Identifying potential feedstocks in a cradle-to-farm gate approach for sugar production

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Abstract

The increase in environmental responsibility has led to consider biomass as a renewable counterpart to the use of fossil fuels for the production of bioproducts. One possible route within the biorefinery framework is based on the use of fermentable sugars that can subsequently be used in the formulation of culture media for microbial cultures. Examples of potential raw materials for the production of these sugars are first-generation feedstocks, such as sugar and starch crops, and second-generation feedstocks, such as lignocellulose-rich agricultural residues and wood from forestry operations. In this sense, agricultural and forestry activities play a key role in the environmental sustainability of biotechnological processes. Therefore, the assessment of their environmental impacts must be addressed with a view to considering the influence of agricultural and forest management on the associated environmental burden of the value chain of the target product. To achieve this goal, a life cycle assessment was applied as a decision-making tool to compare the environmental performance of different types of feedstocks, such as residual wood chips, maize grain, maize stover, sugar beet, wheat grain and wheat straw. Mass and economic allocation methods were applied to assess the environmental profile of agricultural (maize stover and wheat straw) and forestry (residual wood chips) residues. The results show that economic allocation improves the environmental performance of second-generation feedstocks. Wheat grain showed the worst-case scenario regardless of the type of allocation considered, due to the lower grain yield and the lower amount of recovered wheat residues.
Keywords: LCA, first and second-generation feedstocks, allocation, fermentable sugars

1. Introduction

In recent decades, environmental concerns have increased exploration related to the use of renewable biomass for the production of high added value biochemicals. The term lignocellulosic or waste biorefinery is intended to be a reality beyond a theoretical concept or approach. The globalization and intensification of processes, technological progress, the perspective of circular economy and changes in legislation schemes for environmental protection are some of the factors that are favouring the paradigm shift towards a greater implementation of biotechnological processes. One of the strategies considered by a biorefinery scheme is through the production of fermentable sugars, such as glucose. These sugars, in turn, can be produced from first- and second-generation feedstocks. First-generation biomass is edible crops, such as starch (e.g. wheat and corn) and sugar crops (e.g. sugar beet and sugar cane). On the other hand, second-generation raw materials are considered lignocellulosic crops that do not compete with food and feed markets, such as agricultural waste (e.g. maize residues and wheat straw) and forest operations (e.g. wood chips).

For millennia, the cultivation of wheat and maize have been important crops for many civilizations. Both crops are considered starch cultures because of their high carbohydrate content in the cereal grain. Sugar beet is a relatively new crop from the 19th century, named for its high sucrose content [1]. Sugar beet is an important crop in Europe, which accounts for up to one third of the world production [2]. Maize, wheat and sugar beet are produced mainly for human and animal feed, such as flour and sweeteners. In addition to edible products, these starch and sugar crops are also considered for the biotechnological production of biofuels (e.g. ethanol) and bioproducts (e.g. bioplastics) in widely recognized and mature technological processes [3, 4].

As regards second generation feedstocks, the use of wood and residues from forestry and agricultural activities as resources or feedstocks for the exploitation of specialty chemicals and final products such as bioplastics stems from the need to avoid the use of crops, which may intensify the debate on the disadvantage of diverting arable land from food and feed production to the production of fuels and/or chemicals [5]. Lignocellulosic materials are largely available at relatively low prices [6]. The potential for forest biomass in Europe is expected to be concentrated with the highest density in Northern and Central European countries by 2020. Europe's growing bio-economy is conditioned on the viability of a secure resource supply chain. In this context, forestry activities are considered to be one of the essential pillars to be exploited to ensure the availability of biomass [7].

In general, the intention in implementing systems for the exploitation of second-generation feedstock is to shift away from first generation feedstocks into less controversial resources, such as residual wood chips. The

downside to the use of lignocellulosic biomass is the low yield of production and low optimization of involved processes [8]. Wood and other lignocellulosic biomass have to undergo the necessary transformations to become valuable fractions. For this purpose, lignocellulosic crops need to be broken down into their main components: lignin, cellulose and hemicellulose. The fractionation of lignocellulosic biomass is one of the most complex operations in the biorefinery processes, mainly due to the structure of solid and interconnected cell walls of biomass [9]. In short, it is essential to develop effective and efficient pre-treatment stages to reduce the size of material particles and alter their structure by breaking the chemical bonds. It should be borne in mind that agricultural and forestry activities play a key role in the environmental sustainability of biotechnological processes. Therefore, the assessment of their environmental impacts must be addressed with a view to considering improving agricultural and forest management and achieving a significant reduction in the associated environmental burden of the value chain of the target product.

