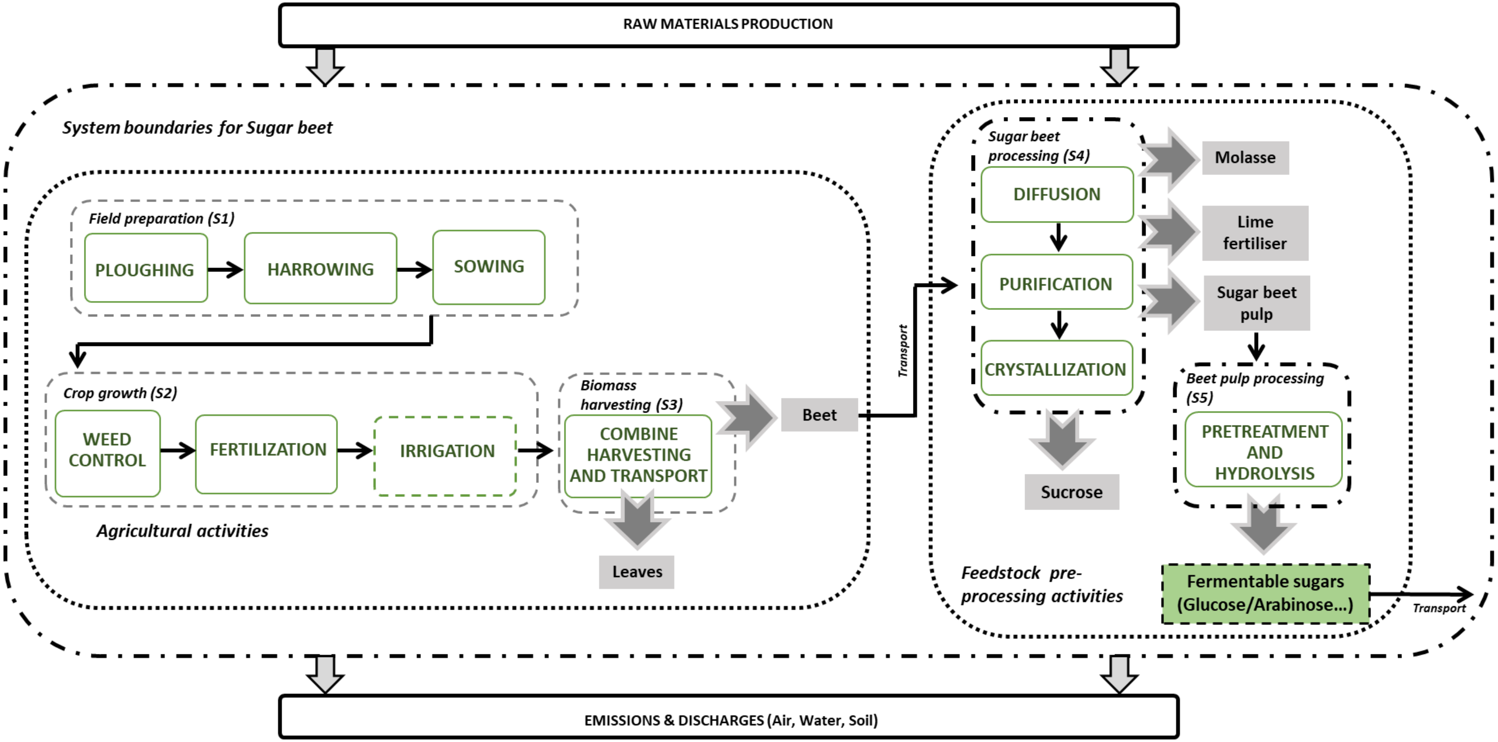

Figure 7.2. System description - fermentable sugars from sugar beet pulp.

7.3.3 Life cycle inventory phase

Evaluating the cause and fate of environmental impacts related to agriculture is not straightforward, as agriculture is a complex system that includes anthropogenic factors (agricultural machinery, fertilisers, pesticides, irrigation, ...) and geoclimatic conditions (type of soil, rainwater, wind, temperature ...). In this study, due to the unavailability of primary data, inventory data for agricultural and pre-processing activities were collected from the literature, as shown in Table 7.2. STAR-ProBio partners modelled the data for maize stover and beet pulp processing.

In this study, 20 different scenarios for fermentable sugars were evaluated and considering 6 countries: United Kingdom (UK), France (FR), Germany (DE), United States (US), Italy (IT) and Belgium (BE). As depicted in Table 7.2, for maize agriculture, different scenarios were considered, such as scenarios with 30% stover removal rate (e.g., Scenario A4) or no removal (Scenario A5), low yield (Scenario A6) and high yield (Scenario A7). Different pre-processing units were considered for maize and sugar beet, in which different by-products were generated (Scenarios P1, P2, P3 and P4). Data for agriculture (A) and processing (P) are integrated, generating 20 different scenarios (Table 7.3). It was decided to use a stover removal rate of 30%, as it is an acceptable quantity of stover that can be removed from agricultural systems without jeopardizing soil quality (Khanna and Paulson, 2016).

The maize grain in scenarios A4, A5, A6, A7 and A8 will pass through a pre-processing step (scenarios P3 and P4), creating 10 scenarios for maize grain. The stover that was removed in maize scenarios A4, A6, A7 and A8 is then subjected to a stover processing (scenario P5), accounting 4 scenarios for maize stover. The sugar beets (scenarios A1, A2 and A3) go through a sucrose production facility (scenarios P1 and P2), delivering sugar beet pulp as by-product. This beet pulp will be processed into total sugars (scenario P6), bringing 6 scenarios for sugar beet pulp.

The background processes in this study are the production and transportation of machineries and infrastructure, fertilisers, pesticides, fossil fuels and electricity. The field emissions and methods used are shown in Table A1 (Annex A). The transportation of the raw material from the farm to the pre-processing facility, as well the transport of the biomass processed to the downstream processes are considered.

The assumptions made for transportation in Europe considers lorry trucks with a 300 km distance from the farm to the pre-processing plant. Regarding the transport of fermentable sugars to the biorefinery, the factories will be located very close to each other (50 km). As for maize production in the United States, maize grain is assumed to be transported to Europe from the Corn Belt region of the United States. The grain travels by barge along the Mississippi River to the Port of New Orleans and is shipped to Europe. Stover produced in the US is supposed to be processed locally as it is not worth transporting it from the US to Europe due to its low bulk density and low price.

This study assumes that it is necessary to add more nutrients to the soil due to the removal of stover. On average, there are about 7.5 kg of N, 2.5 kg of P_2O_5 and 8.2 kg of K_2O per t of dry stover (David, 2013). Additional energy was assumed for the baling process, using Ecoinvent v3.5 as a parameter, which considers 700 kg of straw for each unit of baling, with process name “baling [unit] - CH”(Wernet et al., 2016) .

Table 7.2. Inventory data for agricultural activities (A) and pre-treatment (P) processes. Acronyms: UK – United Kingdom; FR – France; DE – Germany; US – United States; IT – Italy, BE – Belgium; SR – stover removal; LY – low yield; HY – high yield.

Agriculture	**Scenario**	**Source**
Sugar beet, UK	A1	(Renouf et al., 2008)
Sugar beet, FR	A2	(Muñoz et al., 2014)
Sugar beet, DE	A3	(Ecoinvent database®, 2015)
Maize grain and 30% stover removal (SR), US	A4	(Renouf et al., 2008)
Maize grain with non-stover removal (Non-SR), US	A5	(Renouf et al., 2008)
Maize grain and 30% SR, low yield (LY), IT	A6	(Noya et al., 2015)
Maize grain and 30% SR, high yield (HY), IT	A7	(Noya et al., 2015)
Maize grain and 30% SR, BE	A8	(Boone et al., 2016)
Processing	**Scenario**	**Source**
Beet sugar. By-products: lime fertiliser and beet pulp	P1	(Renouf et al., 2008)
Beet sugar. By-products: molasse and beet pulp	P2	(Maravíc et al., 2015)
Maize glucose. By-products: maize gluten feed, meal and oil	P3	(Renouf et al., 2008)
Maize glucose. By-products: maize gluten feed, meal and germ	P4	(Moncada et al., 2018)
Fermentable sugars from maize stover	P5	Confidential data from STAR-ProBio partner
Fermentable sugars from sugar beet pulp	P6	Confidential data from STAR-ProBio partner

Table 7.3. Different types of scenarios for maize, maize stover and sugar beet pulp.

Feedstocks	Fermentable sugars production Scenarios (Sc)	Agriculture (A) and pre-treatment (P) code
Maize1	Sc1	A4P3
Maize2	Sc2	A4P4
Maize3	Sc3	A5P3
Maize4	Sc4	A5P4
Maize5	Sc5	A6P3
Maize6	Sc6	A6P4
Maize7	Sc7	A7P3
Maize8	Sc8	A7P4
Maize9	Sc9	A8P3
Maize10	Sc10	A8P4
Stover1	Sc11	A4P5
Stover2	Sc12	A6P5
Stover3	Sc13	A7P5
Stover4	Sc14	A8P5
Beet pulp1	Sc15	A1P1P6[a]
Beet pulp2	Sc16	A1P2P6
Beet pulp3	Sc17	A2P1P6
Beet pulp4	Sc18	A2P2P6
Beet pulp5	Sc19	A3P1P6
Beet pulp6	Sc20	A3P2P6

a. The production of fermentable sugars from sugar beet pulp goes through a processing of sugar beet (P1 or P2) first to produce beet pulp and then undergo a pre-treatment and hydrolysis step (P6).

Field emissions derived from direct land use change (LUC) were not taken into account as no significant changes in land use have been reported during the past 20 years in the countries and crops evaluated. To determine if land use changes occur, the three-step approach was used as recommended (Milà I Canals et al., 2013), as exemplified in the Annex B.

7.3.4 Allocation

When a production delivers valuable by-products, such as in the wet milling process, the environmental outcomes should not only be attributed to the main product (e.g., sucrose), but also the by-products (e.g., molasses and sugar beet pulp). Hence, in this context, the allocation process must be taken into account in the calculation. Table 7.4 shows the economic values considered for the agricultural crops and products of the pre-processing activities. The data were gathered through databases and peer-reviewed studies.

Table 7.4. Economic values for maize grain, maize stover and sugar beet.

Agriculture	Price	Source
Maize grain (US)	135 $/t	(USDA, 2019)
Maize grain (IT)	196 $/t	(EUROSTAT, 2019)
Maize grain (BE)	203 $/t	(EUROSTAT, 2019)
Maize stover	58.5 $/t	(Humbird et al., 2011)
Pre-processing (Sugar beet)	**Price**	**Source**
Sucrose	308 €/t	(European Commission, 2019)
Sugar beet pulp	4 €/t	Calculated by STAR-ProBio partner
Molasses	105 €/t	(Maravíc et al., 2015)
Calcium carbonate	100 €/t	(Durlinger et al., 2017)
Pre-processing (Maize)	**Price**	**Source**
Glucose	230 $/t	(USDA, 2019)
Maize gluten feed	89 $/t	(USDA, 2019)
Maize gluten meal	536 $/t	(USDA, 2019)
Maize oil	808 $/t	(USDA, 2019)
Maize germ	300 $/t	(Moncada et al., 2018)

7.3.5 Life cycle impact assessment

With the aim to evaluate the environmental burdens of the bio-based case studies, 10 impact categories were chosen as depicted in Table 7.5.

Table 7.5. Life cycle impact categories chosen.

Impact category	**Acronym**	**Unit**	**Source**
Acidification	AC	mol H+-eq	(Posch et al., 2008; Seppälä et al., 2006)
Particulate matter	PM	Death's incidence	(Fantke et al., 2016)
Climate change	CC	kg CO_2-eq	(IPCC, 2013)
Affected biodiversity	BIO	$m^2 \cdot$year·PAS	(Millenium Ecosystem Assessment, 2005)
Terrestrial eutrophication	TE	Mol N-eq	(Posch et al., 2008; Seppälä et al., 2006)
Freshwater eutrophication	FE	kg P-eq	(Struijs et al., 2013)
Human toxicity, cancer	HT	CTUh	(Rosenbaum et al., 2008)
Land use, soil quality index	LU	Pt (Dimensionless)	(Bos et al., 2016)
Soil erosion	SE	kg soil erosion	(Borrelli et al., 2017)
Fossil resource depletion	FD	MJ	(Guinée et al., 2002; Van Oers et al., 2002)

The environmental indicators affected biodiversity (BIO) and soil erosion (SE) must be calculated manually, as they do not have characterization factors in LCA software. Regarding the biodiversity indicator, the agricultural areas used in this report have a temperate climate, therefore, the species richness factor is considerably lower when compared to tropical areas. Yet, this impact category leads to high uncertainty, as biodiversity is an intricate concept with various interpretations. It can be evaluated in terms of species numbers, density, rarity and diversity, for instance. The most common indicator of biodiversity, however, is species richness (Durán et al., 2018). The quantification of the biodiversity indicator is based on the 2005 Millennium Ecosystem Assessment (Millenium Ecosystem Assessment, 2005), related to terrestrial biomes, and only considers amphibians, birds, mammals and reptiles. Despite the complexity of quantifying biodiversity, the presence of endemic species, for example, indicates that the region is preserved as these species are very sensitive to changes in land use.

With the objective to calculate the biodiversity indicator BIO, the land occupation for each scenario needs to be multiplied by the species richness of each country, as indicated below:

$$\mathrm{BIO} \ = \mathrm{PAS}\ (\text{potentially affected species}) \ \times \ \mathrm{m}^2 \ \times \text{year}$$

The soil erosion (SE) indicator , according to Revised Universal Soil Loss Equation (RUSLE) (Panagos et al., 2015) is:

$$\mathrm{SE} = \mathrm{R}^*\mathrm{K}^*\mathrm{C}^*\mathrm{LS}^*\mathrm{P}$$

Where:

SE is the annual soil erosion ($\mathrm{t \cdot ha^{-1} \cdot yr^{-1}}$)

R is the rainfall erosivity factor ($\mathrm{MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}}$)

K is the soil erodibility factor ($\mathrm{t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}}$)

C is the cover management factor (no dimension) and is related to the type of crop cultivated

LS is the slope length and steepness factor (no dimension)

P is the support practice (no dimension)

The calculation of soil erosion requires very specific data, which implies local measurements and observations. In this case, since most of the agricultural data are derived from the literature and databases, it was not possible to quantify this indicator with in-situ data and default values were applied in this chapter. However, this leads to great uncertainty, as soil erosion figures may have very different values within the same region, depending on soil type, climate and agricultural management category. However, these results can serve as a basis for further evaluation. Both impact categories (BIO and SE) have default values which can be assessed in the STAR-ProBio report Deliverable D2.2 (See http://www.star-probio.eu/wp-content/uploads/2017/04/STAR-ProBio_D2.2_v1.2.pdf). Land occupation plays an important role in these two indicators. The values for each country assessed in this report for BIO and SE indicators are shown in Table 7.6.

Table 7.6. Soil erosion (SE) and Potential affected species (PAS) values for United Kingdom (UK), France (FR), Germany (DE), United States (US), Italy (IT) and Belgium (BE).

Countries	**Soil erosion (SE) ($t \cdot ha^{-1} \cdot yr^{-1}$)**	**Potential Affected species (PAS)**
UK (Beet)	3.14	3237
FR (Beet)	0.73	3714
DE (Beet)	0.37	3202
US (Maize)	17.53	2519
IT (Maize)	1.25	3357
BE (Maize)	0.95	3602

7.4 RESULTS AND DISCUSSION

The results of this life cycle assessment are focused on the production of raw materials and the upstream processing of fermentable sugars from maize grain, maize stover and sugar beet pulp. As a first step, the outcomes from agricultural activities (Section 7.4.1) are evaluated and finally the figures for fermentable sugars are described (Section 7.4.2).

7.4.1 Agriculture

An environmental assessment of agricultural activities was evaluated for maize and sugar beet crops. As it can be observed from Figures 7.3, 7.4, 7.5 and 7.6, agricultural machinery, transportation, field emissions and fertilisation play an important role in the global environmental burdens. Pesticides and seed production have very low contribution in all the agricultural scenarios. The results for all the agricultural scenarios are included in Annex A (Figures A3, A4, A5 and A6).

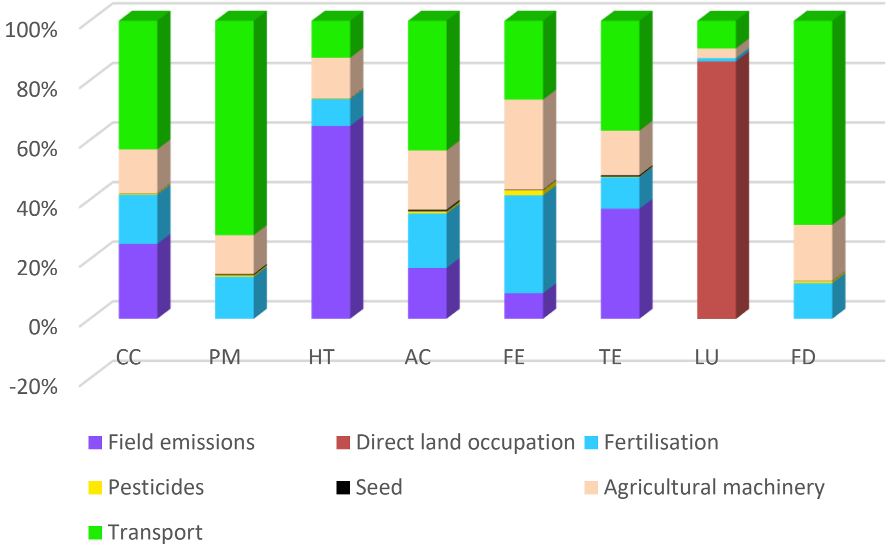

Figure 7.3. Process contribution for the production of sugar beet in France (FR) (scenario A2). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; and FD – Fossil Depletion.

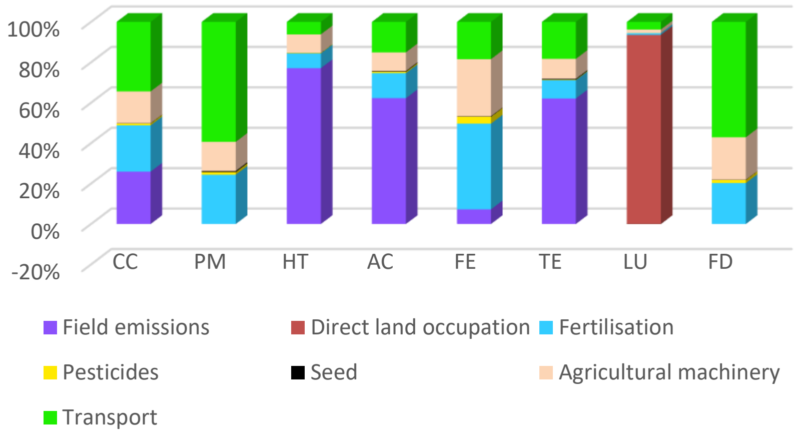

Figure 7.4. Process contribution for the production of sugar beet in Germany (DE) (scenario A3). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; and FD – Fossil Depletion.

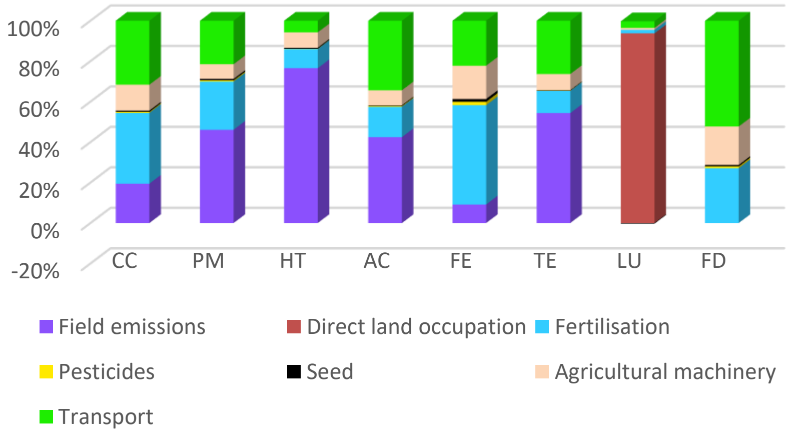

Figure 7.5. Process contribution for the production of maize grain in the US (scenario A4). Economic allocation. CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; and FD – Fossil Depletion.

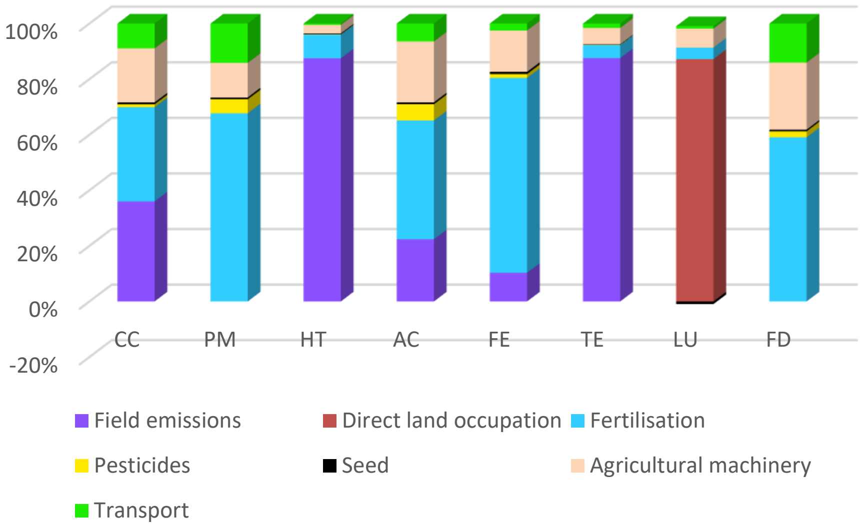

Figure 7.6. Process contribution for the production of maize grain in Italy (scenario A6). Economic allocation. CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; and FD – Fossil Depletion.

The results from biodiversity (BIO) and soil erosion (SE) were not included in Figures above (Figures 7.3, 7.4, 7.5 and 7.6) as most of the contribution derives from direct land occupation, making the other processes contribution insignificant. The absolute values for each scenario are shown in Annex A (Table A2 for economic allocation and Table A3 for mass allocation) using 1 kg of raw material as a functional unit. As noted, the numbers are considerably different for each scenario, both for mass and economic allocation. This is because agriculture is a complex system that involves many anthropogenic and non-anthropogenic variables. These variables can include yields, land occupation, geoclimatic conditions, type of agrochemicals used, type of machinery, tillage methods, residues removal rate, etc. It must be kept in mind that the yield is very different for maize and sugar beet. The average world yield of sugar beet in 2017 was about 61 t, compared to

5.7 t for maize grain (FAOSTAT, 2019). Therefore, crops with high yields have less environmental burden if the functional unit considered is per kg of biomass produced.

Table 7.7 shows the average values of the 10 impact indicators and their respective standard deviations taking into consideration 1 kg of feedstock production as functional unit (sugar beet, maize grain and stover). Standard deviations are considerably high since agricultural systems are very different for each scenario. As regards sugar beet, there is no need for allocation as the beet leaves are left in the field after the harvest process. On the other hand, as 30% of maize stover is harvested in almost all the scenarios, apart from scenario A5, economic and mass allocations were performed. As seen in Table 7.7, economic allocation significantly reduces the environmental results for maize stover, due to the low price of this biomass. On the other hand, mass allocation slightly benefits the results for maize grain.

Table 7.7. Environmental impacts of 1 kg of feedstock production. Average impacts and standard deviation of the different feedstocks from economic and mass allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; FD – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion.

Impact categories	**Sugar beet**	**Maize grain**		**Maize stover**	
		Economic allocation	**Mass allocation**	**Economic allocation**	**Mass allocation**
CC	0.12 ± 0.03	0.42 ± 0.21	0.37 ± 0.20	0.13 ± 0.09	0.31 ± 0.18
PM	$(1.11 \pm 0.98) \cdot 10^{-08}$	$(2.41 \pm 1.47) \cdot 10^{-08}$	$2.13 \pm 1.39 \cdot 10^{-08}$	$7.71 \pm 6.08 \cdot 10^{-09}$	$1.77 \pm 1.26 \cdot 10^{-08}$
HT	$(4.07 \pm 1.42) \cdot 10^{-09}$	$(2.95 \pm 2.53) \cdot 10^{-08}$	$2.52 \pm 2.01 \cdot 10^{-08}$	$9.53 \pm 8.73 \cdot 10^{-09}$	$2.51 \pm 2.35 \cdot 10^{-08}$
AC	$(1.05 \pm 0.49) \cdot 10^{-03}$	$(5.75 \pm 3.01) \cdot 10^{-03}$	$5.11 \pm 2.96 \cdot 10^{-03}$	$1.39 \pm 1.49 \cdot 10^{-03}$	$4.28 \pm 2.59 \cdot 10^{-03}$
FE	$(2.08 \pm 1.01) \cdot 10^{-05}$	$(8.44 \pm 5.61) \cdot 10^{-05}$	$7.32 \pm 4.74 \cdot 10^{-05}$	$2.67 \pm 2.09 \cdot 10^{-05}$	$6.69 \pm 5.18 \cdot 10^{-05}$
TE	$(3.36 \pm 1.27) \cdot 10^{-03}$	$(3.36 \pm 2.12) \cdot 10^{-02}$	$2.87 \pm 1.69 \cdot 10^{-02}$	$1.05 \pm 0.76 \cdot 10^{-02}$	$2.83 \pm 1.95 \cdot 10^{-02}$

Impact categories	**Sugar beet**	**Maize grain**		**Maize stover**	
		Economic allocation	**Mass allocation**	**Economic allocation**	**Mass allocation**
LU	14.17 ± 6.04	54.60 ± 34.62	46.89 ± 27.78	14.97 ± 15.43	46.88 ± 32.35
FD	1.24 ± 0.35	4.00 ± 2.05	3.51 ± 1.91	1.29 ± 0.83	3.07 ± 1.81
BIO	548 ± 123	2561 ± 1730	2185 ± 1368	658 ± 702	2263 ± 1585
SE	$(2.72 \pm 3.44) \cdot 10^{-02}$	0.67 ± 0.81	0.61 ±0.74	0.20 ± 0.37	0.43 ± 0.72

7.4.2 Agriculture + processing

This section assesses the environmental burdens of producing fermentable sugars from three types of biomass (beet pulp, maize grain and stover). These renewable carbohydrate materials are used as intermediate sources on the path to bio-based production. More specifically, they are the sources of input for producing the selected STAR-ProBio case studies PLA and PBS. The results are presented with a functional unit of 1 kg of fermentable sugars. The average impacts of all scenarios for maize grain, stover and beet pulp and their corresponding standard variations are summarized in Table 7.8. To assess the impacts from the 20 scenarios, see Annex A (Table A4). As shown, fermentable sugars from beet pulp have the best environmental profile in all impact categories. On the other hand, maize grain presents better figures for CC, PM, FE and FD than maize stover. The higher numbers for stover are mainly due to background processes in the maize stover processing stage and the highest figures for maize grain are closely associated to agriculture. For maize grain, it shows the greatest environmental impacts for HT, AC and TE, as well as, and not surprisingly, for the impact categories that are related to land use and agricultural activities (i.e., BIO, SE and LU). The standard variation is greater for maize grain and stover than for beet pulp because most of the impact of beet pulp comes from the processing phase and not from the different agricultural activities, which have very different profiles.

Table 7.8. Comparison results of fermentable sugars from different feedstocks. FU: 1 kg of fermentable sugars.

Impact categories	Maize grain	Maize stover	Beet pulp
CC	0.56±0.20	0.64±0.16	0.32±0.01
PM	$(3.03\pm1.4)\cdot10^{-08}$	$(3.40\pm1.15)\cdot10^{-08}$	$(1.87\pm0.38)\cdot10^{-08}$
HT	$(3.19\pm2.4)\cdot10^{-08}$	$(2.32\pm1.35)\cdot10^{-08}$	$(4.31\pm0.44)\cdot10^{-09}$
AC	$(6.93\pm2.87)\cdot10^{-03}$	$(6.10\pm2.40)\cdot10^{-03}$	$(2.23\pm0.16)\cdot10^{-03}$
FE	$(1.12\pm0.53)\cdot10^{-04}$	$(1.98\pm0.37)\cdot10^{-04}$	$(1.11\pm0.03)\cdot10^{-04}$
TE	$(3.78\pm2.00)\cdot10^{-02}$	$(2.78\pm1.29)\cdot10^{-02}$	$(5.39\pm0.48)\cdot10^{-03}$
FD	6.15±1.96	8.87±1.58	5.02±0.12
LU	58±32	34±22	4.1±2.0
BIO	2720±1634	2051±1041	488±72
SE	0.71±0.76	0.49±0.69	$(2.18\pm2.03)\cdot10^{-02}$

The Table A5, in Annex A, presents the environmental results of the 20 scenarios using mass allocation. As observed, mass allocation benefits the 1G feedstock maize grain. This is in line with wheat-based glucose, assessed in Chapter 6, which also showed better results for mass allocation. On the other hand, economic allocation shows a better environmental profile for the 2G feedstocks sugar beet pulp and maize stover. From a global point of view, the results of economic allocation have less environmental impacts, due to the low economic value of second-generation raw materials. For instance, for beet pulp, the average value of all the 6 scenarios for CC is about 0.32 kg (economic allocation), compared to 1.05 kg CO$_2$ eq (mass allocation) for the production of 1 kg of fermentable sugars. Figure A7, in Annex A, presents a comparison with mass and economic allocation. It is clear that the choice of allocation method has a considerable effect on the results, especially for maize stover and beet pulp. In the work of (Tsiropoulos et al., 2013), which performed an LCA of maize-based glucose in Europe, it is stated that the results related to by-products are more sensitive to changes in the allocation.