The life cycle assessment (LCA) tool is an interesting method for accounting the environmental impacts of processes and products from a holistic point of view. Most LCA studies on starch and sugar crops focus on the analysis of the environmental impact of these crops for food purposes [10]–[14]. For wood, LCA studies focus mainly on wood for building materials [15]; pulp and paper industry[16]; and the production of pellets for fuels [17]. However, LCA research on the cultivation of raw materials for the production of fermentable sugars on the route to bioproducts is less common [18], [19]. It should be noted that cultivation activities may have different profiles for each region, depending on many variables, such as geoclimatic and economic conditions. Bearing in mind that bioproduct producers are not responsible for previous activities, understanding the impacts of the production of raw materials allows them to choose raw materials that represent less environmental impact and therefore, a better option on the road towards the concept of biorefinery.

2. Material and methods

2.1 Goal and scope definition

This study applies LCA methodology with a cradle to farm approach. 1 kg of feedstock at the farm gate has been chosen as functional unit for accounting the environmental outcomes. The feedstocks under investigation are residual wood chips, maize grain, maize stover, sugar beet, wheat grain, and wheat straw. Fig.1 shows the system boundaries and the processes involved in the production system being evaluated. A more detailed explanation of the system boundaries is explained in the following sections.

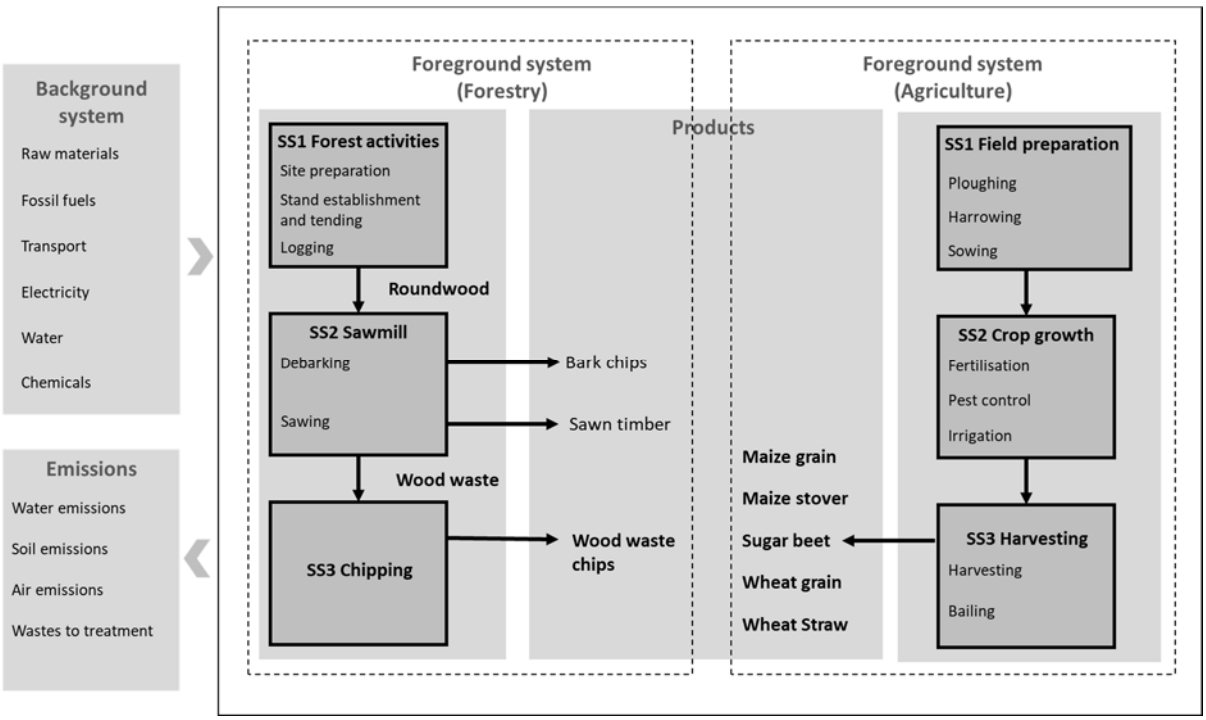

Fig.1. Flowchart of agricultural and forestry activities, including the following case studies. Scenario 1) Wood waste chips (FR); Scenario 2) Maize grain (US); Scenario 3) maize stover (US); Scenario 4) maize grain (IT); Scenario 5) maize stover (IT); Scenario 6) sugar beet (UK); Scenario 7) wheat grain (FR) and Scenario 8) wheat straw (FR). Acronym: FR – France; US – United States; IT – Italy; UK – United Kingdom

2.1.1 System boundaries – Forestry

The production system was assessed from a cradle-to-gate perspective, considering input and output flows from the production of raw materials and resources up to the sawmill gate to produce sawn timber, bark chips and wood waste, mainly in the form of chips. Further processing of sawn timber or bark were not considered in this study, focusing on residual wood chips. The value chain, including silviculture and sawmilling activities, comprised an additional step for shredding wood waste. The evaluated system consisted of three main subsystems, each of which included activities related to the same processing category: forestry and forestry activities, sawmill and mechanical pre-treatment of residual wood.