A different approach to understanding the system and its environmental impacts is to identify the environmental hotspots through LCA. The hotspots analysis for each scenario is depicted in Figures 7.7 (a, b and c), using economic allocation and Figures 7.8 (a, b and c), using mass allocation. As depicted in the figures, the agricultural phase plays a key role in the overall results of maize grain, whether applying economic or mass allocation. However, for the maize stover and beet pulp scenarios, the processing phase has a considerable contribution, especially for the beet pulp in the “TS production” process. This is because the raw beet pulp is practically priceless. Pulp prices start to appear when beet pulp pellets are produced, because additional energy is needed to dry the pulp, with almost 30% of all energy used in a sugar mill. On the other hand, if mass allocation is applied, the agricultural phase is now the main contributor, given the high amount of raw beet pulp produced. The comparison between mass and economic allocation shows that, for fermentable sugars from maize grain, the differences on the results are not as sensitive as those compared to maize stover and sugar beet pulp.

The LCA outcomes show that the valorisation of the by-products as renewable fermentation materials is very sensitive to allocation. In addition, the prices of these products are not as stable as first-generation raw materials, such as maize grain, which benefits from technological development (for instance, pre-treatment process to glucose production) and economic support (for instance, subsidies). That is why an early techno-economic evaluation of these raw materials must be carried out. In addition, it was observed that choosing the type of raw material and methods used in LCA can alter considerably the results. Therefore, it is very important to investigate aspects of sustainability at a very early stage in the development of a new product or process to help the decision-making process. In general, the use of fermentable sugar from beet pulp through economic allocation shows the best environmental result.

Table A6, in Annex A, presents a comparison of the results with the literature and also with Chapter 6, showing that there are a variety of possible raw materials that can be used as fermentation biomass and that the results are quite different from each other. It is important to note that each study has different system boundaries and allocation methods used, which makes comparison difficult. When comparing the 1G feedstocks, the maize grain (Chapter 7) and the wheat grain (Chapter 6), it shows that apart from HT and TE, the maize grain has the best environmental profile.

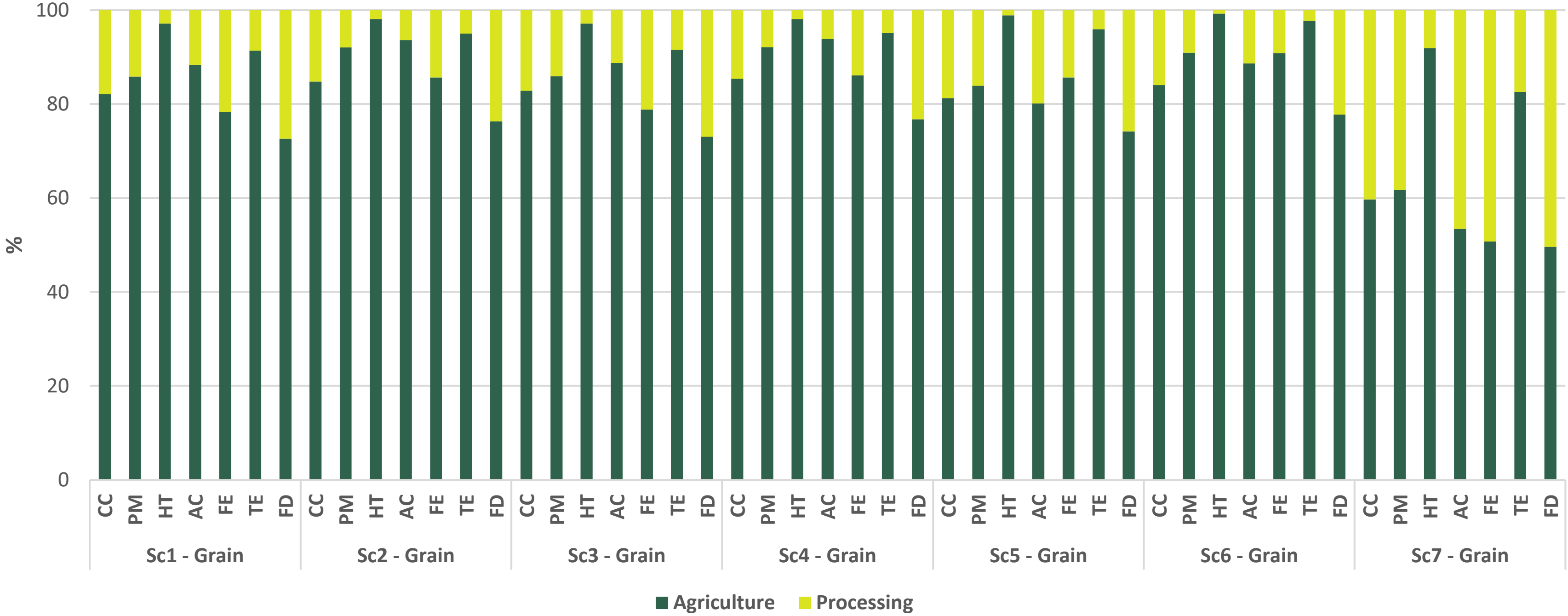

Figure 7.7 (a). Comparative profile of fermentable sugars production from different scenarios using economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; FD – Fossil Depletion.

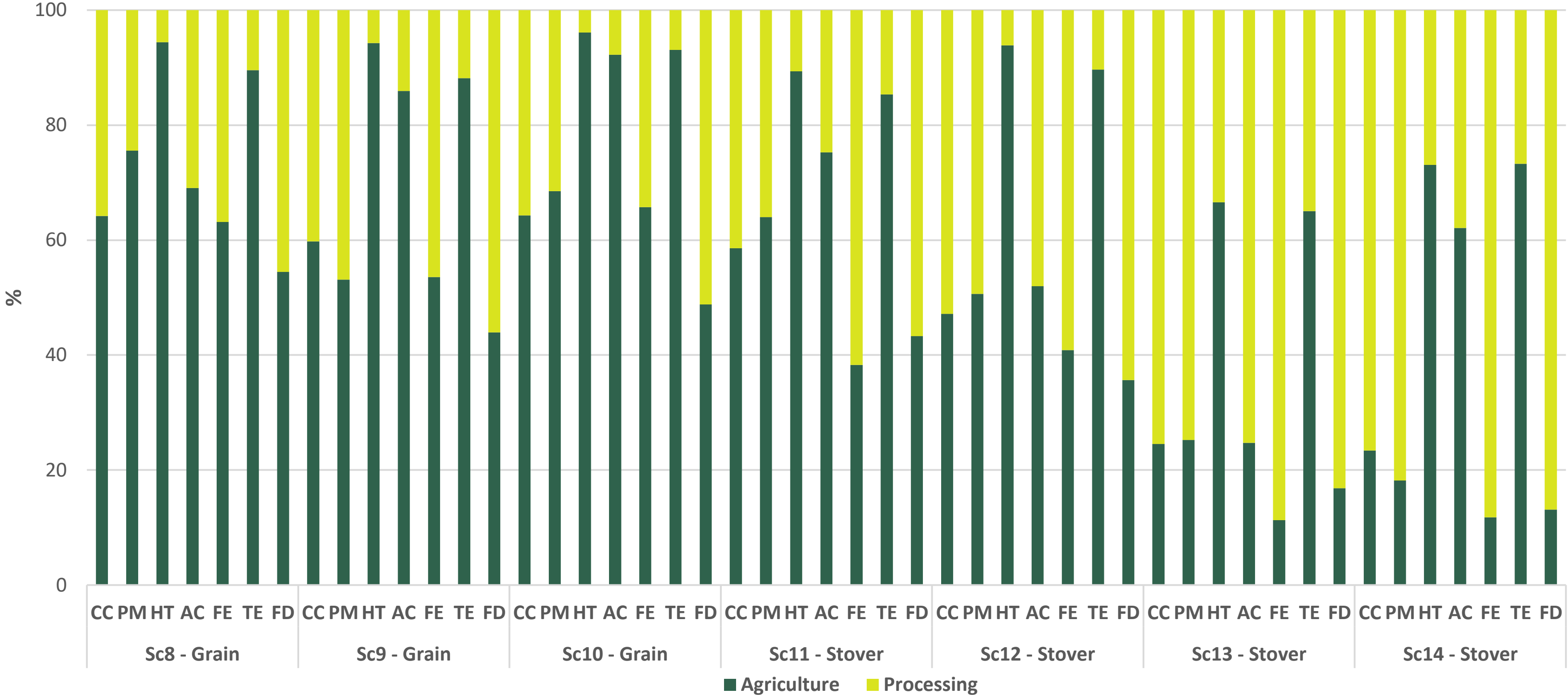

Figure 7.7 (b). Comparative profile of fermentable sugars production from different scenarios using economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; FD – Fossil Depletion.

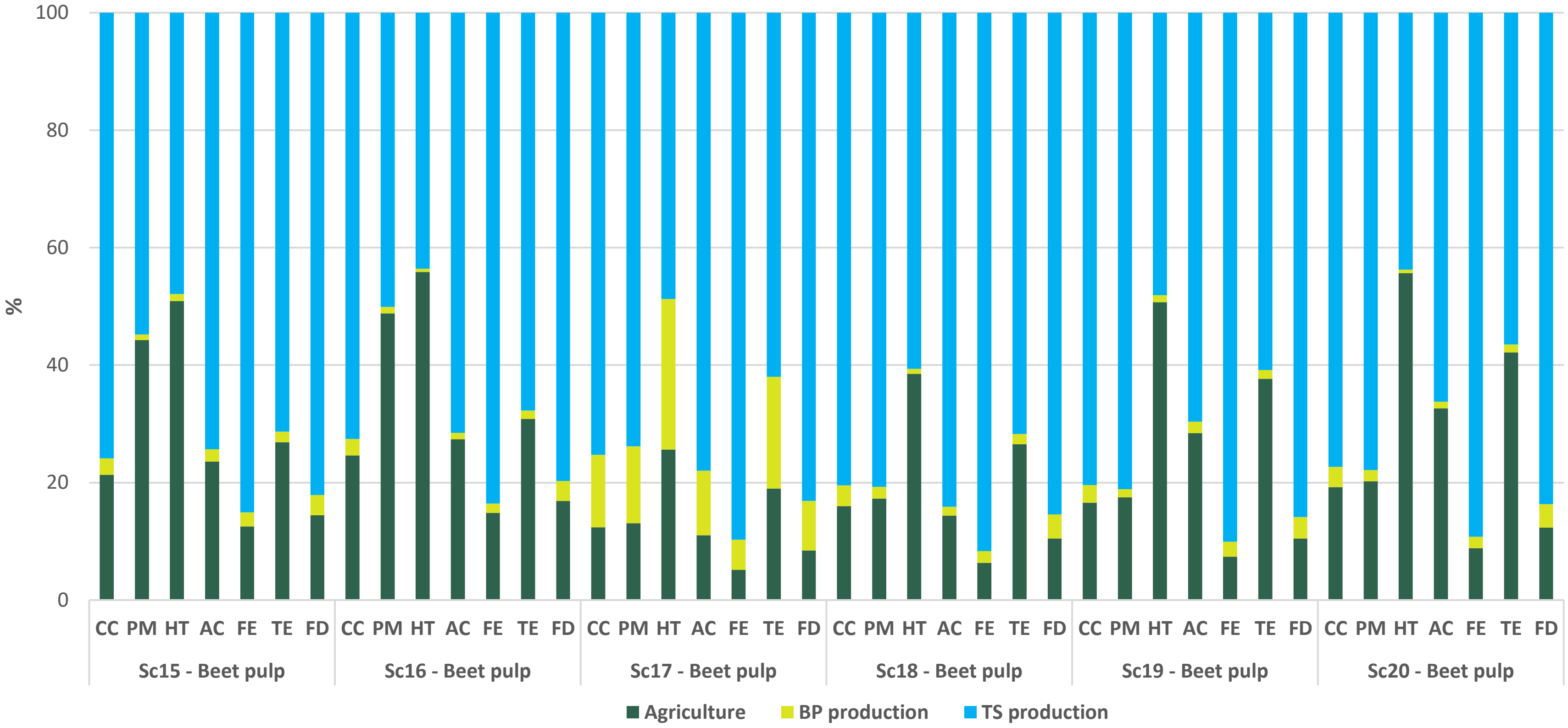

Figure 7.7 (c). Comparative profile of fermentable sugars production from different scenarios using economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; FD – Fossil Depletion; BP process – Beet pulp processing; TS processing – Total Sugars processing.

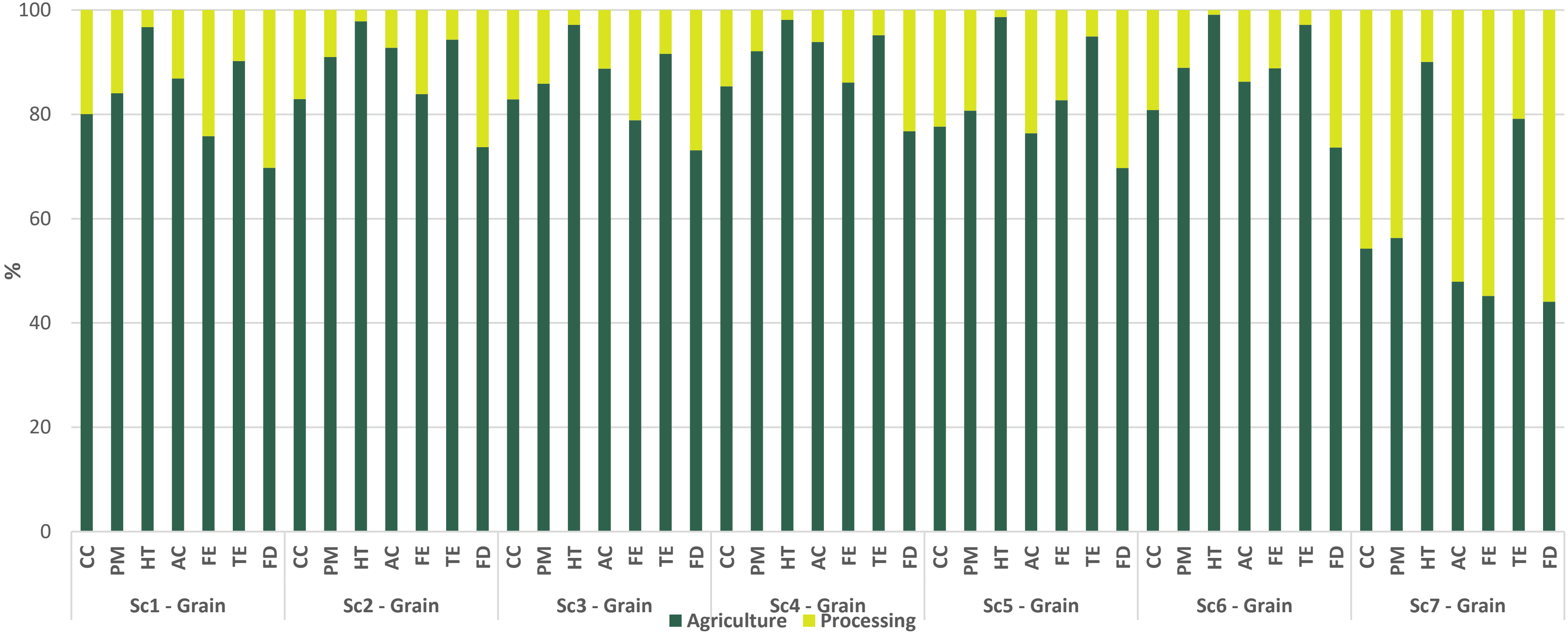

Figure 7.8 (a). Comparative profile of fermentable sugars production from different scenarios using mass allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; FD – Fossil Depletion.

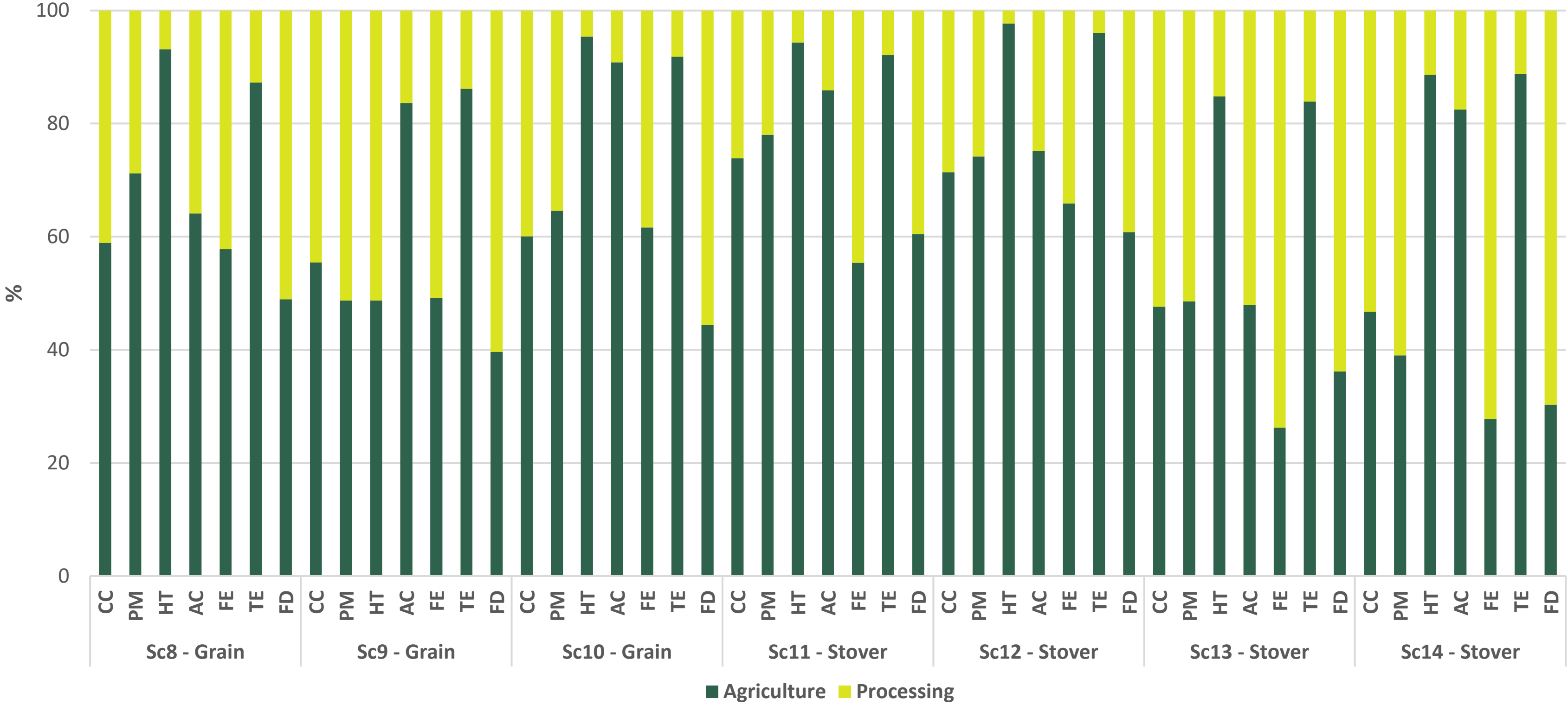

Figure 7.8 (b). Comparative profile of fermentable sugars production from different scenarios using mass allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; FD – Fossil Depletion.

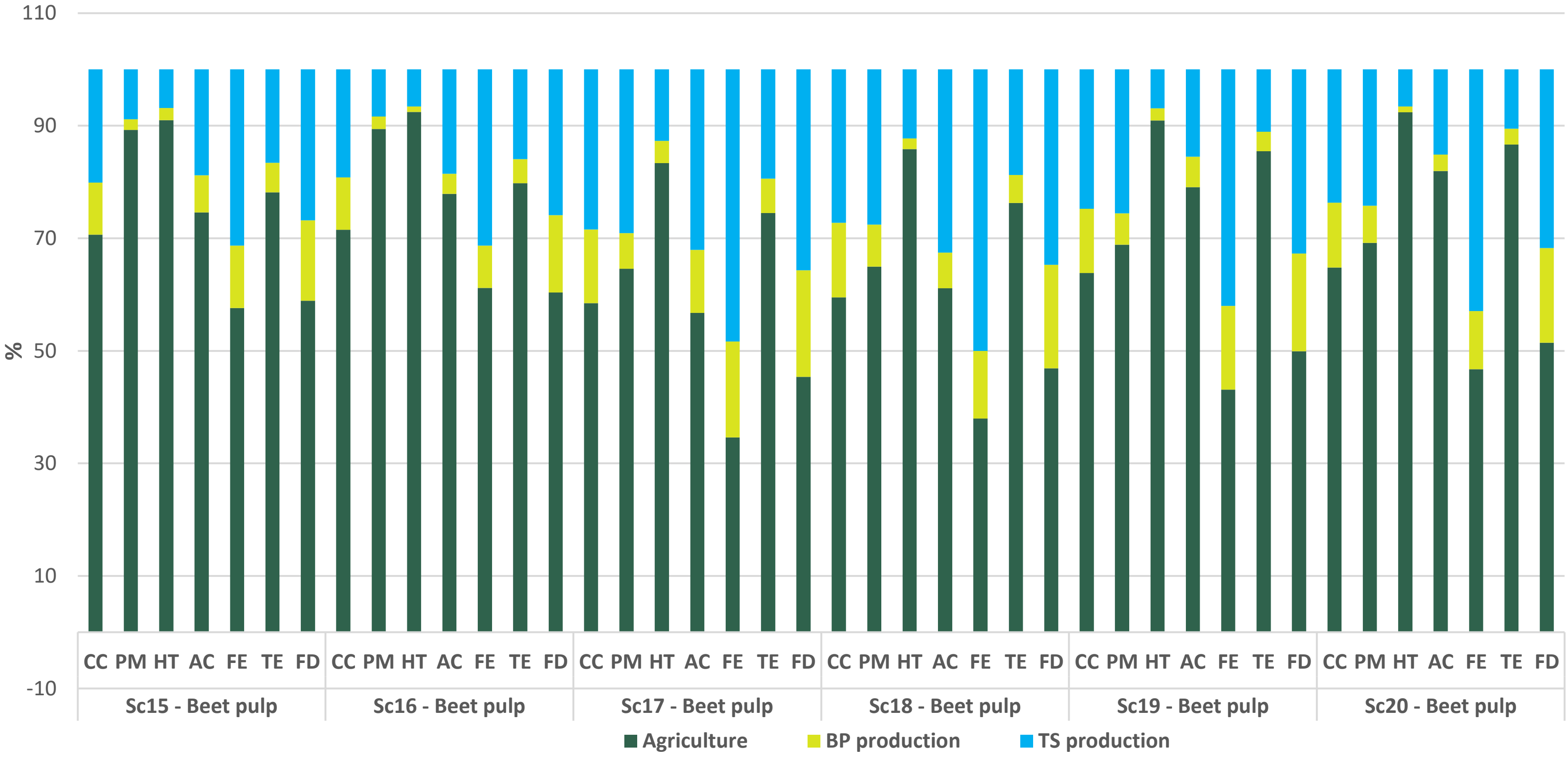

Figure 7.8 (c). Comparative profile of fermentable sugars production from different scenarios using mass allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; FD – Fossil Depletion; BP process – Beet pulp processing; TS processing – Total Sugars processing.

7.3 CONCLUSIONS

Understanding the environmental aspect of agricultural activities and pre-processing of the production of bio-based products is very important as these upstream activities embody a very distinct and independent stage in the supply chain. Agriculture, for example, is highly determined by geographic and climatic conditions. One pathway to enhance the production of bioproducts is through the use of carbohydrate-rich biomass (e.g., fermentable sugars). This chapter evaluated the upstream LCA of fermentable sugars from maize grain, stover and beet pulp as they are renewable material inputs to the production of the case studies of the STAR-ProBio project: PLA and PBS.

Regarding agriculture cultivation, the results show that field emissions, transport, chemical fertilisation and agricultural activities are critical factors for environmental impacts. In the analysis of the production of fermentable sugars, the contribution analysis shows that agricultural activities have a fundamental role in the total impacts for maize grain. However, agriculture contributes less if maize stover is used and even less with beet pulp, due to its very low market value. This evaluation shows that the use of fermentable sugars from beet pulp will reduce the environmental impacts, if economic allocation is applied.

Sensitivity analysis comparing economic and mass allocation methods shows that the results for maize grain are not as sensitive compared to stover or beet pulp. Both showed extremely high variation in results. Therefore, the outcomes of this LCA should be combined with technoeconomic analysis, not only considering internal operations, but evaluating these feedstocks from a macroeconomic perspective to understand how the market system behaves if these raw materials are used on a larger scale for bioproducts in the future.

It is very important to discern upstream from downstream processes, as evidence shows that upstream processes have unique characteristics that will affect the overall sustainability of bio-based products. Biorefinery plants, for example, can obtain their biomass from various suppliers and countries, from different types of agricultural systems and geoclimatic conditions. Not to mention the economic and social aspects, such as local development, working conditions, salary, etc., which may vary according to each biomass supplier. In addition, first generation raw materials, for example, can be highly subsidized, not showing the true value of these raw materials.

This chapter is an attempt to present the environmental impacts of upstream processes for the Star-ProBio case studies. A variety of gaps will be explored in the future, such as the use of other types and innovative raw materials, for instance, micro and macro algae and cellulose from forestry operations. Additionally, new pre-treatment technologies, especially for processing lignocellulosic crops and new ways of integrating supply chains between the upstream and downstream processes of bio-based products, are expected to emerge in the future.

REFERENCES

Adom, F., Dunn, J.B., Han, J., 2014. GREET Pretreatment Module. Chicago.

Blanco, J., Iglesias, J., Morales, G., Melero, J.A., Moreno, J., 2020. Comparative Life Cycle Assessment of Glucose Production from Maize Starch and Woody Biomass Residues as a Feedstock. MDPI Appl. Sci. 10, 1–14. https://doi.org/10.3390/app10082946

Boone, L., Van, V., Meester, S. De, Vandecasteele, B., Muylle, H., Roldán-ruiz, I., Nemecek, T., Dewulf, J., 2016. Environmental life cycle assessment of grain maize production : An analysis of factors causing variability. Sci. Total Environ. 553, 551–564. https://doi.org/10.1016/ j.scitotenv.2016.02.089

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K. Van, Montanarella, L., Panagos, P., 2017. An assessment of the global impact of 21st century land use change on soil erosion. Nat. Commun. 8, 13. https://doi.org/10.1038/s41467-017-02142-7

Bos, U., Horn, R., Beck, T., Lindner, jan P., Fischer, M., 2016. LANCA - Characterization Factors for Life Cycle Impact Assessment - v2.0.

Camara-Salim, I., Feijoo, G., Moreira, M.T., 2020. Upstream Environmental Assessment, in: Transition Towards a Sustainable Biobased Economy. The Royal Society of Chemistry, pp. 12–43. https://doi.org/https://doi.org/10.1039/9781839160271-00012

Camia, A., Rober, N., Jonsson, R., Pilli, R., García-Condado, S., López-Lozano, R., van der Velde, M., Ronzon, T., P, G., M'Barek, R., Tamosiunas, S., Fiore, G., Araujo, R., Hoepffner, N., Marelli, L., Giuntoli, J., 2018. Biomass production, supply, uses and flows in the European Union. https://doi.org/10.2760/181536

David, E., 2013. Sustainable Corn Stover Harvest. Iowa.

Duraisam, R., Salelgn, K., Berekete, A.K., 2017. Production of Beet Sugar and Bio-ethanol from Sugar beet and it Bagasse: A Review. Int. J. Eng. Trends Technol. 43, 222–233. https://doi.org/10.14445/ 22315381/IJETT-V43P237

Durán, A.P., Green, J.M.H., West, C.D., Visconti, P., Burgess, N.D., Virah-Sawmy, M., Balmford, A., 2018. Putting species back on the map: devising a robust method for quantifying the biodiversity impacts of land conversion. bioRxiv. https://doi.org/10.1101/447466

Durlinger, B., Koukouna, E., Broekema, R., Van Paassen, M., Scholten, J., 2017. Agri-footprint 4.0. Gouda.

Ecoinvent database®, 2015. Ecoinvent database® [WWW Document]. URL http://www.ecoinvent.org/database

EEA, 2013. Crop production and agricultural soils, EMEP/EEA emission inventory guidebook.

European Commission, 2019. EU Sugar Market Observatory [WWW Document]. URL https://ec.europa.eu/agriculture/sites/agriculture/ files/market-observatory/sugar/doc/price-reporting_en.pdf (accessed 4.5.19).

European Commission, 2017. PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3.

EUROSTAT, 2019. Agricultural markets. Market data on national and European agriculture [WWW Document]. URL https://agridata.ec.europa.eu/extensions/DataPortal/

agricultural_markets.html (accessed 2.18.19).

Faist-Emmenegger, M., Reinhard, J., Zah, R., 2009. Sustainability Quick Check for Biofuels. Intermediate background report. Dübendorf.

Fantke, P., Evans, J., Hodas, N., Joshua, A., Jantunen, M., Jolliet, O., Mckone, T.E., 2016. Health impacts of fine particulate matter, in: Global Guidance for Life Cycle Impact Assessment Indicators. p. 166.

FAO, 2009. Sugar Beet White Sugar, Agribusiness Handbooks.

FAOSTAT, 2019. Crop statistics [WWW Document]. URL http://www.fao.org/faostat/en/#data (accessed 1.10.19).

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.., De Bruijn, J.A., Van Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards.

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D., Dudgeon, D., 2011. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol. Renew. Energy 303, 147. https://doi.org/ 10.2172/1013269

IPCC, 2013. Anthropogenic and natural radiative forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/ CBO9781107415324.018

Kathage, J., Gómez-barbero, M., Rodríguez-cerezo, E., 2016. Framework for assessing the socio-economic impacts of Bt maize cultivation. https://doi.org/10.2788/739670

Khanna, M., Paulson, N., 2016. To Harvest Stover or Not: Is it Worth it?

Maravíc, N., Kiss, F., Seres, L., Bogdanovic, Branislav, Bogdanovic, Biljana, Seres, Z., 2015. Economic analysis and LCA of an advanced industrial-scale raw sugar juice purification procedure. Food Bioprod. Process. 5, 19–26. https://doi.org/10.1016/j.fbp.2015.02.004

Milà I Canals, L., Rigarlsford, G., Sim, S., 2013. Land use impact assessment of margarine. Int. J. Life Cycle Assess. 18, 1265–1277. https://doi.org/10.1007/s11367-012-0380-4

Millenium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Synthesis. Washington, DC.

Modelska, M., Berlowska, J., Kregiel, D., Cieciura, W., Antolak, H., Tomaszewska, J., Binczarski, M., Szubiakiewicz, E., Witonska, I.A., 2017. Concept for recycling waste biomass from the sugar industry for chemical and biotechnological purposes. Molecules 22, 1–26. https://doi.org/10.3390/molecules22091544

Moncada, J., Vural Gursel, I., Huijgen, W.J.J., Dijkstra, J.W., Ramírez, A., 2018. Techno-economic and ex-ante environmental assessment of C6 sugars production from spruce and corn. Comparison of organosolv and wet milling technologies. J. Clean. Prod. 170, 610–624. https://doi.org/10.1016/j.jclepro.2017.09.195

Morales, M., Pielhop, T., Saliba, P., Hungerbühler, K., Rohr, P.R. Von, 2016. Sustainability assessment of glucose production technologies from highly recalcitrant softwood including scavengers. Biofuels, Bioprod. Biorefining 11, 441–453. https://doi.org/10.1002/bbb.1756

Muñoz, I., Flury, K., Jungbluth, N., Rigarlsford, G., I Canals, L.M., King, H., 2014. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int. J. Life Cycle Assess. 19, 109–119. https://doi.org/10.1007/s11367-013-0613-1

Nemecek, T., Bengoa, X., Lansche, J., Mouron, P., Riedener, E., Rossi, V., Humbert, S., 2015. Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 3.0. Lausanne and Zurich.

Noya, I., González-García, S., Bacenetti, J., Arroja, L., Moreira, M.T., 2015. Comparative life cycle assessment of three representative feed cereals production in the Po Valley (Italy). J. Clean. Prod. 99, 250–265. https://doi.org/10.1016/j.jclepro.2015.03.001

Nwaneshiudu, I.C., Ganguly, I., Pierobon, F., Bowers, T., Eastin, I., 2016. Environmental assessment of mild bisulfite pretreatment of forest residues into fermentable sugars for biofuel production. Biotechnol. Biofuels 1–10. https://doi.org/10.1186/s13068-016-0433-1

Ortiz-reyes, E., Anex, R.P., 2019. Life cycle environmental impacts of non-cellulosic fermentable carbohydrates for the production of biofuels and chemicals. Int. J. Life 25, 548–563. https://doi.org/10.1007/ s11367-019-01708-5

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015. The new assessment of soil loss by water erosion in Europe. Environ. Sci. Policy 54, 438–447. https://doi.org/10.1016/j.envsci.2015.08.012

Papageorgiou, M., Skendi, A., 2018. Introduction to cereal processing and by-products. Sustain. Recover. Reutil. Cereal Process. By-Products 1–25. https://doi.org/10.1016/B978-0-08-102162-0.00001-0

Posch, M., Seppälä, J., Hettelingh, J.P., Johansson, M., Margni, M., Jolliet, O., 2008. The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. Int. J. Life Cycle Assess. 13, 477–486. https://doi.org/10.1007/s11367-008-0025-9

Prasad, A., Sotenko, M., Blenkinsopp, T., Coles, S.R., 2016. Life cycle assessment of lignocellulosic biomass pretreatment methods in biofuel production. Int. J. Life Cycle Assess. 21, 44–50. https://doi.org/10.1007/s11367-015-0985-5

Renouf, M.A., Wegener, M.K., Nielsen, L.K., 2008. An environmental life cycle assessment comparing Australian sugarcane with US corn and UK sugar beet as producers of sugars for fermentation. Biomass and Bioenergy 32, 1144–1155. https://doi.org/10.1016/j.biombioe.2008.02.012

Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A.J., Jolliet, O., Juraske, R., Koehler, A., Larsen, H.F., MacLeod, M., Margni, M., Mackone, T.E., Payet, J., Schuhmacher, M., Van De Meent, D., Hauschild, M.Z., 2008. USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int. J. Life Cycle Assess. 13, 532–546. https://doi.org/10.1007/s11367-008-0038-4

Rüdelsheim, P.L.J., Smets, G., 2011. Baseline information on agricultural practices in the EU Maize (Zea mays L .). Brussels.

Seppälä, J., Posch, M., Johansson, M., Hettelingh, J.P., 2006. Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. Int. J. Life Cycle Assess. 11, 403–416. https://doi.org/10.1065/lca2005.06.215

Struijs, J., Beusen, A., van Jaarsveld, H., Huijbregts, M.A.., 2013. Eutrophication, in: ReCiPe 2008. A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and Endpoint Level. pp. 58–66. https://doi.org/10.2307/40184439

Tao, L., Tan, E.C.D., Aden, A., Elander, R.T., 2014. Techno-Economic Analysis and Life-Cycle Assessment of Lignocellulosic Biomass to Sugars Using Various Pretreatment Technologies, in: Biological Conversion of Biomass for Fuels and Chemicals: Explorations from Natural Utilization Systems. pp. 358–380.

Thomas, V.M., Choi, D.G., Luo, D., Realff, M., 2012. A supercritical Water Approach to Cellulosic Sugars: Lifecycle Energy, Greenhouse Gas and Water Implications.

Tomaszewska, J., Bieliński, D., Binczarski, M., Berlowska, J., Dziugan, P., Piotrowski, J., Stanishevsky, A., Witońska, I.A., 2018. Products of sugar beet processing as raw materials for chemicals and biodegradable polymers. RSC Adv. 8, 3161–3177. https://doi.org/10.1039/ C7RA12782K

Tsiropoulos, I., Cok, B., Patel, M.K., 2013. Energy and greenhouse gas assessment of European glucose production from corn-a multiple allocation approach for a key ingredient of the bio-based economy. J. Clean. Prod. 43, 182–190. https://doi.org/10.1016/j.jclepro.2012.12.035

USDA, 2019. Sugar and Sweeteners Yearbook Tables [WWW Document]. URL https://www.ers.usda.gov/data-products/sugar-and-sweeteners-yearbook-tables.aspx#25442 (accessed 2.19.19).

Van Oers, L., De Koning, A., Guinée, J.B., Huppes, G., 2002. Abiotic resource depletion in LCA. Improving characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA handbook., Aviation Week and Space Technology (New York).

Delft, The Netherlands.

Vargas-Ramirez, J.M., Wiesenborn, D.P., Ripplinger, D.G., Pryor, S.W., 2017. Carbon footprint of industrial-beet sugars stored as raw thick juice for use as a fermentation feedstock. J. Clean. Prod. 162, 1418–1429. https://doi.org/10.1016/j.jclepro.2017.06.153

Vercalsteren, A., Boonen, K., 2015. Life Cycle Assessment study of starch products for the European starch industry association (AAF): sector study.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Wood, D., Rourke, T.O., 1995. Glucose syrups in the fermentation industries, in: Handbook of Starch Hydrolysis Products and Their Derivatives. pp. 230–244. https://doi.org/10.1007/ 978-1-4615-2159-4_8

ANNEX A

Figures

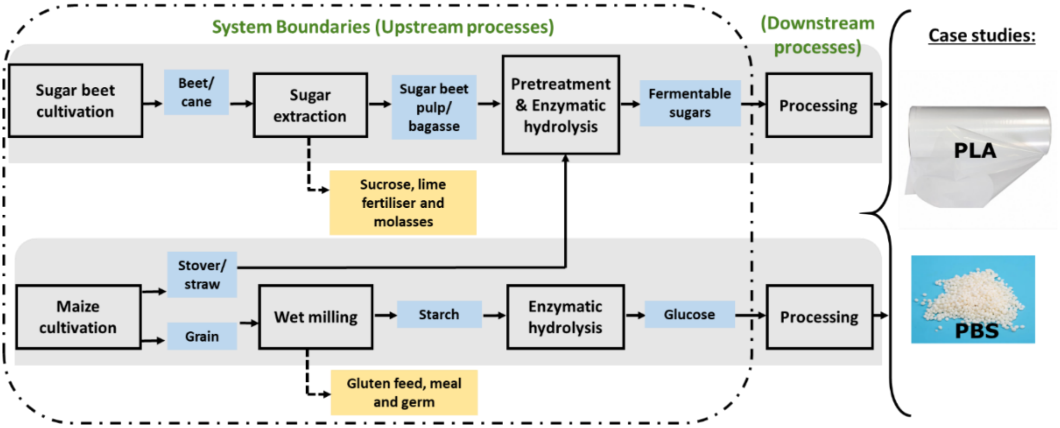

Figure A1. Scheme of upstream processes within the STAR-ProBio framework.

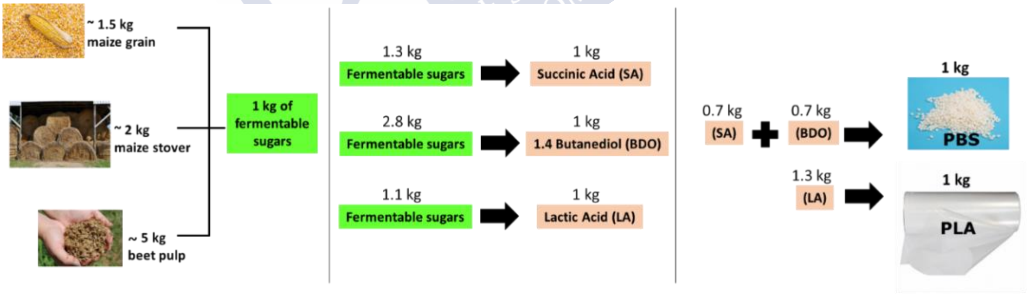

Figure A2. Amounts needed to produce fermentable sugars from maize grain, stover and beet pulp; amounts needed to produce Succinic acid (SA), 1.4 Butanediol (BDO), Lactic acid (LA) and PLA and PBS polymers.

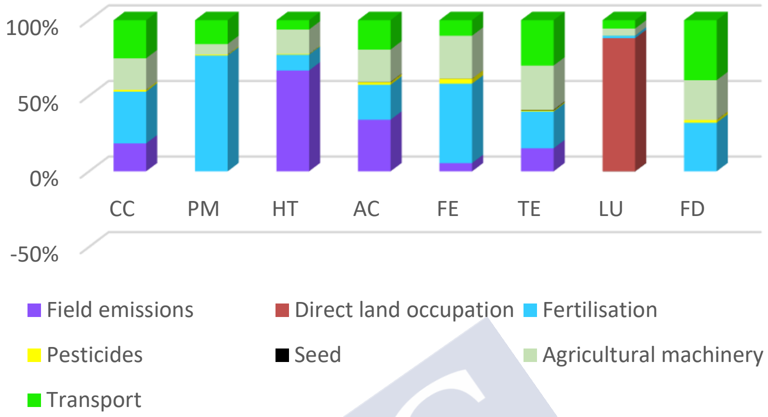

Figure A3. Process contribution for the production of sugar beet in the UK (scenario A1). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; and FD – Fossil Depletion.

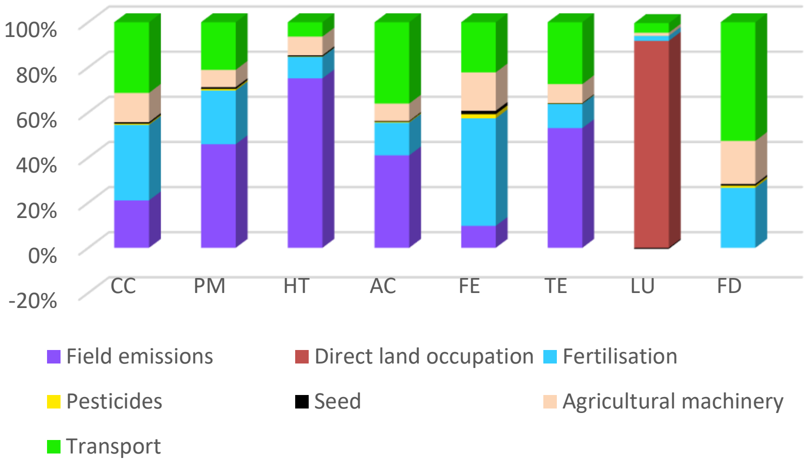

Figure A4. Process contribution for the production of maize grain in the US (scenario A5). Economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; and FD – Fossil Depletion.

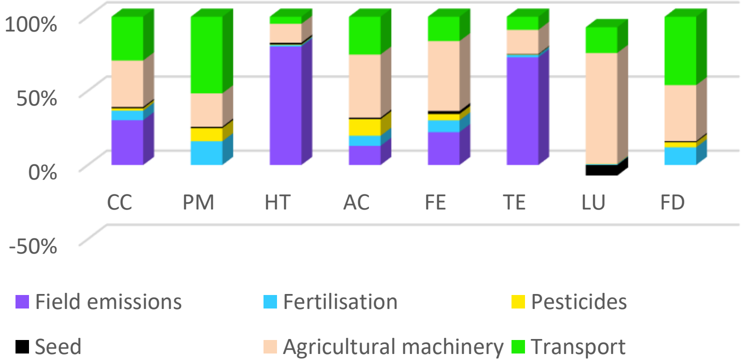

Figure A5. Process contribution for the production of maize grain in Italy (scenario A7). Economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; and FD – Fossil Depletion.

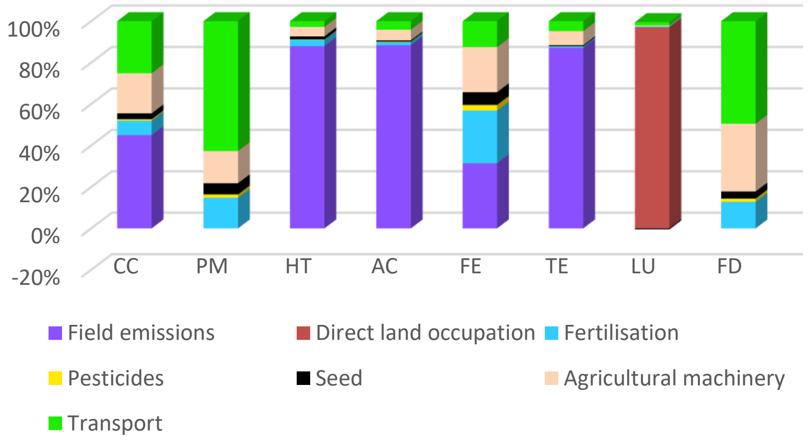

Figure A6. Process contribution for the production of maize grain in Belgium (scenario A8). Economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; and FD – Fossil Depletion.

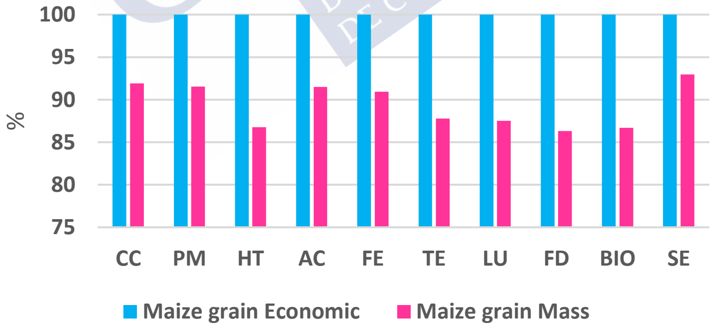

Figure A7 (a). Comparison mass and economic allocation for maize grain. FU: 1 kg of fermentable sugars. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; FD – Fossil Depletion; BIO – Biodiversity; and SE – Soil Erosion.

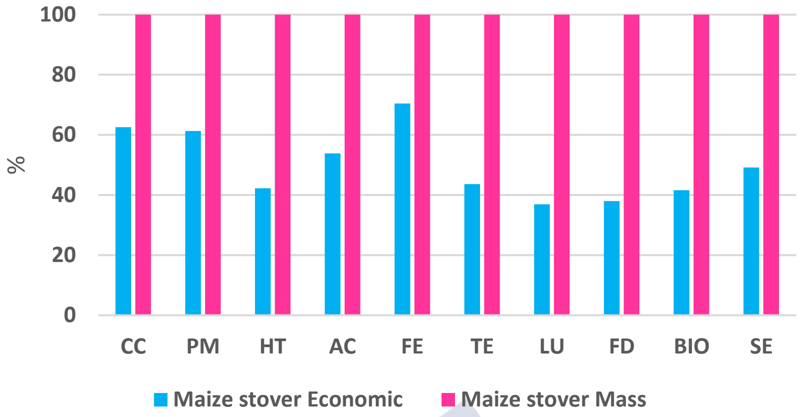

Figure A7 (b). Comparison mass and economic allocation for maize stover. FU: 1 kg of fermentable sugars. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; FD – Fossil Depletion; BIO – Biodiversity; and SE – Soil Erosion.

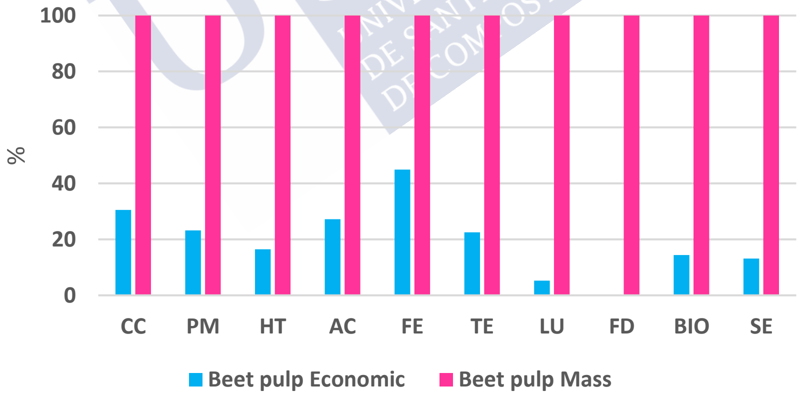

Figure A7 (c). Comparison mass and economic allocation for beet pulp. FU: 1 kg of fermentable sugars. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; FD – Fossil Depletion; BIO – Biodiversity; and SE – Soil Erosion.

Tables

Table A1. Type of field emissions considered, and methods used.

Field emissions	Method
Nitrous oxide (N_2O)	IPCC 2006, Tier 1(Nemecek et al., 2015)
Nitrogen dioxide (NOx)	Table 3-1. Tier 1 emission factors for NOx emissions (EEA, 2013)
Ammonia (NH_3)	Table 3-2. Tier 2 emission factors for total NH_3 emissions (EEA, 2013)
Pesticide emissions	(European Commission, 2017)
Nitrate (NO_3^-) leaching (groundwater)	EMPA (Faist-Emmenegger et al., 2009)
Phosphorus (P) leaching (groundwater)	EMPA (Faist-Emmenegger et al., 2009; Nemecek et al., 2015)
Phosphorus (P) runoff (surface water)	EMPA (Faist-Emmenegger et al., 2009; Nemecek et al., 2015)
Heavy metals emissions	(Durlinger et al., 2017)

Table A2. Environmental impacts for 1 kg of feedstock production. Economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; FD – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion.

Impact categories	**A1 Beet**	**A2 Beet**	**A3 Beet**	**A4 - Grain**	**A4 - Stover**	**A5 - Grain**	**A6 - Grain**	**A6 - Stover**	**A7 - Grain**	**A7 - Stover**	**A8 - Grain**	**A8 - Stover**
CC	0.155	0.091	0.114	0.581	0.251	0.608	0.547	0.158	0.186	0.057	0.187	0.054
PM	$2.25\cdot10^{-08}$	$4.96\cdot10^{-09}$	$6.01\cdot10^{-09}$	$3.63\cdot10^{-08}$	$1.57\cdot10^{-08}$	$3.65\cdot10^{-08}$	$3.13\cdot10^{-08}$	$9.10\cdot10^{-09}$	$9.67\cdot10^{-09}$	$2.99\cdot10^{-09}$	$6.81\cdot10^{-09}$	$1.9\cdot10^{-09}$
HT	$4.91\cdot10^{-09}$	$2.43\cdot10^{-09}$	$4.80\cdot10^{-09}$	$2.67\cdot10^{-08}$	$1.15\cdot10^{-08}$	$2.68\cdot10^{-08}$	$7.26\cdot10^{-08}$	$2.10\cdot10^{-08}$	$8.86\cdot10^{-09}$	$2.74\cdot10^{-09}$	$1.29\cdot10^{-08}$	$3.74\cdot10^{-09}$
AC	$1.16\cdot10^{-03}$	$5.16\cdot10^{-04}$	$1.49\cdot10^{-03}$	$8.17\cdot10^{-03}$	$3.54\cdot10^{-03}$	$8.47\cdot10^{-03}$	$4.33\cdot10^{-03}$	$1.26\cdot10^{-03}$	$1.23\cdot10^{-03}$	3.82E-04	$6.56\cdot10^{-03}$	$1.90\cdot10^{-03}$
FE	$3.20\cdot10^{-05}$	$1.24\cdot10^{-05}$	$1.78\cdot10^{-05}$	$9.8\cdot10^{-05}$	$4.24\cdot10^{-05}$	$1.02\cdot10^{-04}$	$1.63\cdot10^{-04}$	$4.72\cdot10^{-05}$	$2.80\cdot10^{-05}$	8.69E-06	$3.14\cdot10^{-05}$	$9.11\cdot10^{-06}$
TE	$2.92\cdot10^{-03}$	$2.38\cdot10^{-03}$	$4.79\cdot10^{-03}$	$3.11\cdot10^{-02}$	$1.35\cdot10^{-02}$	$3.19\cdot10^{-02}$	$6.91\cdot10^{-02}$	$2.00\cdot10^{-02}$	$1.39\cdot10^{-02}$	$4.30\cdot10^{-03}$	2.19E-02	$6.33\cdot10^{-03}$
LU	13.91	8.26	20.34	62.29	26.98	48.07	102	29.63	5.30	1.64	55.18	15.99
FD	1.63	0.948	1.13	5.31	2.30	5.43	5.75	1.6	1.97	0.609	1.56	0.454
BIO	690	462	492	2517	1090	1924	4899	1420	195	60.56	3272	948
SE	$6.70\cdot10^{-02}$	$9.10\cdot10^{-03}$	$5.69\cdot10^{-03}$	1.75	0.758	1.33	0.182	$5.29\cdot10^{-02}$	$7.29\cdot10^{-03}$	$2.26\cdot10^{-03}$	$8.63\cdot10^{-02}$	$2.50\cdot10^{-02}$

Table A3. Environmental impacts for 1 kg of feedstock production. Mass allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; FD – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion.

Impact categories	**A1 Beet**	**A2 Beet**	**A3 Beet**	**A4 - Grain**	**A4 - Stover**	**A5 - Grain**	**A6 - Grain**	**A6 - Stover**	**A7 - Grain**	**A7 - Stover**	**A8 - Grain**	**A8 - Stover**
CC	0.155	0.091	0.114	0.505	0.503	0.608	0.438	0.444	0.149	0.161	0.156	0.156
PM	$2.26\cdot10^{-08}$	$4.96\cdot10^{-09}$	$6.01\cdot10^{-09}$	$3.17\cdot10^{-08}$	$3.15\cdot10^{-08}$	$3.66\cdot10^{-08}$	$2.51\cdot10^{-08}$	$2.55\cdot10^{-08}$	$7.74\cdot10^{-09}$	$8.38\cdot10^{-09}$	$5.70\cdot10^{-09}$	$5.68\cdot10^{-09}$
HT	$4.92\cdot10^{-09}$	$2.44\cdot10^{-09}$	$4.88\cdot10^{-09}$	$2.33\cdot10^{-08}$	$2.32\cdot10^{-08}$	$2.69\cdot10^{-08}$	$5.81\cdot10^{-08}$	$5.89\cdot10^{-08}$	$7.09\cdot10^{-09}$	$7.68\cdot10^{-09}$	$1.08\cdot10^{-08}$	$1.08\cdot10^{-08}$
AC	$1.16\cdot10^{-03}$	$5.16\cdot10^{-04}$	$1.49\cdot10^{-03}$	$7.11\cdot10^{-03}$	$7.08\cdot10^{-03}$	$8.47\cdot10^{-03}$	$3.47\cdot10^{-03}$	$3.52\cdot10^{-03}$	$9.87\cdot10^{-04}$	$1.07\cdot10^{-03}$	$5.49\cdot10^{-03}$	$5.47\cdot10^{-03}$
FE	$3.21\cdot10^{-05}$	$1.25\cdot10^{-05}$	$1.79\cdot10^{-05}$	$8.53\cdot10^{-05}$	$8.49\cdot10^{-05}$	$1.02\cdot10^{-04}$	$1.30\cdot10^{-04}$	$1.32\cdot10^{-04}$	$2.25\cdot10^{-05}$	$2.43\cdot10^{-05}$	$2.63\cdot10^{-05}$	$2.62\cdot10^{-05}$
TE	$2.92\cdot10^{-03}$	$2.38\cdot10^{-03}$	$4.79\cdot10^{-03}$	$2.71\cdot10^{-02}$	$2.69\cdot10^{-02}$	$3.19\cdot10^{-02}$	$5.53\cdot10^{-02}$	$5.61\cdot10^{-02}$	$1.11\cdot10^{-02}$	$1.20\cdot10^{-02}$	$1.83\cdot10^{-02}$	$1.82\cdot10^{-02}$
LU	13.91	8.26	20.35	54.20	53.97	48.08	81.74	82.96	4.25	4.60	46.19	45.99
FD	1.64	0.95	1.14	4.62	4.60	5.44	4.61	4.67	1.58	1.71	1.31	1.31
BIO	690	462	492	2190	2180	1924	3919	3977	156	169	2738	2726
SE	$6.70\cdot10^{-02}$	$9.10\cdot10^{-03}$	$5.69\cdot10^{-03}$	1.52	1.52	1.34	0.145	0.148	$5.83\cdot10^{-03}$	$6.31\cdot10^{-03}$	$7.22\cdot10^{-02}$	$7.19\cdot10^{-02}$

Table A4. Environmental impacts of 1 kg of fermentable sugar from the different scenarios (economic allocation). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; FD – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion.

Impact category	**Sc1**	**Sc2**	**Sc3**	**Sc4**	**Sc5**	**Sc6**	**Sc7**	**Sc8**	**Sc9**	**Sc10**
CC	0.759	0.710	0.788	0.739	0.722	0.675	0.335	0.301	0.336	0.302
PM	$4.55\cdot10^{-08}$	$4.10\cdot10^{-08}$	$4.57\cdot10^{-08}$	$4.11\cdot10^{-08}$	$4.01\cdot10^{-08}$	$3.58\cdot10^{-08}$	$1.68\cdot10^{-08}$	$1.33\cdot10^{-08}$	$1.38\cdot10^{-08}$	$1.03\cdot10^{-08}$
HT	$2.95\cdot10^{-08}$	$2.83\cdot10^{-08}$	$2.97\cdot10^{-08}$	$2.84\cdot10^{-08}$	$7.88\cdot10^{-08}$	$7.58\cdot10^{-08}$	$1.04\cdot10^{-08}$	$9.73\cdot10^{-09}$	$1.47\cdot10^{-08}$	$1.39\cdot10^{-08}$
AC	$9.92\cdot10^{-03}$	$9.04\cdot10^{-03}$	$1.02\cdot10^{-02}$	$9.35\cdot10^{-03}$	$5.80\cdot10^{-03}$	$5.07\cdot10^{-03}$	$2.48\cdot10^{-03}$	$1.85\cdot10^{-03}$	$8.20\cdot10^{-03}$	$7.38\cdot10^{-03}$
FE	$1.34\cdot10^{-04}$	$1.19\cdot10^{-04}$	$1.38\cdot10^{-04}$	$1.22\cdot10^{-04}$	$2.04\cdot10^{-04}$	$1.86\cdot10^{-04}$	$5.94\cdot10^{-05}$	$4.61\cdot10^{-05}$	$6.30\cdot10^{-05}$	$4.96\cdot10^{-05}$
TE	$3.65\cdot10^{-02}$	$3.39\cdot10^{-02}$	$3.74\cdot10^{-02}$	$3.47\cdot10^{-02}$	$7.73\cdot10^{-02}$	$7.33\cdot10^{-02}$	$1.81\cdot10^{-02}$	$1.61\cdot10^{-02}$	$2.66\cdot10^{-02}$	$2.43\cdot10^{-02}$
LU	67.60	66.09	52.33	51.35	110	107	6.43	7.02	59.97	58.72
FD	7.84	7.21	7.98	7.34	8.32	7.67	4.26	3.74	3.83	3.33
BIO	2721	2619	2085	2005	5284	5091	236	216	3540	3406
SE	1.89	1.82	1.45	1.39	0.196	0.189	$8.82\cdot10^{-03}$	$8.06\cdot10^{-03}$	$9.34\cdot10^{-02}$	$8.98\cdot10^{-02}$

Table A4. (Cont.) Environmental impacts of 1 kg of fermentable sugar from the different scenarios (economic allocation). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; FD – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion.

Impact category	**Sc11**	**Sc12**	**Sc13**	**Sc14**	**Sc15**	**Sc16**	**Sc17**	**Sc18**	**Sc19**	**Sc20**
CC	0.893	0.700	0.490	0.482	0.328	0.343	0.330	0.309	0.309	0.321
PM	$5.12\cdot10^{-08}$	$3.74\cdot10^{-08}$	$2.47\cdot10^{-08}$	$2.25\cdot10^{-08}$	$2.29\cdot10^{-08}$	$2.5\cdot10^{-08}$	$1.7\cdot10^{-08}$	$1.55\cdot10^{-08}$	$1.55\cdot10^{-08}$	$1.61\cdot10^{-08}$
HT	$2.7\cdot10^{-08}$	$4.67\cdot10^{-08}$	$8.57\cdot10^{-09}$	$1.07\cdot10^{-08}$	$4.34\cdot10^{-09}$	$4.77\cdot10^{-09}$	$4.26\cdot10^{-09}$	$3.43\cdot10^{-09}$	$4.32\cdot10^{-09}$	$4.75\cdot10^{-09}$
AC	$9.77\cdot10^{-03}$	$5.03\cdot10^{-03}$	$3.21\cdot10^{-03}$	$6.37\cdot10^{-03}$	$2.20\cdot10^{-03}$	$2.29\cdot10^{-03}$	$2.10\cdot10^{-03}$	$1.95\cdot10^{-03}$	$2.35\cdot10^{-03}$	$2.47\cdot10^{-03}$
FE	$2.31\cdot10^{-04}$	$2.41\cdot10^{-04}$	$1.60\cdot10^{-04}$	$1.61\cdot10^{-04}$	$1.15\cdot10^{-04}$	$1.17\cdot10^{-04}$	$1.09\cdot10^{-04}$	$1.07\cdot10^{-04}$	$1.09\cdot10^{-04}$	$1.10\cdot10^{-04}$
TE	$3.28\cdot10^{-02}$	$4.65\cdot10^{-02}$	$1.37\cdot10^{-02}$	$1.80\cdot10^{-02}$	$4.87\cdot10^{-03}$	$5.13\cdot10^{-03}$	$5.61\cdot10^{-03}$	$4.85\cdot10^{-03}$	$5.72\cdot10^{-03}$	$6.16\cdot10^{-03}$
LU	51.90	57.40	-0.805	29.05	2.84	4.05	3.90	0.996	5.73	7.54
FD	11.04	9.73	7.53	7.20	5.09	5.24	5.03	4.89	4.87	5.00
BIO	2441	3186	357	2221	487	547	614	450	396	438
SE	1.69	0.118	$1.33\cdot10^{-02}$	0.154	$4.73\cdot10^{-02}$	$5.31\cdot10^{-02}$	$1.21\cdot10^{-02}$	$8.85\cdot10^{-03}$	$4.58\cdot10^{-03}$	$5.07\cdot10^{-03}$

Table A5. Environmental impacts of 1 kg of fermentable sugar from the different scenarios (mass allocation). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; FD – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion.

Impact category	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10
CC	0.689	0.640	0.801	0.748	0.615	0.569	0.300	0.266	0.308	0.273
PM	$4.11\cdot10^{-08}$	$3.65\cdot10^{-08}$	$4.64\cdot10^{-08}$	$4.17\cdot10^{-08}$	$3.39\cdot10^{-08}$	$2.96\cdot10^{-08}$	$1.5\cdot10^{-08}$	$1.14\cdot10^{-08}$	$1.28\cdot10^{-08}$	$9.27\cdot10^{-09}$
HT	$2.62\cdot10^{-08}$	$2.5\cdot10^{-08}$	$3.02\cdot10^{-08}$	$2.88\cdot10^{-08}$	$6.42\cdot10^{-08}$	$6.15\cdot10^{-08}$	$8.59\cdot10^{-09}$	$7.99\cdot10^{-09}$	$1.26\cdot10^{-08}$	$1.19\cdot10^{-08}$
AC	$8.92\cdot10^{-03}$	$8.04\cdot10^{-03}$	$1.04\cdot10^{-02}$	$9.47\cdot10^{-03}$	$4.95\cdot10^{-03}$	$4.22\cdot10^{-03}$	$2.25\cdot10^{-03}$	$1.62\cdot10^{-03}$	$7.17\cdot10^{-03}$	$6.35\cdot10^{-03}$
FE	$1.23\cdot10^{-04}$	$1.07\cdot10^{-04}$	$1.41\cdot10^{-04}$	$1.24\cdot10^{-04}$	$1.72\cdot10^{-04}$	$1.54\cdot10^{-04}$	$5.43\cdot10^{-05}$	$4.08\cdot10^{-05}$	$5.84\cdot10^{-05}$	$4.48\cdot10^{-05}$
TE	$3.27\cdot10^{-02}$	$3.01\cdot10^{-02}$	$3.80\cdot10^{-02}$	$3.52\cdot10^{-02}$	$6.35\cdot10^{-02}$	$5.97\cdot10^{-02}$	$1.53\cdot10^{-02}$	$1.34\cdot10^{-02}$	$2.32\cdot10^{-02}$	$2.09\cdot10^{-02}$
LU	59.88	58.44	53.20	52.01	89.92	87.35	5.38	5.99	51.14	50.03
FD	7.22	6.57	8.11	7.43	7.20	6.56	3.90	3.38	3.61	3.10
BIO	2409	2309	2120	2031	4302	4128	197	178	3016	2889
SE	1.67	1.60	1.47	1.41	0.160	0.153	$7.37\cdot10^{-03}$	$6.63\cdot10^{-03}$	$7.96\cdot10^{-02}$	$7.62\cdot10^{-02}$

Table A5. (Cont.) Environmental impacts of 1 kg of fermentable sugar from the different scenarios (mass allocation). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; FD – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion.

Impact category	**Sc11**	**Sc12**	**Sc13**	**Sc14**	**Sc15**	**Sc16**	**Sc17**	**Sc18**	**Sc19**	**Sc20**
CC	1.41	1.29	0.706	0.694	1.23	1.29	0.875	0.913	1.00	1.05
PM	$8.4\cdot10^{-08}$	$7.14\cdot10^{-08}$	$3.59\cdot10^{-08}$	$3.02\cdot10^{-08}$	$1.42\cdot10^{-07}$	$1.5\cdot10^{-07}$	$4.31\cdot10^{-08}$	$4.55\cdot10^{-08}$	$4.9\cdot10^{-08}$	$5.18\cdot10^{-08}$
HT	$5.1\cdot10^{-08}$	$1.25\cdot10^{-07}$	$1.88\cdot10^{-08}$	$2.53\cdot10^{-08}$	$3.03\cdot10^{-08}$	$3.17\cdot10^{-08}$	$1.64\cdot10^{-08}$	$1.69\cdot10^{-08}$	$3.01\cdot10^{-08}$	$3.15\cdot10^{-08}$
AC	$1.71\cdot10^{-02}$	$9.74\cdot10^{-03}$	$4.64\cdot10^{-03}$	$1.38\cdot10^{-02}$	$8.70\cdot10^{-03}$	$8.85\cdot10^{-03}$	$5.11\cdot10^{-03}$	$5.03\cdot10^{-03}$	$1.06\cdot10^{-02}$	$1.08\cdot10^{-02}$
FE	$3.19\cdot10^{-04}$	$4.17\cdot10^{-04}$	$1.93\cdot10^{-04}$	$1.97\cdot10^{-04}$	$3.12\cdot10^{-04}$	$3.12\cdot10^{-04}$	$2.02\cdot10^{-04}$	$1.96\cdot10^{-04}$	$2.33\cdot10^{-04}$	$2.28\cdot10^{-04}$
TE	$6.08\cdot10^{-02}$	0.121	$2.98\cdot10^{-02}$	$4.27\cdot10^{-02}$	$2.10\cdot10^{-02}$	$2.18\cdot10^{-02}$	$1.79\cdot10^{-02}$	$1.86\cdot10^{-02}$	$3.15\cdot10^{-02}$	$3.30\cdot10^{-02}$
LU	108	168	5.34	91.43	75.89	79.66	44.16	45.98	111	117
FD	15.83	15.98	9.81	8.98	15.59	16.14	11.73	12.04	12.79	13.17
BIO	4709	8505	584	5920	4094	4291	2851	2963	2979	3108
SE	3.27	0.316	$2.18\cdot10^{-02}$	0.410	0.397	0.416	$5.60\cdot10^{-02}$	$5.83\cdot10^{-02}$	$3.44\cdot10^{-02}$	$3.59\cdot10^{-02}$

Table A6. Comparison results with literature. FU: 1 kg of fermentable sugars. Acronyms: CC – Climate Change; FD – Fossil Depletion; AC – Acidification; on; TE – Terrestrial Eutrophication; Freshwater Eutrophication; and HT – Human Toxicity.

Source	Feedstocks	CC	FD	AC	TE	FE	HT
(Renouf et al., 2008)[a]	Maize	1	6	_	_	_	_
	Sugar beet	0.6	5.5	_	_	_	_
	Sugarcane	0.1	-7	_	_	_	_
(Thomas et al., 2012)[b]	Hardwood mill residuals	0.32	3.88	_	_	_	_
(Tsiropoulos et al., 2013)	Maize	0.7- 1.1	6.8- 9.3				
(Vercalsteren and Boonen, 2015)[c]	Mix of potato, maize and wheat	0.843	_	$1.15\cdot10^{-2}$	$4.82\cdot10^{-2}$	$3.00\cdot10^{-4}$	_
(Prasad et al., 2016)[b]	Maize stover	0.94	_	_	_	$2.60\cdot10^{-2}$	_
(Nwaneshiudu et al., 2016)[b]	Softwood harvest residues	0.353	_	0.112	_	_	$3.38\cdot10^{-9}$
(Vargas-Ramirez et al., 2017)[a]	Sugar beet	0.46	3.323	_	_	_	_
(Moncada et al., 2018)[c]	Spruce	0.18	2.29	_	_	_	_
	Maize	0.79	9.01	_	_	_	_
(Ortiz-reyes and Anex, 2019)[d]	Energy cane	0.436	2.78	_	_	_	_
	Sweet sorghum	0.517	2.6	_	_	_	_
	Sugarcane	0.448	2.56	_	_	_	_
	Maize	0.681	7.8	_	_	_	_
	Sugar beet	0.931	7.99	_	_	_	_
(Blanco et al., 2020)[e]	Maize starch	1.76	_	_	_	_	_
	Woody biomass residues	0.82	_	_	_	_	_
Chapter 6	Wheat	0.95	6.4	$8.92\cdot10^{-3}$	$3.40\cdot10^{-2}$	$2.28\cdot10^{-4}$	$7.35\cdot10^{-9}$

Source	Feedstocks	CC	FD	AC	TE	FE	HT
This study[d]	Maize grain	0.56	6.15	$6.93 \cdot 10^{-3}$	$3.78 \cdot 10^{-2}$	$1.12 \cdot 10^{-4}$	$3.19 \cdot 10^{-8}$
	Maize stover	0.64	8.87	$6.10 \cdot 10^{-3}$	$2.78 \cdot 10^{-2}$	$1.98 \cdot 10^{-4}$	$2.32 \cdot 10^{-8}$
	Sugar beet pulp	0.32	5.02	$2.23 \cdot 10^{-3}$	$5.39 \cdot 10^{-3}$	$1.11 \cdot 10^{-4}$	$4.31 \cdot 10^{-9}$

a – System expansion allocation; b – allocation no specified; c – mass allocation; d – economic allocation; e – no allocation

ANNEX B

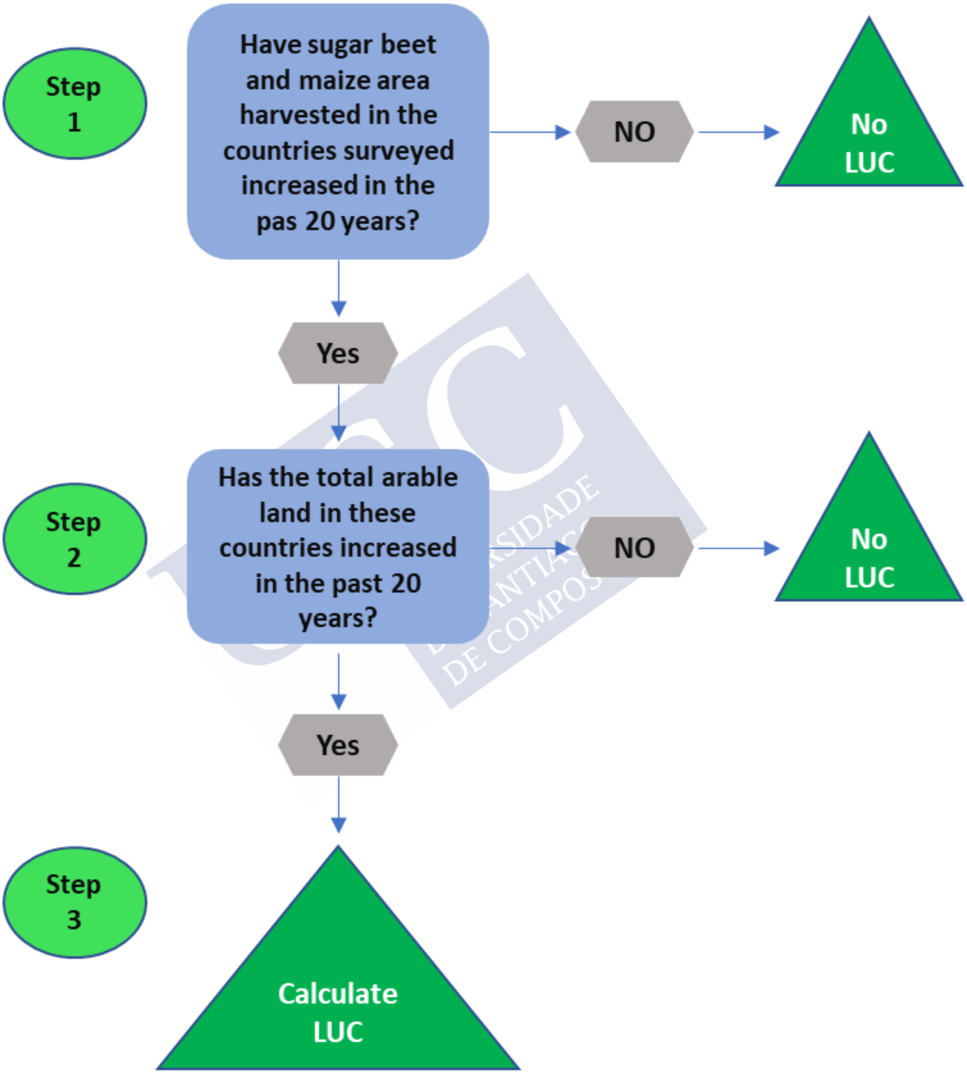

Figure B1. Decision tree to evaluate the occurrence of land use change (LUC). Adapted from: (Milà I Canals et al., 2013).

The harvested area[5] of sugar beet in the three countries France, Germany and the United Kingdom can be depicted in Figure B2. As observed, there has been a decrease in the harvested area of sugar beet in the last 20 years. Similarly, the area used for sugar beet has decreased in Europe and the world in 20 years (Figure B3). On the other hand, sugarcane, one of the main substitutes of sugar beet, in addition to having a considerably larger amount of harvested area, also shows a great increase in these areas in the last two decades.

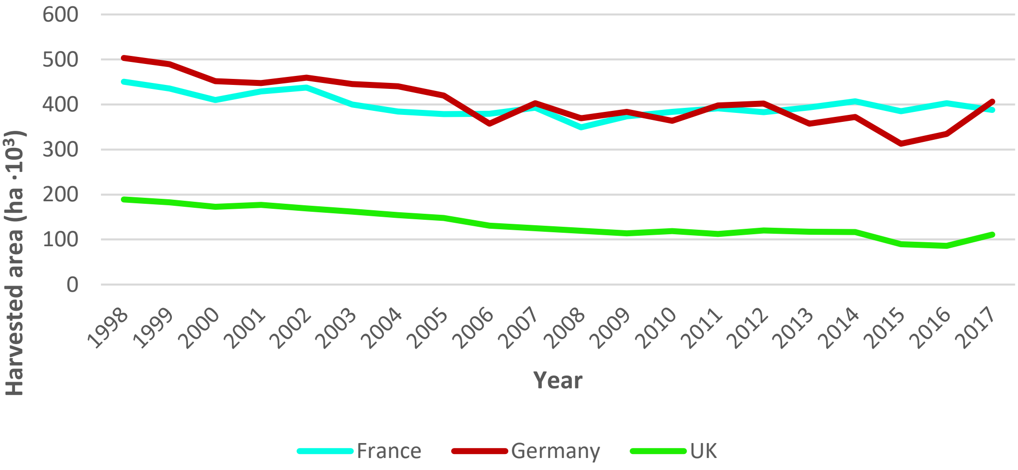

Figure B2. Harvested area (ha) of sugar beet crop in France, Germany and the United Kingdom (UK) over the last 20 years. Source: (FAOSTAT, 2019).

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[5] According to FAOSTAT, data for harvested area is: "*refer to the area from which a crop is gathered. Area harvested, therefore, excludes the area from which, although sown or planted, there was no harvest due to damage, failure, etc. If the crop under consideration is harvested more than once during the year as a consequence of successive cropping (i.e., the same crop is sown or planted more than once in the same field during the year), the area is counted as many times as harvested. On the contrary, area harvested will be recorded only once in the case of successive gathering of the crop during the year from the same standing crops.*" Retrieved from FAO: http://www.fao.org/waicent/faostat/agricult/pr_ele-e.htm

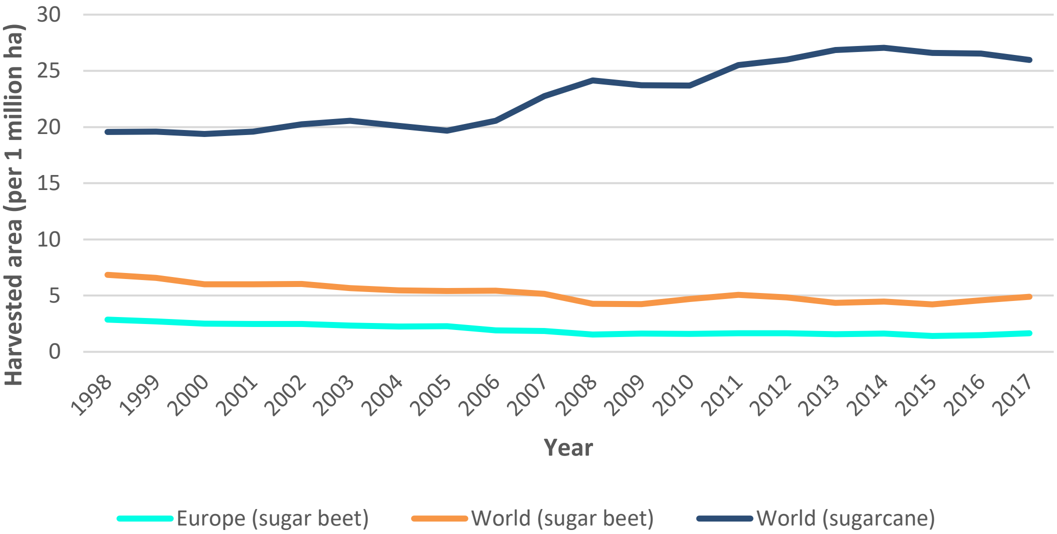

Figure B3. Harvested area (ha) of sugar beet crops in Europe and the world and area harvested (ha) for sugarcane in the world over the last 20 years. Source: (FAOSTAT, 2019).

The area used for maize production in the three countries Belgium, Italy and the United States (US) is depicted in Figure B4. As observed, the harvested area of Italy shows a slight drop, while areas in Belgium and the US have slightly increased. It is also clear that the harvested area of maize in the world is increasing but decreasing in Europe (Figure B5). The area used for harvesting wheat in the world has not shown significant changes in the last 20 years. Wheat is also an important starch crop to produce fermentable sugars. Although the area used for harvesting maize in Belgium and the US has slightly grown, the arable land[6] in those countries has decreased (Figure B6).

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[6] According to FAOSTAT, arable land is: "The total of areas under temporary crops, temporary meadows and pastures, and land with temporary fallow. Arable land does not include land that is potentially cultivable but is not

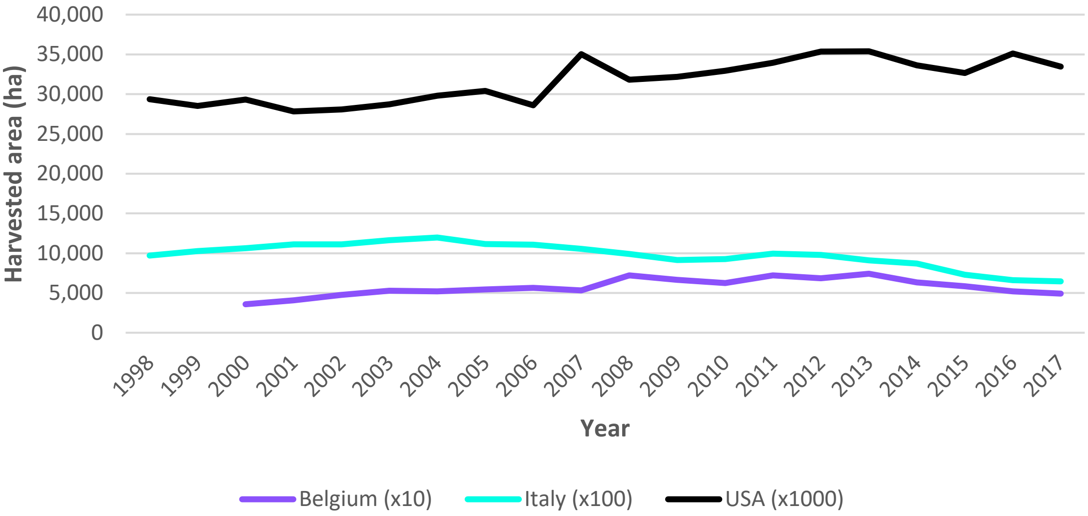

Figure B4. Harvested area (ha) of maize production in Belgium[a], Italy and United States (US) over the last 20 years. Source: (FAOSTAT, 2019).

[a] No data is available for Belgium for 1998 and 1999.

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normally cultivated." Retrieved from FAO: http://www.fao.org/faostat/en/#data/RL

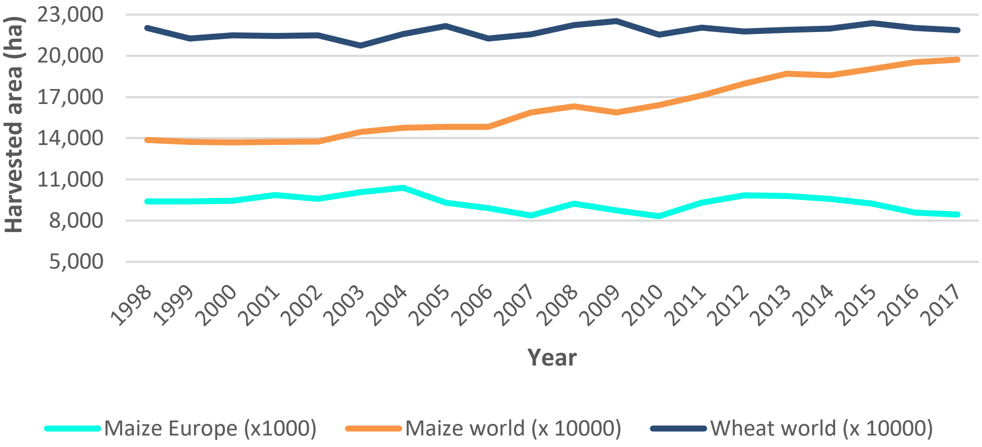

Figure B5. Harvested area (ha) of maize production in Europe and the world and area harvested (ha) for wheat in the world over the last 20 years. Source: (FAOSTAT, 2019).

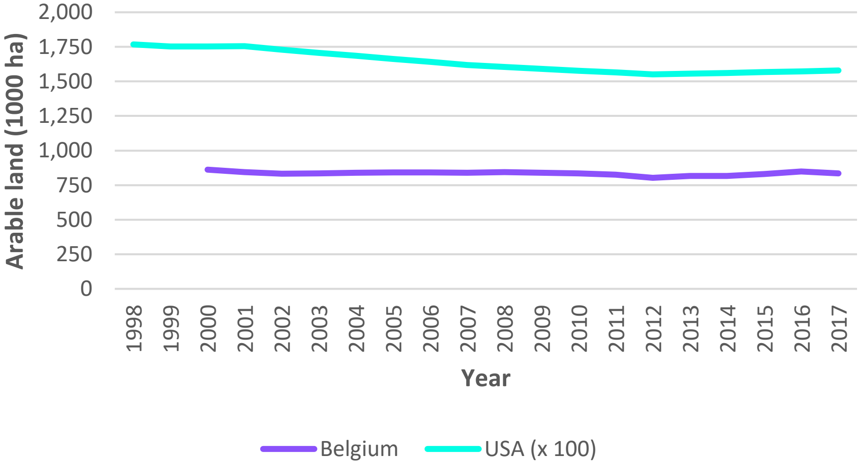

Figure B6. Area used for arable land (ha) in Belgium[a] and United States (US) over the last 20 years. Source: (FAOSTAT, 2019).

[a] No data is available for Belgium in the years 1998 and 1999.

CHAPTER 8: ENVIRONMENTAL ASSESSMENT OF BUTYRIC ACID PRODUCTION[7]

SUMMARY

Butyric acid is a valuable chemical that can be produced from oil or renewable feedstocks. However, due to technological advantages, it is currently synthesised at an industrial level by chemical synthesis. In view of the environmental concerns, attempts to produce butyric acid from renewable raw materials via microbial fermentation have been carried out. One possible route is the production of butyric acid from lignocellulosic feedstocks. This chapter aims to investigate the environmental profile of butyric acid production from wheat straw. The Life Cycle Assessment (LCA) methodology was applied considering two product formulations: butyric acid in combination with acetic acid (BA1) and butyric acid with high purity (BA2). The chosen functional units (FUs) considered are 1 kg of BA1 and BA2. A sensitivity analysis was performed by considering 100% renewable energy and using sugar beet pulp and maize stover as alternative lignocellulosic raw materials.

The figures show that, when it comes to identify the hotspots of the process, the production of steam, electricity, enzyme cellulase and

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[7] Chapter based on the publication:

Iana Câmara-Salim[a], Sara González-García[a], Gumersindo Feijoo[a], Maria Teresa Moreira[a]. Screening the environmental sustainability of microbial production of butyric acid produced from lignocellulosic waste streams, Industrial Crops and Products, Volume 162, 2021, 113280, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2021.113280.

[a] CRETUS Institute, Department of Chemical Engineering, School of Engineering, Universidade de Santiago de Compostela, Rúa Lope Gómez de Marzoa, s/n, 15782 Santiago de Compostela, Spain

wheat straw were the main processes with the highest environmental shares for both products, BA1 and BA2. The best environmental profile corresponded to BA1 due to the lower amount of energy and inputs required. The results of the sensitivity analysis reveal that the use of 100% renewable energy in the production process would significantly reduce the environmental burdens. On the other hand, the use of beet pulp or maize stover as alternatives to wheat straw did not significantly change the global environmental results. This chapter shows the importance of applying the LCA methodology to identify possible process improvement alternatives at an early stage of product development.

8.1 INTRODUCTION

The concept of biorefinery is based on the principle of avoiding the use of fossil fuels through the use of renewable biomass for the manufacture of products that are valuable to society, such as biofuels and biochemicals. Many recent studies have investigated different types of renewable raw materials for use in industrial fermentation processes. These raw materials range from first generation feedstocks (Renouf et al., 2008; Sheikha and Ray, 2017) to the use of lignocellulosic materials from agricultural and industrial waste (Bakker et al., 2013; Joanna et al., 2018; Liu et al., 2013). One of the pillars in the biorefinery scheme is developed through microbial fermentations so that the conversion of fermentable sugars into biological platform molecules takes place. In this context, butyric acid is a promising biochemical alternative.

Butyric acid, a 4-carbon chemical, is a specialized chemical with many applications in the chemical, food, pharmaceutical and cosmetic sectors. Currently, the main use of butyric acid is in the production of cellulose acetate butyrate plastics for the manufacture of textile fibers (Baroi et al., 2017). In the pharmaceutical industry, butyric acid is considered an important therapeutic agent for broad-spectrum treatments such as hemoglobinopathies and gastrointestinal disorders (Huang et al., 2011). In the food, beverage and cosmetics sectors, butyric acid esters can be used as a flavouring for food and beverages as well as fragrance and aroma for cosmetic products (Dwidar et al., 2012; Jiang et al., 2009).

Currently, butyric acid is produced via oxidation of butyraldehyde through petrochemical-based chemical synthesis. An approach to producing bio-based butyric acid by microbial fermentation has gained potential despite the cost and technological constraints (Dwidar et al., 2012; Luo et al., 2018). In the framework of industrial biotechnology process, a variety of different renewable raw materials have been investigated for butyric acid production, comprising sugars produced from food crops (Dwidar et al., 2013; Huang et al., 2016a; Wang et al., 2015), food waste (Stein et al., 2017; Vandák et al., 1995), algae (Lee et al., 2015; Ra et al., 2017), glycerol from the biodiesel industry (Varrone et al., 2017) and syngas (Park et al., 2017; Ueki et al., 2014).

Beyond the cost of production but also the controversy in the use of food crops for bio-based chemicals, the choice of raw material has a great influence on the sustainability of butyric acid production (Huang et al., 2011). Examples are sugarcane bagasse (Wei et al., 2013), switchgrass (Liu et al., 2013), oilseed rape straw (Huang et al., 2016b), rice straw (Liu et al., 2013), corn cob (Chen et al., 2017), corn husk (Xiao et al., 2018) and wheat straw (Baroi et al., 2017; Liu et al., 2013). However, several drawbacks have been reported such as the cost of the substrate in the case of non-residual biomass; the need of a previous enzymatic hydrolysis stage for lignocellulosic fractions (Jiang et al., 2018) and the formation of by-products, such as acetic acid, which requires downstream units for its separation and purification. In addition, although reaction stoichiometry predicts a maximum yield of 0.49 $g \cdot g^{-1}$ sugar, the yield of butyric acid remains in lower levels, which become a major technological limitation (Luo et al., 2018).

In this regard, wheat straw has been considered as a possible raw material to produce bioethanol (Talebnia et al., 2010; Wang et al., 2013), bioplastics (Nyambo et al., 2011; Yang et al., 2019), biochemicals (Chang et al., 2018); however, only a few have investigated the techno-economic feasibility of producing butyric acid from wheat straw, going beyond the information available at the experimental stage. While Xiao et al. (2018) and Baroi et al. (2017) simulated the economic aspect of butyric acid production using corn husks and wheat straw as feedstock, respectively, no studies have evaluated the environmental sustainability of bio-based butyric acid.

The objective of this chapter is to evaluate the environmental profile of the production of butyric acid from wheat straw through the evaluation of the life cycle assessment (LCA) methodology, so that it is possible to identify those aspects that may condition the environmental feasibility of the process and thus propose improvement actions at the early stage of development.

8.2 MATERIALS AND METHODS

8.2.1 System description

This chapter performs an LCA to evaluate the environmental profile of butyric acid, using wheat straw as feedstock. The LCA methodology follows the ISO 14040 and 14044 guidelines from a cradle-to-gate perspective, from wheat cultivation to butyric acid production at factory gate (ISO 14040, 2006; ISO 14044, 2006). The chosen functional unit (FU) is 1 kg of butyric acid production, considering two scenarios: 89% butyric acid purity in combination with acetic acid (BA1) and butyric acid with 99% purity (BA2) (Baroi et al., 2017).

It was assumed that crop cultivation takes place in Spain, and that the processing site is located very close to the farm. Therefore, the transportation of the raw material to the manufacturing facility was disregarded. Inventory data for agricultural activities was taken from Chapter 4 (Câmara-Salim et al., 2020) and processing activities from the work of Baroi et al. (2017). The system description is depicted in Figure 8.1.

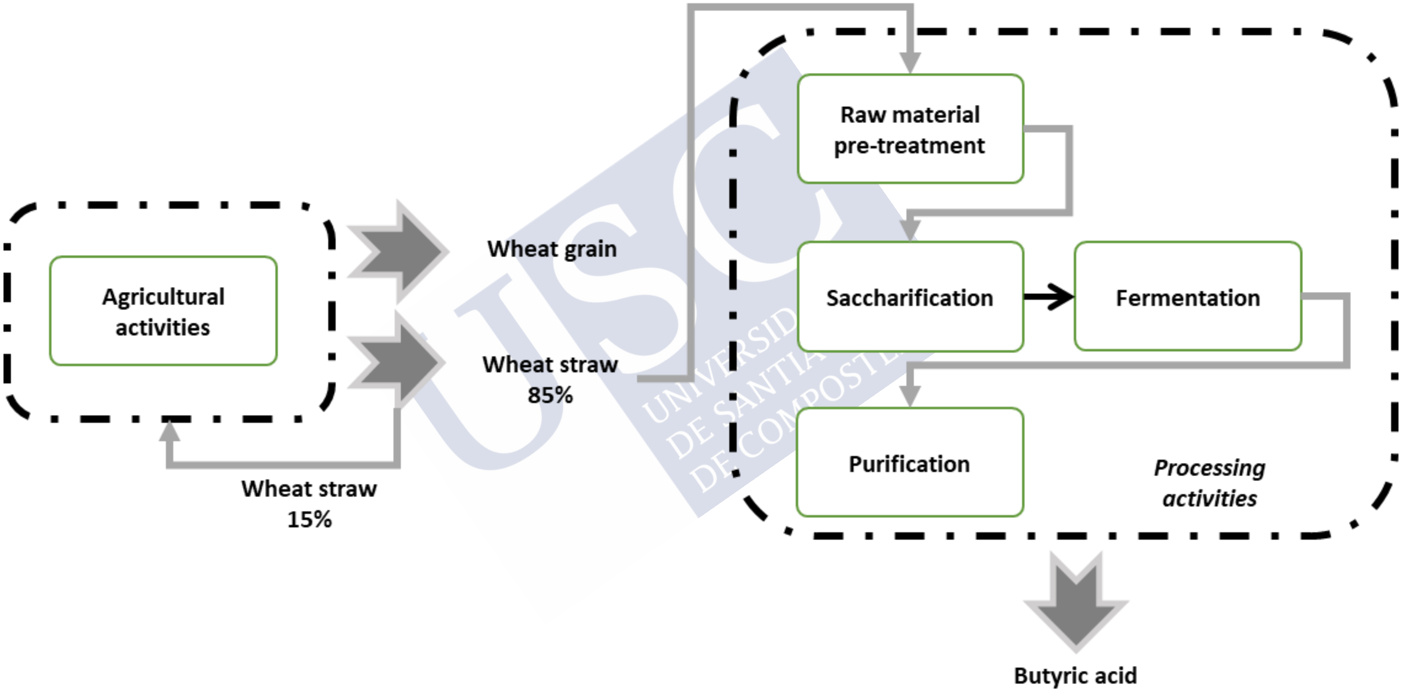

Figure 8.1. Process description of butyric acid production from wheat straw.

8.2.1.1 Agricultural activities

In this assessment, the wheat crop (*Triticum aestivum* L.) is cultivated in a rotation system with potatoes in an area of approximately 600 ha and more than 200 agricultural fields (Galicia, Spain). Cultivation begins in November with the preparation of the soil and is harvested the following year in August. The main agricultural inputs and outputs are summarized in Table 8.1. The yield of the wheat grain is about 5.5 $t \cdot ha^{-1}$ and 40% of wheat grain weight is straw, which is predominantly baled and marketed as a low-value product for animal feed. A minor fraction (ca. 15%) remains in the field as a soil conditioner. Accordingly, it was assumed that the 85% of the straw is harvested, baled and used to produce butyric acid.

Table 8.1. Inventory data for agricultural process - wheat straw cultivation (per hectare). Data from Chapter 4 (Câmara-Salim et al., 2020).

Key parameters for wheat straw production

Wheat grain yield	5.5 t·ha^{-1}
Wheat straw yield	2.2 t·ha^{-1}
Wheat grain price	0.18 €·ha^{-1}
Wheat straw price	0.07 €·ha^{-1}
Allocation factor grain	88.6%
Allocation factor straw	11.4%
Harvested wheat straw	85%
Straw moisture content	15%
Grain moisture content	12%
Nitrogen application, as N	86 kg·ha^{-1}
Phosphorus application, as P	60 kg·ha^{-1}
Potassium application, as K	60 kg·ha^{-1}
Pesticides application (active ingredient)	1.3 kg·ha^{-1}
Seed	200 kg·ha^{-1}
Diesel	70 L·ha^{-1}
Field emissions:	
N_2O	1.8 kg·ha^{-1}
NO_2	3.4 kg·ha^{-1}
NH_3	3.1 kg·ha^{-1}
NO_3^- leaching	75 kg·ha^{-1}
P-PO_4^{-3} leaching	0.07 kg·ha^{-1}
P-PO_4^{-3} runoff	0.23 kg·ha^{-1}

8.2.1.2 Processing activities

Taking into account the need to recover fermentable sugars from wheat straw, different pre-treatment stages such as acid and enzymatic hydrolysis (saccharification) are necessary prior to the fermentation process. The production of bio-based butyric acid also renders acetic acid as a by-product, which needs to be separated from the main flow. To obtain a higher concentration of the target product, the fermentation stage based on *Clostridium tyrobutyricum* performed in BA1 is modified by the co-cultivation with methanogens such as *Methanosarcina* sp and *Methanosaeta* can catabolize H_2-CO_2 and acetic acid into methane (Ciani et al., 2008) in BA2. Baroi et al. (2017) evaluated the economic costs of a butyric acid facility with an annual capacity of 10,000 tonnes for two product formulations: 1) butyric acid in combination with acetic acid and 2) a high purity butyric acid product. Below follows a summary of the production scheme for both production scenarios. The detailed description can be found in the work by Baroi et al. (2017).

Raw material pre-treatment. At the processing plant, wheat straw is washed and cut to tiny size with a grinder. The pre-treatment of the biomass through a wet explosion facilitates the enzymatic hydrolysis of the lignocellulosic raw material.

Saccharification. In addition, the pre-treated biomass goes through a saccharification stage. Sodium hydroxide is added just before the enzymatic hydrolysis process with the aim of increasing the slurry pH. The cellulose and hemicellulose fractions present in the wheat straw can be converted by enzymes to fermentable monomers for subsequent fermentation. In this case, the enzymatic complex (Cellic CTec2) consisting of a blend of cellulases, β-glucosidases and hemicellulases supplied by Novozymes was considered. After saccharification, the remaining solids (i.e., cake) are separated by a band filter. This stream can be recovered in energy due to its heating power. According to Baroi et al. (2017) approximately half of the total steam demand could be fulfilled by cogeneration. The liquid stream corresponds to fermentable sugars used as in the formulation of the culture medium in the fermentation stage.

Fermentation. The fermentative production process is based on the anaerobic culture of *C. tyrobutyricum*, which is distinguished by high selectivity and greater tolerance to butyric acid compared to other species of bacteria (Baroi et al., 2015). Its potential is also highlighted by its capacity to metabolize both glucose and xylose, two abundant sugar monomers present in pre-treated lignocellulosic biomass. The main difference between the two scenarios takes place in the fermentation stage: BA1 corresponds to microbial production by *C. tyrobutyricum* while BA2 performs the co-fermentation with methanogens, which will transform acetic acid into methane, giving a product of greater purity.

The formulation of the culture medium comprises wheat straw hydrolysate, potassium hydroxide, urea and dipotassium phosphate. Once the maximum yield of butyric acid is produced, the fermenter is coupled to a membrane system that will remove and recover organic acids (i.e., butyric and acetic acids) from the effluent. Lastly, the effluent from the fermentation tank is sent for wastewater treatment.

Purification. The organic acids from the fermentation phase are extracted with the 1-octanol solvent, which is less volatile than butyric and acetic acids. Therefore, octanol will remain at the bottom, while the organic acids will be collected at the top of the distillation unit. The octanol is then recycled back into the purification process. This process delivers the main products: butyric acid BA1 or BA2.

8.2.2 Inventory data

Inventory data (Table 8.1) of wheat straw was collected through in situ interviews, gathered from Chapter 4 (Câmara-Salim et al., 2020). In this LCA, the economic allocation was performed with the aim of distributing the environmental burdens of wheat grain and straw. For the processing unit, the inventory data (Table 8.2) were collected from Baroi et al. (2017), in which the economic evaluation of two formulations of butyric acid was reported.

Table 8.2. Inventory data for Butyric acid production (Baroi et al., 2017).

		BA1	**BA2**	**Unit**
Material inputs	Wheat straw	46,150	51,611	t
	Sulfuric acid	857	857	t
	Sodium hydroxide NaOH	629	719	t
	Enzyme	700	805	t
	Potassium hydroxide KOH	10.58	10.58	t
	Urea	1078	1232	t
	Dipotassium phosphate K_2HPO_4	157	168	t
	1-Octanol solvent	23.52	29.41	t
Utilities	Process water	344,827	394,088	t
	Power Electricity	34,831	38,960	MWh
	Steam	92,227	122,747	t
	Cooling water	12.85	16.15	Mt
Output	**Butyric acid Product**	**10,000**	**10,000**	**t**
Waste disposal	Ash	1,818	1,818	t
	Wastewater	325,000	370,000	m^3

Table 8.3 provides information on the processes considered in the Ecoinvent® database v3.6 for the production of butyric acid (secondary data for background processes). Inventory data for the production of cellulase required in the enzymatic hydrolysis was gathered from the available literature (Gilpin and Andrae, 2017)

Table 8.3. Processes considered in the Ecoinvent® database v3.6 for butyric acid production.

Process name	**Unit**
Sulfuric acid {RER}|market for sulfuric acid| Cut-off, U	t
Sodium hydroxide, without water, in 50% solution state {GLO}| Cut-off, U	t
Potassium hydroxide {GLO} | Cut-off, U	t
Chemical, inorganic {GLO}| market for chemicals, inorganic | Cut-off, U[a]	t
Sodium hydroxide, without water, in 50% solution state {GLO}| Cut-off, U	t
Fatty alcohol {GLO}| Cut-off, U[b]	t
Water, cooling, unspecified natural origin/kg	t
Water, process, unspecified natural origin/kg	t
Electricity, medium voltage {RER}| market group for | Cut-off, U	MWh
Steam, in chemical industry {GLO}| Cut-off, U	MJ
Disposal, inert material, 0% water, to sanitary landfill/CH U[c]	t
Wastewater, average {Europe without Switzerland} | Cut-off, S	t

[a] Due to lack of data, urea was substituted by a general Chemical, inorganic process
[b] Due to lack of data, 1-Octanol solvent was substituted for a general Fatty alcohol process
[c] Process considered for the disposal of ash

8.2.3 Life cycle impact assessment

This work considered the characterization factors of the Recipe 1.12 hierarchist method (Goedkoop et al., 2009) at midpoint level to evaluate the environmental impacts. The software used is SimaPro 9.1 and the selected environmental indicators are Climate Change - CC (CO_2 eq); Particulate Matter – PM (kg PM2.5 eq); Freshwater Eutrophication – FE (kg P eq); Marine Eutrophication – ME (kg N eq); Human carcinogenic Toxicity – HT (kg 1,4-DCB); Land Use – LU (m^2a crop eq); and Fossil Depletion – FD (kg oil eq).

8.2.4 Sensitivity analysis

A sensitivity analysis was conducted to assess how changes in production processes can affect environmental outcomes. Two assumptions were made: 1) Changes in electricity mix and 2) Changes in the feedstock. This sensitivity analysis was performed for Scenario BA1, as there are no notable differences in the distribution of impacts between the processes involved in the two scenarios.

8.2.4.1 Changes in the electricity mix

The results of this study showed that the production and use of steam, electricity and enzyme are the main contributors to the global environmental impacts of butyric acid production. An average electricity profile for Europe was selected, where approximately 50% of the electricity generated in Europe comes from fossil fuels (EUROSTAT, 2020). Therefore, with the aim of reducing the environmental impacts associated with the variation of the parameters, a change in inputs was performed considering electricity generated from renewable energy. In 2018, the share of renewable energy in Europe was about 19%, with wind energy being a very important renewable energy source (with a 36% share), followed by hydropower (33%), solar energy (12%), solid biofuels (10%) and others (9%), this latter including gaseous and liquid biofuels, energy from municipal waste and geothermal energy (Eurostat, 2020).

The use of renewable energy sources must grow in Europe, as it must comply with the Renewable Energy Directive (RED II) to have at least 32% of its electricity coming from renewable energy by 2030 (European parlament and of the Council, 2018). For the base case scenario, the electricity considered is an average of the electricity mix in Europe (see Table 8.3). The inventory, which was taken from the Ecoinvent® V3.6 database, considers the different types of electricity used in Europe, such as nuclear, hydro, natural gas, lignite, etc. For the sensitivity analysis, only renewable energy sources were considered. The type of electricity was modified in the production of butyric acid. The Ecoinvent® v3.6 database was used for the inventory of renewable energy production. Only the three most important renewable energy sources in Europe were considered, and the amount of energy used in the production of butyric acid was divided into 45% wind (onshore farms), 40% hydro and 15% solar. In addition, as the energy used in the production of enzymes and steam is high, it was assumed that these inputs were also produced with the same share of renewable energy as butyric acid.

8.2.4.2 Changes in the feedstock type

Since wheat straw is also largely responsible for the global environmental burdens of butyric acid production (see Figure 8.2), two lignocellulosic alternative feedstocks were considered. Sugar beet pulp is a by-product of sugar production (i.e., sucrose) and is currently mainly used for animal feed or disposed of as landfill waste. However, its high hemicellulosic and low lignin content make it a good candidate for its valorisation in biorefineries (Kühnel et al., 2011). On the other hand, maize stover, which is a component of the maize plant, comprises the stalks, cob and leaves. On average, the production of one kg of grain also results in 1 kg of straw. Stover is usually left in the field as soil amendment or partially removed for animal feed (Prasad et al., 2016).

It was assumed that 30% of the stover was removed and baled for the production of butyric acid, as it is an acceptable removal rate without compromising soil quality (Khanna and Paulson, 2016). Considering the partial removal of stover, an additional application of fertilisers is required to offset nutrient deficit in the soil. That is, an additional 7.5

kg of nitrogen, 2.5 kg of phosphorus and 8 kg of potassium per kg of stover removal (David, 2013). As shown in Table 8.4, on average, wheat straw contains more cellulose than beet pulp. However, the hemicellulose content does not differ much. On the other hand, maize stover has cellulose and hemicellulose fractions similar to those of wheat straw. Considering that lignin does not render fermentable sugars, only cellulose and hemicellulose sugars are substrates in the butyric acid production process.

The Ecoinvent® v3.6 database was used for the inventory of beet pulp production and data from maize agricultural production was retrieved from (Renouf et al., 2008). Assuming that beet pulp is composed on average of 25% cellulose and 27% hemicellulose and the glucose yield of cellulose is 85% and the xylose yield of hemicellulose is 60% (Baroi et al., 2017), an input of 60,000 t of beet pulp was considered. Regarding maize stover, as both raw materials differ slightly in terms of cellulose and hemicellulose content, an equivalent amount of raw material as wheat straw was taken into consideration (46,150 t of maize stover) (See Table 8.2). For a complete overview of the processes and materials involved in the production of maize stover and beet pulp, see Chapter 5.

Table 8.4. Components of sugar beet pulp, wheat straw and maize stover (as dry matter).

Beet pulp	(Martínez et al., 2018)	(Hafez et al., 2014)	(Tomaszewska et al., 2018)	(Cao et al., 2013)
Cellulose	20-25%	32.75%	22–24%	20-24%
Hemicellulose	22-30%	20.06%	30%	25-36%
Lignin	1-3%	1.93%	5.9%	1-6%

Wheat straw	(Rowell, 1992)	(Mullen et al., 2015)	(Swain et al., 2019)	Baroi et al. (2017)
Cellulose	29-35	28-39%	33-40%	39.7%
Hemicellulose	26-32	23-24%	20-25%	23.9%
Lignin	16-21	16-25%	15-20%	20.5%

Maize Stover	Yang et al. (2016)	Prasad et al. (2016)	Emerson et al. (2014)	Aboagye et al. (2017)
Cellulose	36.5	38%	35.5%	35.5%
Hemicellulose	22.1	26%	20.3%	28%
Lignin	18.8	19%	15.1%	16.56

8.3 RESULTS AND DISCUSSION

8.3.1 Environmental analysis

Table 8.5 depicts the environmental results for butyric acid production for Scenarios BA1 and BA2. It is not surprising that the environmental impacts for BA2 are greater than for BA1, due to the higher energy and material inputs. However, BA2 produces high purity butyric acid. It is important to note that, although the environmental profile of BA1 is better than that of BA2, the high purity of butyric acid in BA2 may lead greater economic benefits in this scenario, as this product has a higher economic value.

Table 8.5. Environmental results for butyric acid production in Scenarios BA1 and BA2.

Impact category	Unit	Total (BA1)	Total (BA2)
Climate change	kg CO_2 eq	6.89	8.23
Particulate matter	g PM2.5 eq	8.53	10
Freshwater eutrophication	g P eq	2.63	3.00
Marine eutrophication	g N eq	3.04	3.44
Human carcinogenic toxicity	kg 1,4-DCB	0.155	0.177
Land use	m^2a crop eq	3.20	3.59
Fossil resource scarcity	kg oil eq	1.81	2.18

Figures 8.2(a) and (b) show the comparative profile of the processes for each impact category in BA1 and BA2, respectively. As can be seen, there is a very slight difference in the comparative profile of BA1 and BA2. As shown in Table 8.2, both require similar types of materials and energy, only to a greater extent for BA2. Overall, for both scenarios, the processes of steam production, electricity, enzyme cellulase and wheat straw cause most of the environmental impacts of butyric acid production. Steam is a major factor to CC, PM and FD; while electricity to FE and HT; and wheat straw to ME and LU. The processes with the least environmental impact are those related to the formulation of the culture medium: sodium hydroxide, sulfuric acid, potassium hydroxide, urea, potassium phosphate as well as the extraction solvent: 1-octanol and management of waste and wastewater. This is due to the low quantity and/or the low energy used, in comparison with the other processes. Due to the similarity of BA1 and BA2, the environmental profile by impact category will be examined further in more detail only for BA1.

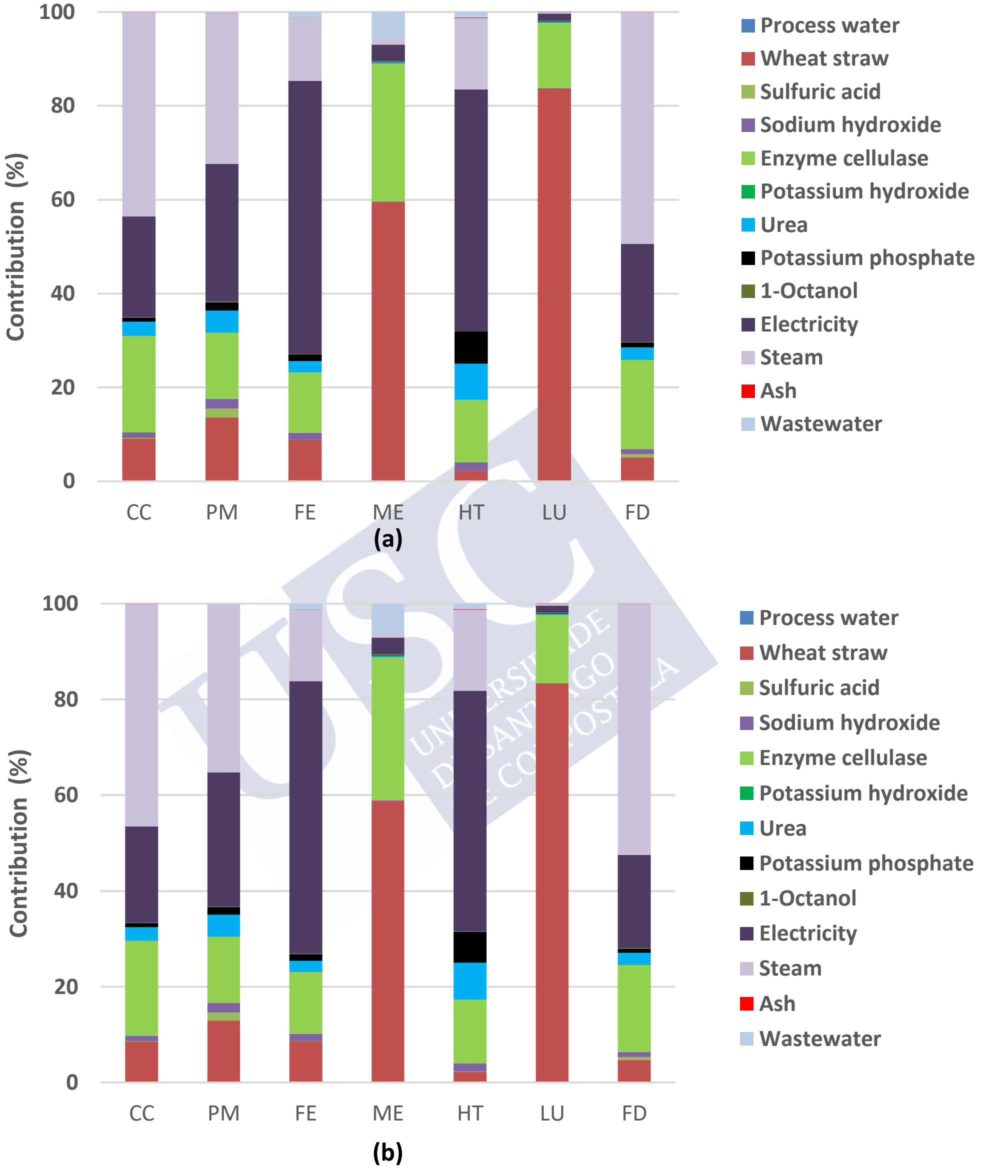

Figure 8.2. Environmental profile of Butyric acid production in a) Scenario BA1 and b) Scenario BA2. Acronym: CC-Climate Change; PM-Particulate Matter; FE – Freshwater Eutrophication; ME – Marine Eutrophication; HT- Human Toxicity; LU – Land Use; and FD – Fossil Depletion.

8.3.1.1 Climate Change

The release of greenhouse gas (GHG) emissions into air, such as carbon dioxide (CO_2), dinitrogen monoxide (N_2O) and methane (CH_4) have a major influence on global warming and climate change. In relation to the CC indicator, steam and electricity are responsible for approximately 65% of the total environmental impacts. Enzyme production contributes 20%, and wheat straw has a less significant share of about 9%. This is mainly due to the GHG emissions caused by energy consumption and dependency on fossil sources (Gilpin and Andrae, 2017). In the case of wheat straw cultivation, emissions are mainly due to the background processes in nitrogen fertiliser production and to the emissions of dinitrogen monoxide (N_2O) from the application of fertilisers. Emissions of CO_2, N_2O and CH_4 account for 81%, 7% and 4% of the CC impact category. CH_4 emissions occur primarily in enzyme and steam production due to the background processes of electricity and heat production.

8.3.1.2 Particulate matter

Particulate matter (PM) is a mixture of small solid and/or liquid particles in the air (for example, dirt, sand) that can seriously damage health (EPA, 2018). Sulphur dioxide (SO_2), $PM_{2.5}$ particles, nitrogen oxides (NOx) and ammonia (NH_3) are examples of substances which favour PM formation. In this study, the production of steam (32%) and electricity (29%) are the main responsible for PM formation, while the enzyme and wheat straw account for 14% and 13%, respectively. SO_2 release contributes to 52% of the total PM released into the air. In addition, $PM_{2.5}$ particles and NOx are responsible for 23% and 13% of PM impacts.

8.3.1.3 Freshwater and marine eutrophication

Freshwater (FE) and marine (ME) eutrophication occurs when large amounts of nutrients cause an increase in plants and algae, thereby reducing oxygen levels in the water and damaging the aquatic ecosystem. For the FE impact category, 58%, 13% and 12% of the impacts are caused by electricity, enzyme, and steam production, respectively. About 95% of the impacts come from phosphate in water. As for ME, 59% comes from wheat straw cultivation (mainly because of fertilisation activities) and 29% from enzyme production. About 96% of the impacts are from the discharge of nitrate into waterbodies.

8.3.1.4 Human carcinogenic toxicity

Human carcinogenic toxicity (HT) in the ReCiPe methodology is expressed as kg of 1,4-dichlorobenzene equivalents (1,4DCB-eq) and is an indicator of the health effects caused by exposure to carcinogens. In this work, electricity production is a key impacting process to HT indicator (51%), followed by steam (15%) and enzyme (13%). In this study, chromium VI into water contributes to 95% of the impacts, mainly due to electricity production from fossil resources.

8.3.1.5 Land use

Land use (LU), which is expressed in terms of land occupation (m^2) per year of an equivalent annual crop (m^2a crop eq). Not surprisingly, the high impact of LU (83%) is due to wheat straw, as agricultural activities require greater land occupation. Enzyme production is also indirectly responsible for LU (14%), as it uses corn starch in its production process.

8.3.1.6 Fossil fuel depletion

Fossil resource depletion is measured in ReCiPe by taking into account kg of crude oil equivalent. The use of natural gas is responsible for 50% of the total FD impacts, followed by hard coal (38%) and crude oil (38%). Steam (44%), electricity (20%) and enzyme (19%) processes are the main contributors to FD.

8.3.2 Sensitivity analysis

Figure 8.3 shows the results of the sensitivity analysis taking into account the BA1 base case scenario, the change in the type of electricity generation (Sensitivity analysis 1) and the change in both electricity and type of raw material (Sensitivity analysis 2 and 3). As observed, there is a significant decrease in environmental impacts when changing the base case scenario to renewable energy (Sensitivity Analysis 1), except for LU and ME. This is because LU and ME are more related to the cultivation stage (the wheat straw).

Compared with the results of sensitivity analysis 1, when sugar beet pulp was substituted for wheat straw (sensitivity analysis 2), the results show an increase in PM and a decrease in LU, but do not show significant changes in the other impact categories. The change of raw material from wheat straw to maize stover (Sensitivity Analysis 3) also shows a slight change in the environmental impact results. However, there is a large reduction in the impact categories ME and LU.

In general, it can be concluded that the use of beet pulp and especially maize stover would greatly reduce the impacts of LU. It is important to consider that although more raw material is needed for beet pulp due to its low cellulose content, the sugar beet crop is known for its very high yield. The maize farming in this scenario has a much higher yield than wheat cultivation in Galicia, that is, 9.1 kg of maize grain per hectare, compared to 5.5 kg of wheat grain. Agricultural management in maize cultivation is also releasing much less nitrogen to water bodies, considerably reducing the ME indicator. Overall, the results show that the type of energy used has a significant influence on the environmental performance of butyric acid production, but a slight variation when changing the feedstocks, apart from ME and especially LU impact categories.

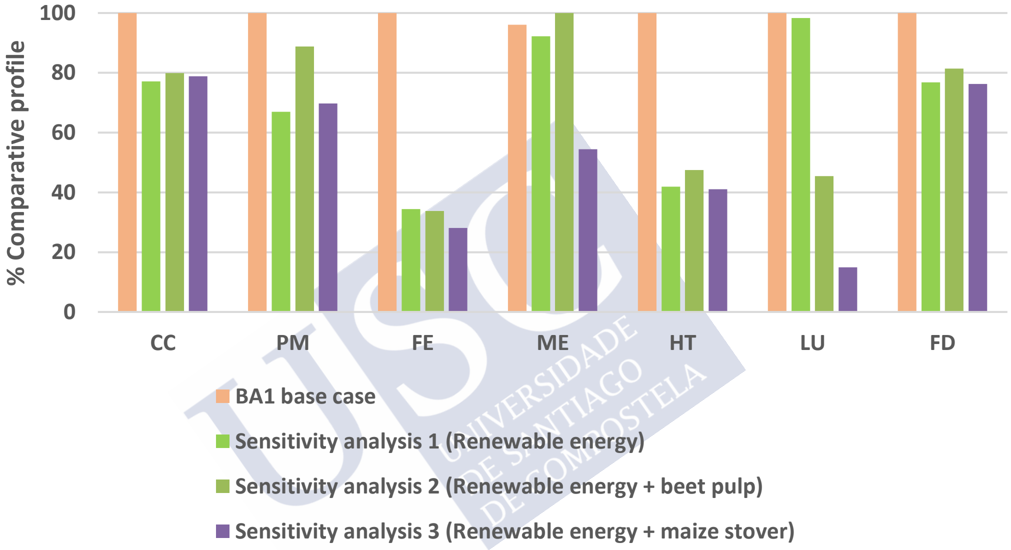

Figure 8.3. Sensitivity analysis: comparative profile of 1) butyric acid production in BA1 (base case); 2) butyric acid production with 100% renewable energies (Sensitivity analysis 1); 3) butyric acid production with 100% renewable energy and sugar beet pulp as raw material and (Sensitivity analysis 2) 4) butyric acid production with 100% renewable energy and maize stover as raw material (Sensitivity analysis 3). Acronym: CC – Climate Change; PM – Particulate Matter; FE – Freshwater Eutrophication; ME – Marine Eutrophication; HT – Human Toxicity; LU – Land Use; and FD – Fossil Depletion.

8.3.3 Limitation of the study and future prospects

This chapter was based on the experimental analysis carried out by Baroi et al. (2017) on the production of butyric acid via microbial fermentation. The previous sections analysed the environmental results of BA1 and BA2 products, taking into account some improvement scenarios carried out in the sensitivity analysis. One limitation of this present work is that there is no other LCA study of butyric acid production either via a chemical and bio-based pathway. This hinders the possibility to compare the results of this present study with others. In addition, the energy data found is provided as a "black box". Therefore, it is not possible to accurately analyse the environmental impacts by process, but rather as the system as a whole. In this context, there is room for future environmental research on the production of butyric acid either to compare it with other types of production processes and to improve inventory data.

Future research should also evaluate other types of biomass, as there are a multitude of renewable raw materials that can be used in industrial fermentation processes. Moreover, previous research has evaluated the economic feature of butyric acid production via microbial fermentation (Baroi et al, 2017). Therefore, a social analysis is recommended to assess the whole sustainability aspect of butyric acid production.

8.4 CONCLUSIONS

The main drivers of the adoption of biorefinery technologies will come from the reduction in the use of non-renewable fossil resources while adding value and exploiting the potential chemical value of biomass waste. Butyric acid is an important chemical that has many applications in the chemical, food, cosmetic and pharmaceutical industries. Due to its economic and technological advantages, butyric acid is produced mainly from a fossil source. The environmental concern increased the interest in producing butyric acid through a fermentation route. One possible way is to use lignocellulosic raw material as a carbon source.

With the aim to evaluate the environmental burdens of butyric acid production via microbial fermentation, the LCA methodology was applied. The environmental outcomes show an impact of approximately 6.9 kg and 8.2 kg CO_2 eq (CC), as well as 1.8 kg and 2.18 kg of oil eq (FD), for 1 kg of BA1 and BA2 production, respectively. The results also depict that steam, followed by electricity, enzyme and, at a lower level, wheat straw, are the most impactful processes for both scenarios. The sensitivity analysis also reveals that the change in the type of electricity has a considerable influence on the results. Future research is needed to compare this LCA study with the chemical butyric acid production processes. Also, there are plenty of room to use different types of renewable feedstocks to produce bio-based butyric acid. As the economic profile of butyric acid via a fermentation route was previously analysed, it would be interesting to include the social implications of the biotechnological production of butyric acid to have the whole butyric acid sustainability picture.

REFERENCES

Aboagye, D., Banadda, N., Kambugu, R., Seay, J., Kiggundu, N., Zziwa, A., Kabenge, I., 2017. Glucose recovery from different corn stover fractions using dilute acid and alkaline pretreatment techniques. J. Ecol. Environ. 41, 1–11. https://doi.org/10.1186/s41610-017-0044-1

Bakker, R., Elbersen, W., Poppens, R., Lesschen, J.P., 2013. Rice straw and Wheat straw. Potential feedstocks for the Biobased Economy. Wageningen.

Baroi, G.N., Baumann, I., Westermann, P., Gavala, H.N., 2015. Butyric acid fermentation from pretreated and hydrolysed wheat straw by an adapted Clostridium tyrobutyricum strain. Microb. Biotechnol. 8, 874–882. https://doi.org/10.1111/1751-7915.12304

Baroi, G.N., Gavala, H.N., Westermann, P., Skiadas, I. V., 2017. Fermentative production of butyric acid from wheat straw: Economic evaluation. Ind. Crops Prod. 104, 68–80. https://doi.org/10.1016/ j.indcrop.2017.04.008

Câmara-Salim, I., Almeida-García, F., Feijoo, G., Teresa Moreira, M., González-García, S., 2020. Life cycle assessment of a potato-wheat cropping system in the region of Galicia, Spain (Under review). Environ. Manage.

Cao, X., Ro, K.S., Libra, J.A., Kammann, C.I., Lima, I., Berge, N., Li, L., Li, Y., Chen, N., Yang, J., Deng, B., Mao, J., 2013. Effects of Biomass Types and Carbonization Conditions on the Chemical Characteristics of Hydrochars. J. Agric. Food Chem. 61, 9401–9411.

Chang, C., Deng, L., Xu, G., 2018. Efficient conversion of wheat straw into methyl levulinate catalyzed by cheap metal sulfate in a biorefinery concept. Ind. Crop. Prod. 117, 197–204. https://doi.org/10.1016/j.indcrop.2018.03.009

Chen, T., Zhang, L., Luo, G., Yuan, W., 2017. Butyric acid production by Clostridium tyrobutyricum in sugar mixtures and corncob hydrolysate containing arabinose. BioResources 12, 7931–7942. https://doi.org/10.15376/ biores.12.4.7931-7942

Ciani, M., Comitini, F., Mannazzu, I., 2008. Fermentation, Encyclopedia of Ecology.

David, E., 2013. Sustainable Corn Stover Harvest. Iowa.

Dwidar, M., Kim, S., Jeon, B.S., Um, Y., Mitchell, R.J., Sang, B.I., 2013. Co-culturing a novel Bacillus strain with Clostridium tyrobutyricum ATCC 25755 to produce butyric acid from sucrose. Biotechnol. Biofuels 6, 1–10. https://doi.org/10.1186/1754-6834-6-35

Dwidar, M., Park, J.Y., Mitchell, R.J., Sang, B.I., 2012. The future of butyric acid in industry. Sci. World J. 2012, 9. https://doi.org/10.1100/2012/471417

Emerson, R., Hoover, A., Ray, A., Lacey, J., Cortez, M., Payne, C., Karlen, D., Birrell, S., Laird, D., Kallenbach, R., Egenolf, J., Sousek, M., Voigt, T., 2014. Drought effects on composition and yield for corn stover , mixed grasses , and Miscanthus as bioenergy feedstocks. Biofuels 5, 275–291. https://doi.org/10.1080/ 17597269.2014.913904

EPA, 2018. Particulate Matter (PM) Basics [WWW Document]. URL https://www.epa.gov/pm-pollution/particulate-matter-pm-basics (accessed 8.5.20).

European parlament and of the Council, 2018. DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast).

Eurostat, 2020. Wind and water provide most renewable electricity [WWW Document]. URL https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20200129-1 (accessed 8.10.20).

EUROSTAT, 2020. Electricity production, consumption and market overview [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview#Electricity_generation (accessed 8.17.20).

Gilpin, G.S., Andrae, A.S.G., 2017. Comparative attributional life cycle assessment of European cellulase enzyme production for use in second-generation lignocellulosic bioethanol production. Int. J. Life Cycle Assess. 22, 1034–1053. https://doi.org/10.1007/s11367-016-1208-4

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., Zelm, R. Van, 2009. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. https://doi.org/10.029/2003JD004283

Hafez, H.N., El-Gharabli, M.S., Mohamed, M.H., Beshet, S.Y., Sasy, A.H., 2014. Evaluation of activated carbons produced from by-products sugar crops grown in Egypt : I . Chemical composition of starting materials. Ann. Agric. Sci. 52, 1–9.

Huang, J., Cai, J., Wang, J., Zhu, X., Huang, L., Yang, S.T., Xu, Z., 2011. Efficient production of butyric acid from Jerusalem artichoke by immobilized Clostridium tyrobutyricum in a fibrous-bed bioreactor. Bioresour. Technol. 102, 3923–3926. https://doi.org/10.1016/ j.biortech.2010.11.112

Huang, J., Dai, H., Yan, R., Wang, P., 2016a. Enhanced production of butyric acid through immobilization of Clostridium tyrobutyricum in a novel inner disc-shaped matrix bioreactor. Ann. Microbiol. 66, 121–129. https://doi.org/10.1007/s13213-015-1088-z

Huang, J., Zhu, H., Tang, W., Wang, P., Yang, S.T., 2016b. Butyric acid production from oilseed rape straw by Clostridium tyrobutyricum immobilized in a fibrous bed bioreactor. Process Biochem. 51, 1930–1934. https://doi.org/10.1016/ j.procbio.2016.08.019

ISO 14040, 2006. Environmental Management-Life Cycle Assessment-Principles and Framework, Geneve, Switzerland.

ISO 14044, 2006. Environmental management — Life cycle assessment — Requirements and guidelines [WWW Document]. Int. Organ. Stand. URL https://www.iso.org/standard/38498.html (accessed 2.15.21).

Jiang, L., Fu, H., Yang, H.K., Xu, W., Wang, J., Yang, S.T., 2018. Butyric acid: Applications and recent advances in its bioproduction. Biotechnol. Adv. 36, 2101–2117. https://doi.org/10.1016/ j.biotechadv.2018.09.005

Jiang, L., Wang, J., Liang, S., Wang, X., Cen, P., Xu, Z., 2009. Butyric acid fermentation in a fibrous bed bioreactor with immobilized Clostridium tyrobutyricum from cane molasses. Bioresour. Technol. 100, 3403–3409. https://doi.org/10.1016/ j.biortech.2009.02.032

Joanna, B., Michal, B., Piotr, D., Agnieszka, W., Dorota, K., Izabela, W., 2018. Sugar Beet Pulp as a Source of Valuable Biotechnological Products, in: Advances in Biotechnology for Food Industry. Elsevier Inc., pp. 359–392. https://doi.org/10.1016/B978-0-12-811443-8/00013-X

Khanna, M., Paulson, N., 2016. To Harvest Stover or Not: Is it Worth it?

Kühnel, S., Schols, H.A., Gruppen, H., 2011. Aiming for the complete utilization of sugar-beet pulp : Examination of the effects of mild acid and hydrothermal pretreatment followed by enzymatic digestion. Biotechnol. Biofuels 4, 14. https://doi.org/10.1186/1754-6834-4-14

Lee, K.M., Choi, O., Kim, K.Y., Woo, H.M., Kim, Y., Han, S.O., Sang, B.I., Um, Y., 2015. Butyric acid production from red algae by a newly isolated Clostridium sp. S1. Biotechnol. Lett. 37, 1837–1844. https://doi.org/10.1007/s10529-015-1869-2

Liu, S., Bischoff, K.M., Leathers, T.D., Qureshi, N., Rich, J.O., Hughes, S.R., 2013. Butyric acid from anaerobic fermentation of lignocellulosic biomass hydrolysates by Clostridium tyrobutyricum strain RPT-4213. Bioresour. Technol. 143, 322–329. https://doi.org/10.1016/ j.biortech.2013.06.015

Luo, H., Yang, R., Zhao, Y., Wang, Z., Liu, Z., Huang, M., Zeng, Q., 2018. Recent advances and strategies in process and strain engineering for the production of butyric acid by microbial fermentation. Bioresour. Technol. 253, 343–354. https://doi.org/10.1016/j.biortech.2018.01.007

Martínez, C.M., Cantero, D.A., Cocero, M.J., 2018. Production of saccharides from sugar beet pulp by ultrafast hydrolysis in supercritical water. J. Clean. Prod. 204, 888–895. https://doi.org/10.1016/ j.jclepro.2018.09.066

Mullen, A.M., Álvarez, C., Pojić, M., Hadnadev, T.D., Papageorgiou, M., 2015. Classification and target compounds, Food Waste Recovery: Processing Technologies and Industrial Techniques. https://doi.org/10.1016/B978-0-12-800351-0.00002-X

Nyambo, C., Mohanty, A.K., Misra, M., 2011. Effect of maleated compatibilizer on performance of PLA/wheat straw-based green composites. Macromol. Mater. Eng. 296, 710–718. https://doi.org/10.1002/mame.201000403

Park, S., Yasin, M., Jeong, J., Cha, M., Kang, H., Jang, N., Choi, I.G., Chang, I.S., 2017. Acetate-assisted increase of butyrate production by Eubacterium limosum KIST612 during carbon monoxide fermentation. Bioresour. Technol. 245, 560–566. https://doi.org/10.1016/j.biortech.2017.08.132

Prasad, A., Sotenko, M., Blenkinsopp, T., Coles, S.R., 2016. Life cycle assessment of lignocellulosic biomass pretreatment methods in biofuel production. Int. J. Life Cycle Assess. 21, 44–50. https://doi.org/10.1007/s11367-015-0985-5

Ra, C.H., Jeong, G.T., Kim, S.K., 2017. Hyper-thermal acid hydrolysis and adsorption treatment of red seaweed, Gelidium amansii for butyric acid production with pH control. Bioprocess Biosyst. Eng. 40, 403–411. https://doi.org/10.1007/ s00449-016-1708-4

Renouf, M.A., Wegener, M.K., Nielsen, L.K., 2008. An environmental life cycle assessment comparing Australian sugarcane with US corn and UK sugar beet as producers of sugars for fermentation. Biomass and Bioenergy 32, 1144–1155. https://doi.org/10.1016/ j.biombioe.2008.02.012

Rowell, R.M., 1992. Opportunities for Lignocellulosic Materials and Composites, in: Lignocellulosic Materials and Composite. pp. 13–27.

Sheikha, A.F. El, Ray, R.C., 2017. Potential impacts of bioprocessing of sweet potato : Review. Crit. Rev. Food Sci. Nutr. 57, 455–471. https://doi.org/10.1080/ 10408398.2014.960909

Stein, U.H., Wimmer, B., Ortner, M., Fuchs, W., Bochmann, G., 2017. Maximizing the production of butyric acid from food waste as a precursor for ABE-fermentation. Sci. Total Environ. 598, 993–1000. https://doi.org/10.1016/ j.scitotenv.2017.04.139

Swain, M.R., Singh, A., Sharma, A.K., Tuli, D.K., 2019. Bioethanol Production From Rice and Wheat Straw: An Overview, in: Bioethanol Production from Food Crops. Elsevier Inc., pp. 213–231. https://doi.org/10.1016/B978-0-12-813766-6/00011-4

Talebnia, F., Karakashev, D., Angelidaki, I., 2010. Production of bioethanol from wheat straw: An overview on pretreatment, hydrolysis and fermentation. Bioresour. Technol. 101, 4744–4753. https://doi.org/10.1016/ j.biortech.2009.11.080

Tomaszewska, J., Bieliński, D., Binczarski, M., Berlowska, J., Dziugan, P., Piotrowski, J., Stanishevsky, A., Witońska, I.A., 2018. Products of sugar beet processing as raw materials for chemicals and biodegradable polymers. RSC Adv. 8, 3161–3177. https://doi.org/10.1039/C7RA12782K

Ueki, T., Nevin, K.P., Woodard, T.L., Lovley, D.R., 2014. Converting Carbon Dioxide to Butyrate with an Engineered Strain of <span

class="named-content genus-species" Bio 5, 19–23. https://doi.org/10.1128/ mBio.01636-14.Editor

Vandák, D., Tomáška, M., Zigová, J., Šturdík, E., 1995. Effect of growth supplements and whey pretreatment on butyric acid production by Clostridium butyricum. World J. Microbiol. Biotechnol. 11, 363. https://doi.org/10.1007/BF00367124

Varrone, C., Floriotis, G., Heggeset, T.M.B., Le, S.B., Markussen, S., Skiadas, I. V., Gavala, H.N., 2017. Continuous fermentation and kinetic experiments for the conversion of crude glycerol derived from second-generation biodiesel into 1,3 propanediol and butyric acid. Biochem. Eng. J. 128, 149–161. https://doi.org/10.1016/j.bej.2017.09.012

Wang, L., Littlewood, J., Murphy, R.J., 2013. Environmental sustainability of bioethanol production from wheat straw in the UK. Renew. Sustain. Energy Rev. 28, 715–725. https://doi.org/10.1016/j.rser.2013.08.031

Wang, L., Ou, M.S., Nieves, I., Erickson, J.E., Vermerris, W., Ingram, L.O., Shanmugam, K.T., 2015. Fermentation of sweet sorghum derived sugars to butyric acid at high titer and productivity by a moderate thermophile Clostridium thermobutyricum at 50°C. Bioresour. Technol. 198, 533–539. https://doi.org/10.1016/ j.biortech.2015.09.062

Wei, D., Liu, X., Yang, S.T., 2013. Butyric acid production from sugarcane bagasse hydrolysate by Clostridium tyrobutyricum immobilized in a fibrous-bed bioreactor. Bioresour. Technol. 129, 553–560. https://doi.org/10.1016/ j.biortech.2012.11.065

Xiao, Z., Cheng, C., Bao, T., Liu, L., Wang, B., Tao, W., Pei, X., Yang, S.T., Wang, M., 2018. Production of butyric acid from acid hydrolysate of corn husk in fermentation by Clostridium tyrobutyricum: Kinetics and process economic analysis. Biotechnol. Biofuels 11, 1–12. https://doi.org/10.1186/s13068-018-1165-1

Yang, J., Ching, Y.C., Chuah, C.H., 2019. Applications of lignocellulosic fibers and lignin in bioplastics: A review. Polymers (Basel). 11, 1–26. https://doi.org/10.3390/ polym11050751

Yang, S., Zhang, Y., Yue, W., Wang, W., Wang, Y.Y., Yuan, T.Q., Sun, R.C., 2016. Biotechnology for Biofuels Valorization of lignin and cellulose in acid - steam - exploded corn stover by a moderate alkaline ethanol post - treatment based on an integrated biorefinery concept. Biotechnol. Biofuels 9, 1–14. https://doi.org/10.1186/s13068-016-0656-1

CHAPTER 9: ENVIRONMENTAL ASSESSMENT OF METHIONINE PRODUCTION[8]

SUMMARY

Industrial biotechnology has been used as a basic strategy for the industrial production of amino acids such as lysine, threonine or tryptophan, which are produced through fermentation process using high performance strains of *Corynebacterium glutamicum* and *Escherichia coli*. However, this is not the case with methionine, which is produced by chemical synthesis or hydrolysis of proteins. In the context of the bioeconomy, the development of alternative routes that explore the potential of microorganisms in methionine production has increased with the aim to reduce the need of fossil fuels and also improve health and the environment. Therefore, it is essential to analyse the environmental benefits linked to the microbial production of methionine at an early stage of development as a substitute for its chemical-based counterpart.

Guided by principles of environmental sustainability, it is interesting to apply methodologies of life cycle assessment (LCA) as a tool to identify environmental indicators associated with both processes: chemical and biotechnological, even considering the possibility of valorising waste

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[8] Chapter based on the publication (Under review):

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[a] CRETUS Institute, Department of Chemical Engineering, School of Engineering, Universidade de Santiago de Compostela, Rúa Lope Gómez de Marzoa, s/n, 15782 Santiago de Compostela, Spain

through anaerobic digestion. Process modelling through mass and energy balances allows data collection for representative scenarios of chemical and biotechnological processes. The least impact associated with biotechnological scenarios of methionine production stands out, especially when the biogas produced from the anaerobic digestion of biomass is converted into heat and electricity.

9.1 INTRODUCTION

Amino acids are biomolecules composed of amino and carboxyl groups, which constitute the building blocks of proteins. Methionine is one of the eight essential amino acids considered a key component of modern animal nutrition, especially widely used in the poultry sector (Shim et al., 2016). Fundamental effects of methionine have been identified as protein synthesis and regulation of cell division. It is also an essential component for glutathione production and an important methyl donor (Schnekenburger and Diederich, 2015; Srijit, 2016; Wang et al., 1997).

Faced with the inevitable challenge of feeding a growing world population, meat production in the globe is expected to double by 2050 (FAO, 2019). Currently, the annual production of methionine is about 1 million tons (Martin et al., 2018), with the largest factories located in the USA and Asia (Jane, 2018). In the next five years, the methionine market is expected to increase at an annual growth rate of about 6 % and to reach $5 billion in 2024 (Shin et al., 2020). Unlike other amino acids, such as Lysine, which is produced by fermentation, methionine is produced industrially by chemical synthesis or by the hydrolysis of proteins, due to economic and technological advantages (Willke, 2014).

The production of methionine via chemical synthesis engenders a mixture of D- and L-methionine (Tian et al., 2016). Furthermore, chemical synthesis involves the use of harmful chemicals, which are toxic and carry a high environmental impact. On the other hand, the methionine produced by protein hydrolysis generates a complex combination that makes it difficult to separate the methionine (Fanatico et al., 2018; Kumar and Gomes, 2005). Due to environmental and health awareness, there is a growing interest in the production of methionine through microbial fermentation. Unlike chemical synthesis, which engenders D, L-methionine, the biotechnological pathway leads to L-methionine (Shim et al., 2016).

In recent decades, research has sought to find efficient production of L-methionine through microbial fermentation, with emphasis on *Corynebacterium glutamicum and Escherichia coli*, as promising strains (Ferla and Patrick, 2014; Ikeda and Takeno, 2013). In this approach, not only the techno-economic feasibility of the production process should be assessed, but also the environmental profile of methionine. The authors (Marinussen and Kool, 2010) performed a life cycle assessment (LCA) of synthetic produced D,L-methionine, but with very limited information. In addition, the work of (Sanders and Sheldon, 2015) carried out a cost and environmental assessment to compare three production processes of methionine: chemical based D,L-methionine, a combined synthetic and fermentation process; and methionine from protein waste.

The environmental sustainability of methionine by fermentation with genetically modified *Corynebacterium glutamicum and Escherichia coli* has not been evaluated. In these circumstances, this chapter aims to open the scope of research on methionine, assessing its environmental impacts in three production scenarios: 1) chemical process; 2) microbial fermentation by *C. glutamicum and* E. *coli*; and 3) the combination of microbial fermentation by *C. glutamicum and* E. *coli* and anaerobic digestion. In the latter, the biowaste undergoes anaerobic digestion for the production of biogas as a biofuel and the digestate as a nitrogen-rich biofertiliser that can be used as a soil amendment.

9.2 MATERIALS AND METHODS

The objective of this chapter is to carry out, by means of LCA, a comparative evaluation of methionine production according to different production routes: chemical and biotechnological. The LCA methodology takes into account the ISO 14040 and 14044 guidelines (ISO 14040, 2006; ISO 14044, 2006) and the Ecoinvent v3.6® database was used for the background processes (Wernet et al., 2016). This study is a cradle-to-gate LCA that considers three methionine production scenarios: 1) Methionine production through a chemical pathway (Met - Sc1); Methionine production by microbial fermentation (Met - Sc2); and 3) Methionine production by microbial fermentation and anaerobic digestion of the biowaste (Met - Sc3). The functional unit considered is 1 kg of methionine production. The following sections describe each process in more detail.

9.2.1 Methionine via chemical pathway

The process traditionally used for the production of methionine is by chemical means, in which the amino acid is obtained from raw materials such as acrolein, methyl mercaptan, ammonium and cyanide, some of these chemical compounds being considered very harmful for the environment (Etzkorn, 2009). A series of reactions have been portrayed in the petrochemical production process of methionine (Sanders and Sheldon, 2015). First, hydantoin (reaction 1) is produced with the use of acrolein, hydrogen cyanide, methyl mercaptan and ammonium carbonate. The hydantoin is then reacted with sodium hydroxide to obtain methionine salt (reaction 2), which will be precipitated as methionine after the addition of hydrochloric acid (reaction 3). Excess acidic and alkaline chemicals will precipitate as salt according to reaction 4. The final product of this route will be a mixture of D- and L- methionine (1:1).

$$C_3H_4O + HCN + CH_3SH + \frac{5}{2}(NH_4^+)_2CO_3 \rightarrow C_6H_{10}N_2SO_2 + \frac{3}{2}H_2CO_3 + 4NH_3 + 2H_2O$$

Reaction 1

$$C_6H_{10}N_2SO_2 + H_2O + NaOH \rightarrow C_5H_{10}NSO_2Na + NH_3 + CO_2$$

Reaction 2

$$C_5H_{10}NSO_2Na + 2HCl \rightarrow C_5H_{11}SNO_2 + NaCl + Cl^-$$

Reaction 3

$$NaOH + HCl \rightarrow NaCl + H_2O$$

Reaction 4

The inventory data was estimated on the production process reported in literature (Sanders and Sheldon, 2015). Table 9.1 depicts the inventory data of inputs and outputs of the system. Table 9.5 in section 9.2.4 shows the processes considered in the Ecoinvent v3.6® database. As the substance Methanethiol (CH_3SH) is not included in the Ecoinvent v3.6® database, data from the literature (National Center for Biotechnology Information, 2020) was used, which considers that to produce 1 kg of methanethiol, it is required 1.62 kg of methanol and 1.2 kg of hydrogen sulphide.

Table 9.1. Inventory data for methionine production via chemical pathway (Met – Sc1).

Inputs	**Quantity**	**Unit**
Acrolein	0.38	kg
Hydrogen cyanide	0.18	kg
Ammonium carbonate	1.63	kg
Methanol	0.59	kg
Sodium hydroxide	0.53	kg
Hydrochloric acid	0.36	kg
Methanethiol	0.32	kg
Water	0.98	kg
Energy	15	MJ
Outputs	**Quantity**	**Unit**
Main product		
D,L-Methionine	1	kg
Emissions to water		
Methanol	0.59	kg
Sodium chloride	0.39	kg

9.2.2 Methionine via microbial fermentation

Fermentation is a process in which microorganisms are capable of producing biomass and metabolites from organic substances, in the presence or not of oxygen. The organic substances used are called substrates, and the microorganisms themselves generate enzymes that carry out their decomposition in order to synthesize them. The fermentation route is the most used for the production of most amino acids and progress in process technology has made it possible to scale it to an industrial level. However, methionine is an exception, and it is not yet possible to achieve high levels of methionine production through a fermentation route, so the chemical process remains prevalent.

The fermentation process that has been selected is based on the work of (Knoll and Buechs, 2007), where a simulation of the process of obtaining L-lysine using *Corynebacterium glutamicum* is described. The main object of study is the production of methionine. However, both methionine and lysine are produced by following the same metabolic pathway. Therefore, taking into account the relationship that exists between the production of both amino acids, this study simulated the process by extrapolating it to the simultaneous production of methionine (Kumar and Gomes, 2005). We approached the production of L-lysine and methionine production modelled in SuperPro Designer® The selected process is divided into 3 sections that combine batch and continuous operations, starting with pre-treatment, then fermentation and finally a purification step (Figure 9.1).

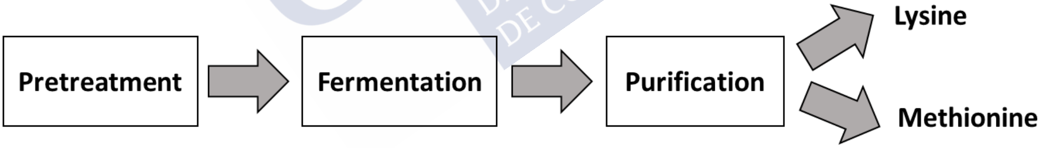

Figure 9.1. Scheme of the methionine production via fermentation pathway.

The *pretreatment* involves the preparation of raw materials, which generally consists of sterilizing the culture medium and the nutrients necessary for the growth of the microorganism. The basic composition of any culture medium requires sources of carbon, nitrogen and minerals. It is important to select it according to the microorganism used and the product to be obtained. As a carbon source, glucose and maltose are the most commonly used. However, other sources of sugars found in the production of methionine by biosynthesis were bananas, cassava, molasses, sugarcane juice, etc (Anusree and Nampoothiri, 2015). Taking into account that the objective of this chapter is to assess the environmental impact of methionine production, it was decided to use second generation raw materials (i.e. molasses residues) as a source of fermentation sugar to avoid the use of first generation feedstocks and also take advantage of industrial process waste.

After carbon, nitrogen is the element that is found in the highest concentration in the culture medium, so it is very important to find an adequate proportion of nitrogen. Various sources of nitrogen have been used, for example, urea, ammonium nitrate, ammonium chloride and sodium nitrate (Kumar and Gomes, 2005). Following the process of Knoll and Buechs (2007), ammonium hydroxide is used in this study as a nitrogen source. Other sources, such as sulphur compounds and oxygen also play an important role in fermentation.

The fermentation process relies essentially on the use of microorganism and the final product. For this reason, genetically modified microorganisms, such as *Corynebacterium glutamicum and Escherichia coli* are used with the aim to achieve a higher production of methionine. Aeration and residence time are key attributes in the fermentation stage. The fermentation stage uses ammonium hydroxide and an air inlet as the source of oxygen necessary for the operation. This stage is performed aerobically and has a total duration of 120 h. To recover the methionine adsorbed on the column, the isoelectric point of methionine (pH 5.74) is taken into account and the column is cleaned with a NH_4OH solution. Once the fermentation is finished, the stream is introduced into a storage tank that operates as an inlet buffer tank to the purification stage.

The purification section begins with a filtration stage, where a cell disruption is carried out to extract the products generated by the microorganism and subsequently separate it from the culture medium. From this process two streams are obtained, one formed by the biomass generated, which is considered a residue of this process; and the second is made up of the main products. The stream composed of the main products is introduced into an evaporator, where 80% of the contained water is separated and recirculated as input to the process. Now a high concentration of methionine and lysine is introduced into a storage tank as a previous step to a drying process, where two streams are obtained, one formed by wastewater and the other formed by granulated methionine, which is finally introduced into a tank of storage. Finally, methionine is produced with an annual capacity of 8,000 t. The inventory data for this process is summarized in Table 9.2. The processes considered in the Ecoinvent v3.6® database are reported in Table 9.5 (section 9.2.4).

Table 9.2. Inventory data for methionine production via microbial fermentation (Met – Sc2).

Inputs	Quantity	Unit
Threonine	0.16	kg
Glucose	23.27	kg
Monopotassium phosphate	0.66	kg
Ammonium Hydroxide	5.67	kg
Water	3.36	kg
Air	94.85	kg
Energy	45.09	MJ
Outputs	**Quantity**	**Unit**
Main products		
L-Methionine	1	kg
L-Lysine	8.20	kg
Waste to treatment		
Wastewater	1.54	m^3
Biowaste	7.41	kg

As the substances monopotassium phosphate and ammonium hydroxide are not available in the Ecoinvent v3.6® database (Wernet et al., 2016), sodium phosphate and ammonium carbonate were used as substitutes, since these compounds perform similar functions (Salemans and Blauw, 2010). In addition, threonine was substituted by a protein produced in the manufacture of cheese whey (Lappa et al., 2019). It was assumed that the wastewater and biowaste produced in this process were treated in a wastewater treatment plant. Since this process system produces two products, mass allocation was chosen to allocate the environmental loads of methionine and lysine.

9.2.3 Methionine via microbial fermentation and process improvement

As observed in Section 9.2.2, there is a large amount of biowaste produced and energy used in the production of methionine through microbial fermentation. Therefore, the treatment of the effluent in an anaerobic digester was considered with the objective of producing energy and nitrogen fertiliser. The biomass is fed into an anaerobic digester, from which the biogas will be generated and converted into heat and electricity in a cogeneration unit and the digestate can be used as a fertiliser (EBA, 2015). Table 9.3 shows the mass balance of the anaerobic digestion process.

Table 9.3. Inputs and outputs of the anaerobic digestion process for an annual methionine production of 8,000 tons.

Component	**Annual flow (x 10^3)**
Biomass	59 tons
Biogas	12.000 m^3
Electricity	156.000 MJ
Fertiliser	11 tons

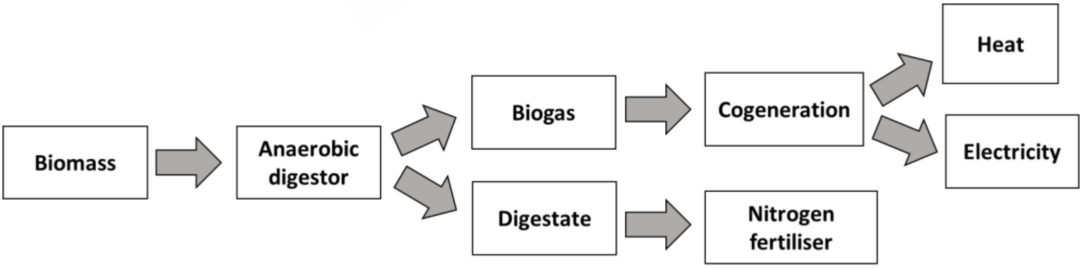

Figure 9.2. Scheme of the anaerobic digestion and its products.

As shown in Figure 9.2, the biomass is fed into an anaerobic digester, producing 0.211 m^3 of biogas and 1.33 kg of digestate per kg of biomass. This translates into a total of 12 million m^3 of biogas, which will be converted into heat and electricity in a cogeneration unit. The heat and electricity will be used to reduce the energy consumption derived from the fermentation process. The life cycle inventory of the improved process is depicted in Table 9.4. Table 9.5 shows the processes considered in the Ecoinvent v3.6® database. As observed in Table 9.4, compared to the inventory data of previous process (See Table 9.2), there is no difference in the methionine and lysine yield. The improvement made in this process is the recovery of the biowaste into energy and nitrogen fertiliser.

Table 9.4. Inventory data for Methionine production via microbial fermentation with anaerobic digestion system (Met – Sc3).

Inputs	**Quantity**	**Unit**
Nitrogen fertiliser (Avoided product)	- 1.48	kg
Threonine	0.16	kg
Glucose	23.27	kg
Monopotassium phosphate	0.66	kg
Ammonium Hydroxide	5.67	kg
Water	3.36	kg
Air	94.85	kg
Energy	25.50	MJ
Biowaste	7.41	kg
Biogas	1.56	m^3
Outputs	**Quantity**	**Unit**
Main products		
Methionine	1	kg
Lysine	8.20	kg
Waste to treatment		
Wastewater	1.54	m^3

9.2.4 General description

This study used SimaPro 9.1 software and CML 2002 method (Guinée et al., 2002) at mid-point level to translate the elementary flows into environmental impact categories. The environmental indicators selected in this work are abiotic depletion (AD - kg Sb eq); acidification (AC - kg SO_2 eq); eutrophication (EP - kg PO_4 eq); climate change (CC - kg CO_2 eq); ozone layer depletion (ODP - kg CFC-11 eq); human toxicity (HT - kg 1,4-DB eq); freshwater aquatic ecotoxicity (FET - kg 1,4-DB eq); terrestrial ecotoxicity (TET - kg 1,4-DB eq) and photochemical oxidation formation (POF - kg C_2H_4 eq). The Table 9.5 shows the processes considered in the Ecoinvent v3.6® database.

Table 9.5. Name of processes in the Ecoinvent v3.6® database.

Inputs	**Name**
Acrolein	Acrolein {GLO}|market for
HCN	Hydrogen cyanide, at plant
$(NH_4)_2CO_3$	Ammonium carbonate {RER} Production
Methanol	Methanol|{GLO}|market for
NaOH	Sodium hydroxide, in 50% solution state {GLO} market for
HCl	Hydrochloric acid {RER}|market for
Water	Water, river
Energy	Electricity, medium voltage |market for
Wastewater	Wastewater, average (waste treatment) {GLO}| market for
Biowaste	Biowaste (waste treatment) {RoW}| by anaerobic digestion
Glucose	Molasses from sugar beet {GLO} | Market for
Threonine	Protein feed, 100% crude {RoW}, treatment of whey by fermentation
KH_2PO_4	Sodium phosphate {GLO}| Market for
NH_4OH	Ammonium carbonate {GLO}| Market for
H_2S	Hydrogen sulphide {GLO}| market for |
Energy	Electricity, medium voltage {RER}| market for |
Nitrogen	Nitrogen fertiliser, as N {GLO}| market for | Alloc Def, U

9.3 RESULTS AND DISCUSSION

The LCA methodology allows translating complex environmental data into interpretable numbers and also comparing products with different process configurations (Guinée et al., 2002). The environmental results of methionine for the 3 scenarios are presented in Table 9.6. The absolute results show that the production of methionine by microbial fermentation with anaerobic digestion (Met - Sc3) presented the best results in all impact categories. On the other hand, the results of methionine by chemical synthesis (Met-Sc1) show a highly polluting process. In scenario Met – Sc1, the CO_2 emissions are about 3 and 10 times higher than those of Met - Sc2 and Met - Sc3, respectively. The authors (Marinussen and Kool, 2010) conducted an LCA of methionine via petrochemical route and reported an average value of 8 kg CO_2 emissions per kg of methionine produced, showing a value slightly higher than this present chapter.

Due to lack of information, production costs were not evaluated in the three scenarios analysed. However, the literature (Sanders and Sheldon, 2015) has estimated the production costs, including capital costs, of methionine via the petrochemical route at 950–1000 $€\cdot t^{-1}$, the methionine produced by a combination of chemical synthesis and fermentation (1348 $€\cdot t^{-1}$) and methionine produced via protein waste (1000 $€\cdot t^{-1}$), demonstrating that biosynthesis of methionine can have cost advantages if produced from waste.

Table 9.6. Comparative results of the three scenarios for methionine production. Met – Sc1 – methionine via chemical process; Met – Sc2 - methionine via microbial fermentation; Met – Sc3- methionine via microbial fermentation with anaerobic digestion. Acronyms: GWP - global warming potential; AD – abiotic depletion; AC – acidification; EP - eutrophication; ODP - ozone layer depletion; HT - human toxicity; FET - freshwater aquatic ecotoxicity; TET - terrestrial ecotoxicity; POF - photochemical oxidation formation.

Impact category	**Unit**	**Met – Sc1**	**Met – Sc2**	**Met – Sc3**
GWP	kg CO_2 eq	7.638	2.717	0.709
AD	kg Sb eq	$8.46\cdot10^{-2}$	$1.74\cdot10^{-2}$	$9.45\cdot10^{-3}$
AC	kg SO_2 eq	$3.20\cdot10^{-2}$	$1.57\cdot10^{-2}$	$6.77\cdot10^{-3}$
EP	kg PO_4 eq	$1.93\cdot10^{-2}$	$8.96\cdot10^{-3}$	$6.40\cdot10^{-3}$
ODP	kg CFC-11 eq	$1.66\cdot10^{-6}$	$2.13\cdot10^{-7}$	$1.01\cdot10^{-7}$
HT	kg 1,4-DB eq	3.292	1.785	0.727
FET	kg 1,4-DB eq	1.984	1.159	0.662
TET	kg 1,4-DB eq	$2.54\cdot10^{-2}$	$2.17\cdot10^{-2}$	$4.73\cdot10^{-3}$
POF	kg C_2H_4 eq	$8.48\cdot10^{-3}$	$8.29\cdot10^{-4}$	$5.73\cdot10^{-4}$

A hotspot analysis is performed to better understand the contribution of each process and allow for potential changes to optimize the methionine production system. The following sections describe in more detail the environmental contribution of each process to the total environmental impacts for Met - Sc1, Met - Sc2 and Met - Sc3, respectively.

9.3.1 Methionine via chemical pathway

Figure 9.3 shows the environmental profile of methionine produced by chemical synthesis. It is clear that electricity and ammonium carbonate play a key role in almost all impact categories. It can be seen from the inventory data (Table 9.1) that a large amount of ammonium carbonate is used in the chemical production process, that is, about 1.62 kg of ammonium carbonate per kg of methionine. Hydrogen cyanide has a higher contribution to GWP and AD, due to the very high energy use for its production (Pesce, 2010). Although acrolein is a toxic and flammable liquid (Etzkorn, 2009), it has a relatively low impact on each category, due to the low amount required in the production of methionine. Hydrochloric acid contributes to ODP as this substance participates in photochemical reactions that occur in the stratosphere and lead to the loss of the ozone layer (WMO, 2010).

Methanethiol is primarily responsible for the ODP impact category. This is because sulfur compounds are involved in its production process, resulting in sulfur oxides that are highly reactive with volatile organic complexes in the presence of sunlight (Taylor et al., 1972). Sodium hydroxide (NaOH) is one of the inputs that relatively influences the environmental results, mainly in the ODP impact category. The production of NaOH causes the release of chlorine and hydrogen molecules into the atmosphere, which are gases involved in the formation of ozone depletion (Huijbregts et al., 2017). Although methanol production is known for its high energy intensity (Chen et al., 2020), its low quantity and the other materials inputs overshadow its contribution to the global impacts. Wastewater process plays a minor role in this scenario. Despite having a very high wastewater flow, it does not include any hazardous compounds, as it was assumed that they were treated or recovered.

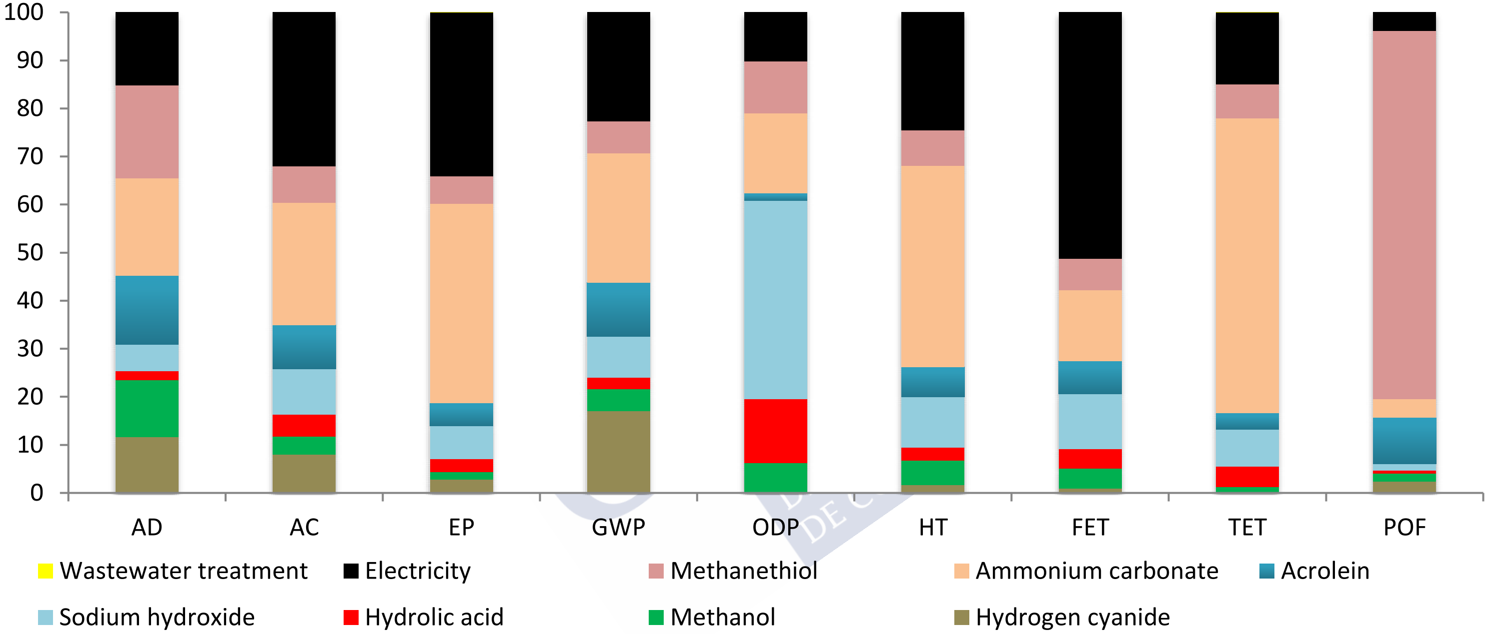

Figure 9.3. Environmental profile of Methionine production in Met – Sc1. Acronyms: Acronyms: AD – abiotic depletion; AC – acidification; EP - eutrophication; GWP - global warming potential; ODP - ozone layer depletion; HT - human toxicity; FET - freshwater aquatic ecotoxicity; TET - terrestrial ecotoxicity; POF - photochemical oxidation formation.

9.3.2 Methionine via microbial fermentation

Figure 9.4 shows the environmental profile of methionine production through a fermentation path. As noted, threonine, glucose and monopotassium phosphate present little environmental impact. Threonine shows a very low environmental share because it is considered as a low-value protein source derived from whey fermentation, a by-product from cheese production. Although glucose is used in large quantities, about 23 kg of glucose per kg of methionine, it has a low environmental impact, even functioning as a sink in the case of TET. This is because the glucose considered in this scenario is derived from molasses, a by-product of sugar production (Durlinger et al., 2017).

Monopotassium phosphate has a relatively low contribution in all impact categories, except for FET due to the discharge of toxic substances in water bodies. On the other hand, ammonium hydroxide and electricity have a great influence on the overall environmental burdens. This system uses high amount of ammonium hydroxide (about 5.6 kg per kg of methionine) as well as energy (about 45 MJ per kg of methionine). The energy requirements in the fermentation process are very high, which represents more than 90% of the total energy involved.

It is important to consider that, due to lack of specific data in the Ecoinvent database, ammonium carbonate was used as substitute to ammonium hydroxide, as nitrogen source. The main issue of ammonium carbonate is caused by ammonia, which has serious environmental implications (Bicer et al., 2016). Wastewater has the least impact on the system as a whole. Biowaste has a small but appreciable impact, especially in the POF, FET and EP impact categories. This is due to the high flow associated with this residue, composed of biomass, proteins, glucose and ammonia.

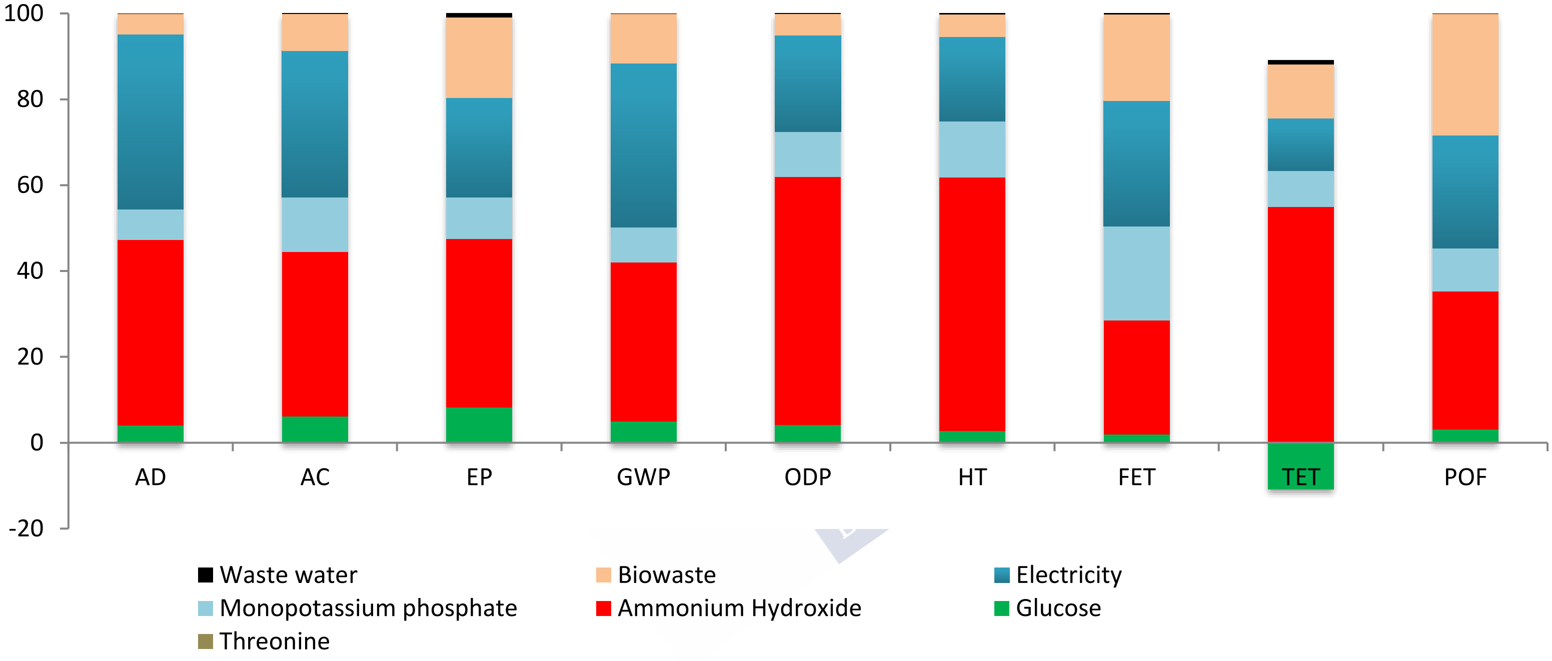

Figure 9.4. Environmental profile of Methionine production in Met – Sc2. Acronyms: Acronyms: AD – abiotic depletion; AC – acidification; EP - eutrophication; GWP - global warming potential; ODP - ozone layer depletion; HT - human toxicity; FET - freshwater aquatic ecotoxicity; TET - terrestrial ecotoxicity; POF - photochemical oxidation formation.

9.3.3 Methionine via microbial fermentation and process improvement

Figure 9.5 depicts the environmental profile of Met-Sc3. The environmental contribution of threonine, glucose and monopotassium phosphate shows the same trend as the previous scenario, that is, a very low contribution to global impacts. As can be seen in Figure 9.5, compared to the previous system (Figure 9.4), electricity continues to affect all impact categories (except TET), however, to a much lesser degree. The introduction of the anaerobic digestion process has reduced the energy consumption of the system by almost half. Consequently, the associated environmental impacts significantly decreased. Ammonium hydroxide continues to be the main cause of environmental impacts, following the same trend as the previous system, especially for TET, HT and ODP.

There is a fundamental difference in relation to the previous system, which is the nitrogen fertiliser, the by-product generated by anaerobic digestion that works as a sink in all impact categories. Nitrogen fertilisers are considered an avoided product. It has a negative value since it is positively impacting the environment by preventing the production of fertilisers by other means. Regarding waste for treatment, wastewater continues to be the least contributor to environmental impacts, being negligible in the graph. The biowaste presents considerable improvements in relation to the previous process, since after the biogas cogeneration process, it supplies itself with the generated heat. Biogas produced through a cogeneration process to convert heat and electricity causes very little environmental impact, which shows that the solution adopted greatly benefits the process.

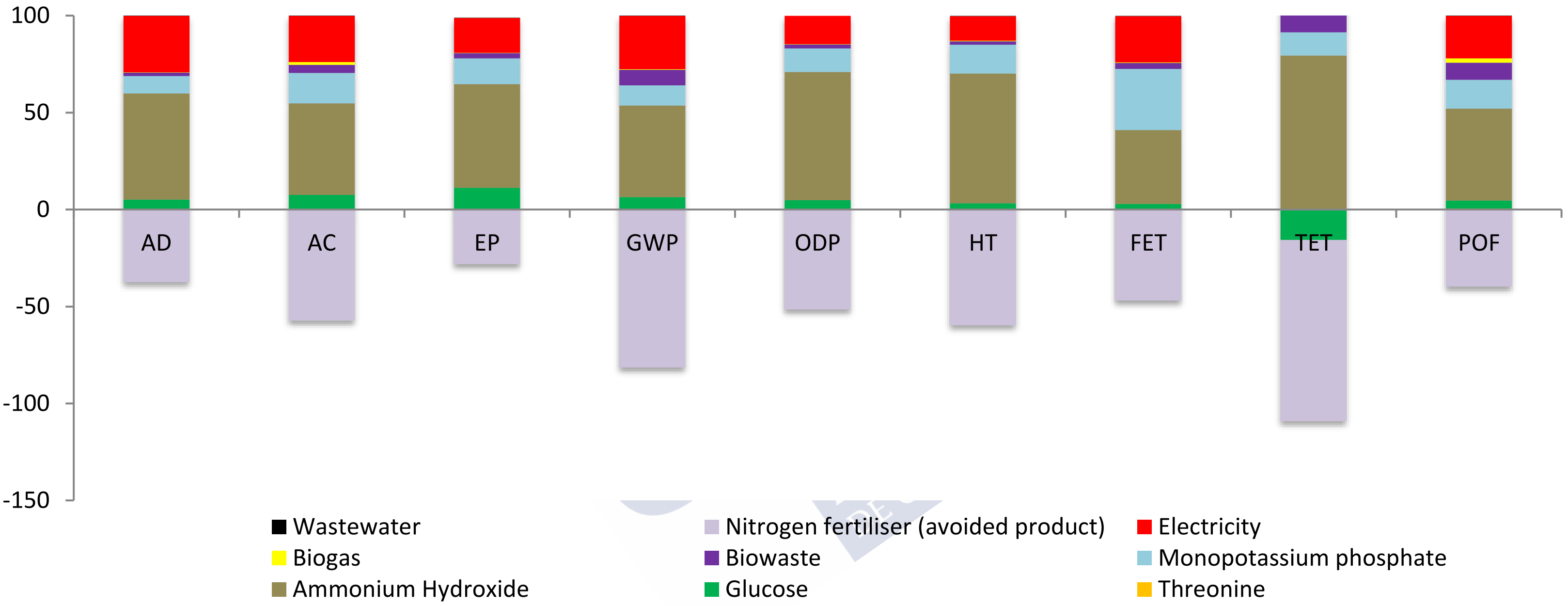

Figure 9.5. Environmental profile of Methionine production in Met – Sc3. Acronyms: Acronyms: AD – abiotic depletion; AC – acidification; EP - eutrophication; GWP - global warming potential; ODP - ozone layer depletion; HT - human toxicity; FET - freshwater aquatic ecotoxicity; TET - terrestrial ecotoxicity; POF - photochemical oxidation formation.

9.4 CONCLUSIONS

Methionine is an essential amino acid that is currently produced by chemical synthesis, which has many environmental implications. The chemical synthesis of this amino acid also produces a less valued product, DL- methionine, instead of L-methionine. Many research efforts have been made to produce L-methionine via microbial fermentation.

This chapter applied the LCA methodology to compare the environmental impacts of different methionine production processes. The application of LCA proved to be a powerful tool to assess the environmental loads of methionine. The results showed that the production of methionine through a fermentation route using anaerobic digestion to reuse energy and produce nitrogen as a fertiliser would significantly reduce the environmental impacts.

It should be noted that this research focused only on environmental metrics and is a starting point for assessing the sustainability of methionine as a whole. It provides information for future research, especially in evaluating the economic feasibility of methionine produced via fermentation routes.

REFERENCES

Bicer, Y., Dincer, I., Zamfirescu, C., Vezina, G., Raso, F., 2016. Comparative life cycle assessment of various ammonia production methods. J. Clean. Prod. 135, 1379–1395. https://doi.org/10.1016/ j.jclepro.2016.07.023

Chen, Z., Shen, Q., Sun, N., Wei, W., 2020. Life cycle assessment of typical methanol production routes : The environmental impacts analysis and power optimization. J. Clean. Prod. 220, 408–416. https://doi.org/10.1016/ j.jclepro.2019.02.101

Durlinger, B., Koukouna, E., Broekema, R., Van Paassen, M., Scholten, J., 2017. Agri-footprint 4.0. Gouda.

EBA, 2015. Digestate Factsheet : the value of organic fertilisers for Europe´s economy, society and environment [WWW Document]. Eur. Biogas Assoc. URL http://europeanbiogas.eu/wp-content/uploads/2015/ 07/Digestate-paper-final-08072015.pdf (accessed 10.23.20).

Etzkorn, W.G., 2009. Acrolein and derivatives. Encyclopedia of Chemical Technology. https://doi.org/10.1002/0471238961.0103181505202611.a01.pub3

Fanatico, A.C., Arsi, K., Upadhyaya, I., Ramos, J.M., Donoghue, D., Donoghue, A.M., 2018. Sustainable Fish and Invertebrate Meals for Methionine and Protein Feeds in Organic Poultry Production. J. Appl. Poult. Res. 27, 437–448. https://doi.org/10.3382/japr/pfy037

FAO, 2019. Meat & Meat Products [WWW Document]. Food Agric. Organ. United Nations. URL http://www.fao.org/ag/againfo/ themes/en/meat/home.html (accessed 10.23.20).

Ferla, M.P., Patrick, W.M., 2014. Bacterial methionine biosynthesis. Microbiol. Soc. 160, 1571–1584. https://doi.org/10.1099/ mic.0.077826-0

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.., De Bruijn, J.A., Van Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards.

Heinzle, E., Biwer, A.P., Cooney, C.L., 2007. Development of Sustainable Bioprocesses: Modeling and Assessment.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Zelm, R. Van, 2017. ReCiPe2016 : a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y

Ikeda, M., Takeno, S., 2013. Amino Acid Production by Corynebacterium glutamicum, in: Springer (Ed.), Microbiology Monographs. Berlin, pp. 108–136. https://doi.org/10.1007/978-3-642-29857-8

ISO 14040, 2006. Environmental Management-Life Cycle Assessment-Principles and Framework, Geneve, Switzerland.

ISO 14044, 2006. Environmental management — Life cycle assessment — Requirements and guidelines [WWW Document]. Int. Organ. Stand. URL https://www.iso.org/standard/38498.html (accessed 2.15.21).

Jane, B., 2018. Why is methionine important for young chicks [WWW Document]. Feed Navig. URL https://www.feednavigator.com/Article/2018/10/29/Why-is-methionine-important-for-young-chicks (accessed 10.23.20).

Knoll, A., Buechs, J., 2007. l-Lysine – Coupling of Bioreaction and Process Model, in: Development of Sustainable Bioprocesses: Modeling and Assessment. pp. 155–167. https://doi.org/https://doi.org/10.1002/9780470058916.ch7

Kumar, D., Gomes, J., 2005. Methionine production by fermentation. Biotechnol. Adv. 23, 41–61.

https://doi.org/10.1016/j.biotechadv.2004.08.005

Lappa, I.K., Papadaki, A., Kachrimanidou, V., Terpou, A., Koulougliotis, D., Eriotou, E., Nikolaos, K., 2019. Cheese Whey Processing : Integrated Biorefinery. Concepts and Emerging Food Applications. MDPI foods 8, 8–15.

Marinussen, M., Kool, A., 2010. Environmental impacts of synthetic amino acid production. Gouda.

Martin, J., Eisoldt, L., Skerra, A., 2018. Fixation of gaseous CO 2 by reversing a decarboxylase for the biocatalytic synthesis of the essential amino acid l -methionine. Nat. Catal. 1, 555–561. https://doi.org/10.1038/s41929-018-0107-4

National Center for Biotechnology Information, 2020. Methanethiol [WWW Document]. PubChem Compd. Summ. CID 878. URL https://pubchem.ncbi.nlm.nih.gov/compound/methanethiol#section=Crystal-Structures (accessed 10.2.20).

Pesce, L.D., 2010. Cyanides. Encyclopedia of Chemical Technology. https://doi.org/https://doi.org/10.1002/0471238961.0103181505202611.a01.pub3

Salemans, J.W.M., Blauw, M., 2010. Life Cycle Analysis for four different ground improvement techniques.

Sanders, J.P.M., Sheldon, R.A., 2015. Comparison of the sustainability metrics of the petrochemical and biomass-based routes to methionine. Catal. Today 239, 44–49. https://doi.org/10.1016/j.cattod.2014.08.003

Schnekenburger, M., Diederich, M., 2015. Nutritional Epigenetic Regulators in the Field of Cancer: New Avenues for Chemopreventive Approaches, in: Epigenetic Cancer Therapy. Elsevier Inc., pp. 391–426. https://doi.org/10.1016/B978-0-12-800206-3.00018-5

Shim, J., Shin, Y., Lee, I., Kim, S.Y., 2016. L -Methionine Production. Adv Biochem Eng Biotechnol 159, 153–177.

https://doi.org/10.1007/10_2016_30.

Shin, D., Szustakiewicz, Y.N., Walter, A.P., 2020. Production of DL-Methionine from Corn Syrup via Biosynthesis with Corynebacterium glutamicum. https://repository.upenn.edu/cbe_sdr/126/

Srijit, T., 2016. Role of Methionine in Poultry and its supplementation by using Polyherbals [WWW Document]. Poult. Ind. URL https://en.engormix.com/ poultry-industry/articles/role-methionine-poultry-its-t38926.htm (accessed 10.23.20).

Taylor, P., Jr, W.E.W., Levy, A., Wimmer, D.B., 1972. A Study of Sulfur Dioxide in Photochemical Smog. J. Air Pollut. Control Assoc. 22, 27–32. https://doi.org/10.1080/00022470.1972.10469605

Tian, Q.Y., Zeng, Z.K., Zhang, Y.X., Long, S.F., Piao, X.S., 2016. Effect of L- or DL-methionine Supplementation on Nitrogen Retention , Serum Amino Acid Concentrations and Blood Metabolites Profile in Starter Pigs. Asian-Australas J Anim Sci. 29, 689–694. https://doi.org/10.5713/ajas.15.0730

Wang, S., Chen, H., Sheen, L., Lii, C., 1997. Methionine and Cysteine Affect Glutathione Level , Glutathione-Related Enzyme Activities and the Expression of Glutathione S-Transferase Isozymes in Rat Hepatocytes. Am. Soc. Nutr. Sci. 2135–2141. https://doi.org/10.1093/jn/127.11.2135

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Willke, T., 2014. Methionine production — a critical review. Appl Microbiol Biotechnol 98, 9893–9914. https://doi.org/10.1007/s00253-014-6156-y

WMO, 2010. Scientific Assessment of Ozone Depletion: 2010. (World Meteorological Organization). Global Ozone Research and

Monitoring Project-Report No. 52, Geneva, pp. 20–23.

SECTION IV
CONCLUSIONS

CHAPTER 10: GENERAL FINDINGS AND CONCLUSIONS

The main objective of this thesis was to assess, through LCA and other complementary tools, the sustainability of different types of bioproducts, considering agricultural crops, crops processed to specialty foods, lignocellulosic residues as valuable by-products, fermentation sugars for bio-based products, biochemical and bio-based amino acids. The study of all these bioproducts contributed to the transition towards a circular bioeconomy and is in line with the growing concern about the negative effects related to inadequate agricultural management, indiscriminate use of fossil resources and the change in social perception for waste recovery and valorisation. The methods used in this work were valuable tools to achieve the objectives of the thesis. The general findings and conclusions of Sections II and III are presented in more detail below.

Section II: Agriculture and food context

This section aimed to assess the environmental profile and the means to improve the sustainability of agricultural crops and lignocellulosic residues. For this purpose, the different stages of the agricultural value chain and pre-processing were evaluated.

The key findings of the LCA analysis of different varieties of wheat (commercial Spanish wheat and native wheat from Galicia) and agricultural systems (native Galician wheat under a crop rotation and monoculture system) in the region of Galicia, Spain were:

- Nitrogen fertilisation and its production, field emissions, and field operations were found to be the most important contributors to environmental loads during wheat cultivation. The application of fertilisers, such as ammonium nitrate, causes the release of N-based compounds into the air, soil and water compartments, for example, nitrous oxide (N_2O), which is a powerful GHG, ammonia (NH_3) and nitrogen oxides (NO_x). The high nitrogen and phosphorus load in the soil also leads to contamination of water bodies linked to eutrophication.

- Galician native wheat grown under crop rotation had the least environmental impacts per kg of grain produced, while commercial Spanish wheat proved to be the worst environmental profile in all impact categories, except for climate change, where Galician wheat grown in monoculture presented a slightly higher result for the climate change impact category. The best results for native wheat in crop rotation are mainly due to the non-use of chemical fertilisers, avoiding environmental damage resulting from the use of chemical fertilisers and also the background emissions from the production of nitrogen fertilisers, known for their high environmental impact.

- Review of the literature related to LCA studies in wheat crops showed that productivity has a large effect on environmental outcomes if the functional unit is per mass of wheat grain produced, for example, per kg. Furthermore, when comparing with the literature, it was possible to demonstrate that the environmental impacts of this study are considerably lower in many impact categories evaluated.

The wheat crops analysed were processed into Galician bread, a specialty product, whose composition is a blend of native Galician wheat and Spanish commercial wheat grains. This mixture must occur because the Galician wheat gives the aroma of the bread, while the commercial wheat the right volume. In addition, two different cases of bread production were evaluated, one produced from wheat grains from a crop rotation and the other from a monoculture system. The results of this analysis showed the following:

- Galician bread that uses Galician wheat grains that went through a crop rotation system, instead of monoculture, had a better environmental profile per kg of bread produced. By far, the process that contributed the most to the environmental impacts of Galician bread is the agricultural phase. Therefore, the milling and baking industries must take into account that their selection in wheat grain influences their environmental profile.

- LCA studies of different types of bread in various regions showed significant variation in results. However, one similarity was that the cultivation phase is, in general, the main cause of the global impacts. Comparison with other European breads showed that Galician bread has less impact on climate change. However, each bread has its singularity in terms of ingredients and preparation methods, which makes the comparison not straightforward.

- Galician bread is a food heritage with cultural and social identity. To be considered food heritage, traditional knowledge is maintained, with an official procedure on the quantity and classification of ingredients and production rules, which gives less agility in the use of alternative inputs to produce bread. For example, the environmental damage of Galician bread could be reduced if higher yields were obtained from wheat cultivation in Spain. However, the uniqueness of the Galician autochthonous grain also depends on the geoclimatic conditions, which influence the productive yields. The use of wheat grains from large producing countries, such as France, would also compromise the legitimacy of being recognized as Spanish bread, i.e., the proper use of appellations of origin.

- The preservation of food heritage is motivated by industry, but mainly by local consumers who find cultural and social significance in specialty products. This, motivated by a growing environmental awareness of consumption, can induce pressure for the production of traditional agri-foods with environmental sustainability claims.

- This study is, as far as is known, the first LCA study of native wheat and traditional bread in the Galician region and also in Spain. It provided a comprehensive inventory data and environmental results for future LCA studies and stakeholders involved in food heritage. It also opens a space for a greater socioeconomic analysis to address the complete sustainability of native wheat and traditional bread in Galicia.

The LCA evaluation of a 3-year potato-wheat crop rotation system in Galicia, Spain, in which the first year is potato cultivation, followed by commercial wheat in the second year and native wheat grain in the third year, using four functional units: productivity (kg^{-1}); land management ($ha^{-1}\cdot year^{-1}$); a financial function (euros $€^{-1}$ of income from sales) and energetic value (MJ^{-1}), reported the following conclusions:

- Allocation choices has a great influence on the environmental results. Comparing the three farming systems, the native wheat grain had the best environmental profile when the functional units used are per $ha^{-1}\cdot year^{-1}$, euros $€^{-1}$ and MJ^{-1}, except for land use impact category. Potato presented better figures for LU due to the very low land occupation from sowing the seed to harvesting of potato, compared to wheat cultivation. Potato crops requires much more fertilisers, pesticides and agricultural operations than the two wheat crops investigated. Commercial wheat also uses more agricultural inputs than native wheat, as this crop requires more agrochemicals and field operations, such as a baling activity . Only 15% of the straw is left in the field for commercial wheat and the rest is sold for animal feed, while all the straw from native wheat remains in the ground.

- On the other hand, the potato showed the best numbers when analysed in terms of productivity (kg^{-1}), as its yield can be up to 10 times higher than that of wheat. In addition, economic allocation is contributing to better results for potatoes and commercial wheat, as both produce valuable by-products for animal feed. However, no allocation was necessary for native wheat because all the straw is left in the field.

- Chemical nitrogen fertilisation contributes to almost all environmental indicators, due to the direct emissions linked to the application of fertilisers, as well as the background processes that involve the intensive use of energy in the production of nitrogen fertiliser.

- When the functional unit has an energetic function (per MJ), the results show potato as the worst profile, due to its high moisture content and low gross caloric value, compared to wheat grain. When the functional unit has a financial function, native wheat contributes less to environmental impacts. In addition to using less agrochemicals and having fewer field operations, native wheat prices are more than double those of potatoes and commercial wheat.

- In the specific case of wheat, in comparison with the previous agricultural systems analysed in Galicia, the environmental impacts of this wheat grown in a crop rotation system with potatoes show a considerable reduction, particularly for the climate change impact category and presented environmental values better than wheat grown in a monoculture system.

- However, it is important to consider that in the potato-wheat rotation study and the previous study of wheat in the same region, different system boundaries were considered, as well as the degree and type of agricultural operations, fertilisers and pesticides. Moreover, the previous study did not consider the effects that the predecessor crop has on the second crop, such as the nutrient value of straw left in the field and the emissions (e.g., N_2O) caused by crop residues.

- This study proves the relevance of carrying out LCA to understand the environmental impacts of regional agricultural systems and provides relevant insights to different stakeholders (for example, farmers, consumers and researchers). In addition, it serves as a basis for future work aimed at comparing the rotating agricultural systems of this region, integrating economic and social aspects. As already mentioned in the previous study in Galicia, the native wheat grain produced in this region is extremely valued by the local society, as well as the potato, which is an important staple in this region, of social, economic and cultural value.

Finally, lignocellulosic residues (maize stover and sugar beet pulp) from agricultural and industrial activities were evaluated, with the objective of seeking ways of valuing residues in a sustainable manner. The environmental and economic profile of these residues were assessed. The economic assessment considered both internal (OPEX) and external (environmental costs) costs. From the outcomes, it can be concluded that:

- The outcomes of the economic and environmental evaluation of the lignocellulosic raw materials show that maize stover has less impact than beet pulp. One reason is because the maize stover undergoes only one agricultural process to be produced, while the beet pulp needs an additional pre-processing step. In addition, the type of functional unit used in this study (per GJ) benefits maize stover, which has a much higher calorific value, compared to sugar beet pulp.

- The economic analysis shows that, for the sugar beet pulp scenarios, the processing step is responsible for 40-60% of the economic costs, followed by costs due to field operations (19-27%). The numbers are higher for the beet pulp scenario in the United Kingdom, because it has a much lower yield than beet pulp in France. Regarding maize stover, the costs of operating the field (36-39%), followed by environmental costs (15-28%) and fertilisers (13-17%) are the main contributors to the total costs.

- For the beet pulp scenarios, environmental costs contribute little to total costs. Rather, they represent a significant contribution to total costs for maize stover. When analysing only external costs, most of the impacts are caused by particulate matter formation due to its high characterization factor.

- Regarding the environmental analysis, the global LCA results reveal a similar trend to the economic evaluation, where maize stover represents the best scenario. However, the contribution analysis shows a different figure than the economic analysis, where agriculture has now a greater impact than the beet pulp processing phase for the beet pulp scenarios.

Sensitivity and uncertainty analysis were performed to assess the robustness of the environmental outcomes, showing that:

- Changes in the stover removal rate from 30% to 50% show a slight increase in the environmental impacts with less than 10% increase in the environmental indicators.

- Almost all impact categories have a coefficient of variation less than 30%, showing robustness of the environmental results.

This study sought to evaluate the environmental and economic profile of lignocellulosic materials. It integrated environmental and economic aspects, taking into account internal and external costs. This study requires future research to consider important aspects related to the use of renewable biomass for the production of bio-products, such as the application of consequential LCA, to understand the consequences related to the displacement of a biomass to produce alternative products.

In addition, although the environmental impacts of these lignocellulosic feedstocks appear to be clearly assessed, understanding the cost associated with pollution remains a difficult task, due to the high subjectivity involved. The integration of environmental prices into LCA is a relatively new issue. Therefore, it is important to strengthen research in environmental economics for a more robust future assessment.

Section III: Agriculture and bio-based context

The objective of this section was to evaluate the environmental impacts of products made in a bio-based context. That is, the environmental sustainability of intermediate products (i.e., glucose, fermentable sugars), biochemical (i.e., butyric acid) and final product (i.e., methionine produced via fermentation). This section also sought to find ways to improve its sustainability throughout its production stage.

The key findings of the LCA analysis of wheat-based glucose in a European context were:

- In the life cycle of wheat-based glucose production, the agricultural phase represents by far the largest cause of environmental impacts. This is mainly due to chemical fertilisers application and diesel use in field operations. The nitrogen fertiliser plays a fundamental role in the cultivation of wheat as one of its main sources of nutrients. In the grain processing phase, heating and electricity use have also a considerable influence on the environmental impact categories of climate change, freshwater eutrophication and abiotic depletion.

- Environmental outcomes vary from country to country, as each case uses different degrees of fertilisers, land occupations, field operations and electricity mix profiles.

- The results obtained in the allocation showed that the economic allocation has a greater impact than the mass allocation for the main product: glucose.

- The technology to convert starch cultures to glucose is very advanced and is used mainly in the food market. In the context of the bioeconomy, interest in using C6 sugars for bioproducts has increased. However, more LCA studies on different types of crops for sugar production should be analysed, as there is a large number of raw materials that can be transformed into fermentable sugars (i.e., C6/C5 sugars). Examples of other raw materials are maize, an important starch crop in the world, and lignocellulosic residues to avoid the use of edible crops.

Moving further with the analysis of fermentable sugars from other types of raw materials, the outcomes of the LCA analysis of fermentable sugars produced from maize grain, maize stover and sugar beet pulp, in a European context, revealed that:

- Like wheat-based glucose, contribution analysis shows that agricultural activities have a fundamental role in the total impacts for maize grain. On the other hand, agriculture contributes less if maize stover is used and even less with beet pulp, due to the low market value of these residues. It can be concluded that agricultural activities play a fundamental role for 1G raw materials while pre-processing activities for 2G raw materials.

- When analysing only agriculture, the environmental results indicate that field emissions, transport, chemical fertilisation and field operations are the main contributors to the total environmental impacts of agricultural production of sugar beet, maize grain and stover.

- This assessment demonstrates that the use of fermentable sugars from beet pulp will reduce the impacts of fermentable sugars production if economic allocation is applied. However, sensitivity analysis comparing economic and mass allocation shows that the results for maize grain are not as sensitive, when compared with maize stover or beet pulp. Both residues have an extremely high variation in the results. Therefore, it is recommended for future research to integrate this LCA study with a techno-economic evaluation, considering both internal and macroeconomic aspects to understand how the market behaves when these renewable feedstocks are used on a larger scale in the production of bioproducts.

- The analysis of fermentable sugars from raw materials 1G and 2G indicates that it is very important to discern upstream from downstream processes, as upstream processes have unique characteristics that will have an impact on the global sustainability of bio-based products. Industrial fermentation plants can obtain their biomass from various suppliers and countries, from different types of agricultural systems, geoclimatic conditions and ecosystems. Not to mention the economic and social conditions which may diverge from each raw material supplier. Moreover, important crops, such as maize and wheat grain, can be highly subsidized, not indicating the true value of these raw materials.

This thesis took a step further, moving from upstream processes to the production of the biochemical butyric acid made from wheat straw. The environmental analysis, which considers two product formulations: butyric acid in combination with acetic acid and high-purity butyric acid, both produced via microbial fermentation, showed that:

- The best environmental profile corresponds to butyric acid produced in combination with acetic acid due to the lower amount of energy and inputs necessary for its production. Contribution analysis shows that steam production, electricity, enzyme cellulase and wheat straw were the processes with the highest environmental shares for both butyric acid products. Steam is a major factor to climate change, particulate matter and fossil depletion; while electricity to freshwater eutrophication and human toxicity; and wheat straw to marine eutrophication and land use. The cellulase enzyme plays an important role in all impact categories.

- The processes with the least environmental burdens are those related to the formulation of the culture medium: sodium hydroxide, sulfuric acid, potassium hydroxide, urea, potassium phosphate as well as the extraction solvent: 1-octanol and management of waste and wastewater. This is due to the low quantity and/or the low energy used, in comparison with the other processes.

A sensitivity analysis was carried out to assess how variations in production processes can influence environmental results. The sensitivity analysis, based on two premises: change in the electricity mix to 100% renewable and change in the raw material used for beet pulp and maize stover, concluded that:

- The use of 100% renewable energy in the production process would significantly improve the environmental profile of butyric acid, particularly for climate change, particulate matter, freshwater eutrophication, human toxicity and fossil depletion. However, the results have not changed much for land use and marine eutrophication, as these impact categories are mostly related to the impacts of wheat straw production.

- On the other hand, beet pulp or maize stover as substitutes for wheat straw did not significantly modify the overall environmental results, apart from some impact categories, especially land use. The impact on land use decreased considerably because the substitute raw materials have a much higher yield than the wheat straw analysed.

A limitation of this work on butyric acid is that it was not possible to compare the results with the literature because, to our knowledge, there is no other LCA study on chemically or biologically produced butyric acid. Additionally, there is plenty of room to analyse different types of biomass to produce bio-based butyric acid. As the economic profile of butyric acid by fermentation was previously evaluated, it is recommended to include the social implications of biotechnological production of butyric acid to have the sustainability profile of butyric acid.

Moving to the production of amino acids, the LCA study that compared three routes of methionine production: through chemical process, microbial fermentation and the combination of microbial fermentation and anaerobic digestion, concluded that:

- Methionine production via a fermentation route using anaerobic digestion to reuse energy and produce nitrogen as a fertiliser significantly showed the best environmental profile in all impact categories. Chemically produced methionine is a highly polluting process, where CO_2 emissions are approximately 3 and 10 times higher than through microbial fermentation and microbial fermentation with anaerobic digestion, respectively.

- In addition, comparison with another LCA study on methionine via chemical synthesis revealed that this study has a slightly better result for the climate change impact category.

- LCA results of methionine produced via chemical synthesis showed that ammonium carbonate and electricity are the main environmental hotspots in almost all impact categories.

- Ammonium hydroxide and electricity have great influence in the overall environmental burdens of methionine via microbial fermentation. On the other hand, the addition of an anaerobic digestion process has decreased the energy consumption almost by half. Ammonium hydroxide remains the major cause to environmental impacts, following the same trend as methionine via microbial fermentation only.

- Nitrogen fertiliser, a by-product of the anaerobic digestion process, acts as a sink in all impact categories, as it is considered an avoided product, positively affecting the environment by preventing the manufacture of fertilisers by other means.

- This LCA research on methionine serves as a reference in future research to evaluate the sustainability of methionine. It provides important information, especially in assessing the economic viability of methionine production through fermentation routes.

LIST OF ACRONYMS

1G	First generation
2G	Second generation
3G	Third generation
4G	Fourth generation
C5 sugar	Five-carbon sugar
C6 sugar	Six-carbon sugar
CAP	Common agricultural policy
CAPEX	Capital Cost
CF	Characterization Factor
COP	Conference of the Parties
DCB	Dichlorobenzene
DDT	Dichloro-Diphenyl-Trichloroethane
DE	Dextrose equivalent
EA	Environmental Auditing
EEA	European Environment Agency
EIA	Environmental Impact Assessment
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
ERA	Environmental Risk Assessment
FAO	The Food and Agriculture Organization of the United Nations
FAOSTAT	The Food and Agriculture Organization Corporate Statistical Database
FU	Functional unit
GHG	Greenhouse gas
HFCS	High-Fructose Corn Syrup
IEA	International Energy Agency
IOA	Input-Output Analysis
ISO	International Organization for Standardization
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LCSA	Life Cycle Sustainability Assessment
LHV	Low Heating Value
MFA	Material Flow Analysis
NPS	National Park Service
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational Costs
PDO	Protected designation of origin
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules Guidance
PLA	Polylactic acid
PBS	Polybutylene succinate
RED	Renewable Energy Directive
RUSLE	Revised Universal Soil Loss Equation
SDG	Standard Development Goals
SLCA	Social Life Cycle Assessment
STAR-ProBio	Sustainability Transition Assessment and Research of Bio-base Products
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USFS	United States Forest Service
USDA	United States Department of Agriculture
WCED	World Commission on Environment and Development

LIST OF PUBLICATIONS

Journal publications

Câmara-Salim, I., Feijoo, G. and Moreira, M.T. (2021). Benchmarking the environmental profile of methionine production by microbial fermentation and its chemical counterpart. Under review in *Biocatalysis and Agricultural Biotechnology* (Major review). - Chapter 9

My contribution: Research, data collection, writing, data analysis

Câmara-Salim, I., Almeida-García, F., Feijoo, G., Moreira, M.T and González-García, S. (2021). Environmental consequences of wheat-based crop rotation in potato farming systems in Galicia, Spain. *Journal of Environmental Management.* Volume 287, 112351, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2021.112351. - Chapter 4

My contribution: Research, data collection, writing, data analysis

Câmara-Salim, I., González-García, S., Feijoo, G. and Moreira, M.T. (2021). Screening the environmental sustainability of microbial production of butyric acid produced from lignocellulosic waste streams, *Industrial Crops and Products*, Volume 162, 113280, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2021.113280. - Chapter 8

My contribution: Research, data collection, writing, data analysis

Câmara-Salim, I., Conde, P., Feijoo, G. and Moreira, M.T. (2021). The use of maize stover and sugar beet pulp as feedstocks in industrial fermentation plants – An economic and environmental perspective, *Cleaner Environmental Systems*, Volume 2, 100005, ISSN 2666-7894, https://doi.org/10.1016/j.cesys.2020.100005. - Chapter 5

My contribution: Research, data collection, writing, data analysis

Câmara-Salim, I., Almeida-García, F., González-García, S., Romero Rodríguez, A., Ruíz-Nogueiras, B., Pereira-Lorenzo, S., Feijoo, G. and Moreira, M.T. (2020). Life cycle assessment of autochthonous varieties of wheat and artisanal bread production in Galicia, Spain, *Science of The Total Environment*, Volume 713, 136720, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2020.136720. - Chapter 3

My contribution: Research, data collection, writing, data analysis

Câmara-Salim, I., González-García, S., Feijoo, G. and Moreira, M.T. (2019). Assessing the environmental sustainability of glucose from wheat as a fermentation feedstock, *Journal of Environmental Management*, Volume 247, Pages 323-332, ISSN 0301-4797, https://doi.org/10.1016/ j.jenvman.2019.06.016 - Chapter 6

My contribution: Research, data collection, writing, data analysis

Bello, S., Câmara-Salim, I., Feijoo, G. and Moreira, M.T. (2021). Inventory review and environmental evaluation of first- and second-generation sugars through life cycle assessment. *Environmental Science and Pollution Research.* 28, 27345–27361. https://doi.org/10.1007/s11356-021-12405-y

My contribution: Research, data collection

Impact factor and ranking of journals (2020)

1) Journal of Environmental Management:

Impact factor: 6.789

Rank in the category Environmental Sciences:34/274

2) Industrial Crops and Products:

Impact factor: 5.645

Rank in the category Agricultural Engineering:2/14

3) Science of the Total Environment:

Impact factor: 7.963

Rank in the category Environmental Sciences: 25/274

4) Environmental Science and Pollution Research:

Impact factor: 4.223

Rank in the category Environmental Sciences: 91/274

5) Biocatalysis and Agricultural Biotechnology:

No impact factor

Rank in the category Biotechnology and Applied Microbiology: 83/161

6) Cleaner Environmental Systems:

This journal is new and has no impact factor and ranking

Book chapters

Câmara-Salim, I., Feijoo, G., and Moreira, M.T. (2020). Chapter 2: Upstream Environmental Assessment. Transition Towards a Sustainable Biobased Economy. *Green Chemistry Series No. 64* Doi: https://doi.org/10.1039/ 9781839160271-00012

My contribution: Research, data collection, writing, data analysis

Câmara-Salim, I., Lijó, L., Moreira, M.T. and Feijoo, G. (2019). Addressing Environmental Criteria and Energy Footprint in the Selection of Feedstocks for Bioenergy Production. *Energy Footprints of the Energy Sector, Environmental Footprints and Eco-design of Products and Processes*, 1-46. Doi: https://doi.org/10.1007/978-981-13-2457-4_1

My contribution: Research, data collection, writing, data analysis

Conference proceedings

Oral contributions

Câmara Salim, I.; Bello, S.; Feijoo, G.; Moreira, M.T. "Identifying new sugar sources and their environmental impacts" – Abstract accepted for oral presentation at 2nd International ADAPTtoCLIMATE Conference. Crete, Greece, June 24-25, 2019.

My contribution: Research, data collection, writing, data analysis

Poster contributions

Câmara-Salim, I.; Feijoo, G.; Moreira, M.T. “Upstream environmental assessment of first- and second-generation sugars” – Abstract accepted for poster presentation at 6th International Environmental Best Practices Conference (EBP6). Olsztyn, Poland, September 24-26, 2019.

My contribution: Research, data collection, writing, data analysis

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