Subsystem 1 – Forest activities (SS1). This subsystem included all forestry operations carried out on hardwood stands from field preparation up to roundwood logging. This involves site preparation activities such as soil scarification to improve natural regeneration, cut-over clearing, disking, planting, draining, nitrogen mineral fertilization (with ammonium nitrate and dolomite with an average composition of 27%N), thinning, harvesting, forwarding and loading onto trucks. The production of all inputs necessary for the forest subsystem, such as fossil fuels (diesel) and mineral nitrogen, was also included within the system boundaries. In this subsystem, all the environmental burdens derived from forestry activities were allocated entirely to the roundwood. Branches, leaves and other residual fractions derived from pruning, thinning and logging activities are left in the forest in order to improve the soil quality and were assigned no environmental impacts [20]. The secondary transport of hardwood biomass from the forest to the wood preparation site was not considered, mainly because the transport routes are very different depending on the final use of biomass (energy production, manufacture of furniture, boards, etc.).

Subsystem 2 – Sawmill (SS2). This subsystem comprises the activities carried out in the sawmill where roundwood is received and transformed into sawn timber, bark chips and residual wood. The activities at the sawmill are grouped into two main sections: debarking and sawing. For this purpose, a representative sawmill located in Northern Europe that processes softwood logs as raw material was considered. According to the standards for LCA studies, it was necessary to assign the environmental burdens of this subsystem to the outflows: wood waste, bark and sawn wood, based on two criteria: mass and economic allocation.

Subsystem 3 – Chipping (SS3). This stage is focused on the chopping process starting from industrial residual wood (sidings and shavings) in the sawmill and includes chopping of industrial residual wood in a stationary electric chopper. Information corresponds to a Swiss company, which is assumed representative for a facility in Central Europe with an annual production of 5000 m^3. According to the dataset, an average production yield of 100% has been assumed, which does not entail production of internal waste [17].

2.1.2 System boundaries – Agriculture

As far as agricultural activities are concerned, the boundaries of the system comprise the main materials and energy needed for the production of wheat grain, maize grain, maize grain and sugar beet at farm gate. Storage and transportation of these feedstocks are not considered in this study. The system boundaries are common for all the agricultural crops in this study, with some small differences that will be explained later. It is divided into three main subsystems: field preparation, crop growth and biomass harvesting. Precise information on the inputs and outputs of materials for each crop will be further detailed in the inventory.

Subsystem 1 – Field preparation (SS1). The subsystem (SS1) includes previous activities carried out to prepare the land for cultivation. These processes entail ploughing, harrowing and finally sowing. Ploughing is considered as a deeper tillage, which involves turning up the soil with a plough tool. Harrowing, on the other hand, is used to smooth the soil surface, just before sowing. The inputs needed for this SS1 subsystem only involve the use of agricultural machinery and energy to carry out agricultural operations. However, in the case of maize in Italy (Scenarios 4 and 5), organic fertilisation is already applied in this subsystem just before the sowing process.

Subsystem 2 – Crop growth (SS2). These feedstocks are arable crops that take less than a year to mature from sowing to harvesting. At this stage, agrochemicals and irrigation are applied. However, as agriculture depends on geoclimatic conditions, not all crops need irrigation, as in the case of maize in the United States (Scenarios 2 and 3), and wheat in France (Scenarios 7 and 8). The amount of fertilizers and pesticides depends on each case study. Some farmers do not use chemical fertilizers, but solid manure, as is the case of maize in Italy (Scenarios 4 and 5).

Subsystem 3 – Biomass harvesting (SS3). This last stage involves harvesting the main agricultural product (e.g. wheat grain) and the bailing of the residual crops (e.g. maize stover and wheat straw). The harvesting process is carried out using a combine harvester, where the machine separates the grain from the remains (stems, leaves, etc.). In the case of sugar beet, the machine cuts the beet leaves and only the beet root is harvested. The weight of

sugar beet leaves represents approximately 30% of the sugar beet mass [21]. The sugar beet leaves in Scenario 6 were not harvested but left in the field as soil conditioner. Maize stover (i.e. cobs, leaves and stalks) accounts for approximately the same weight as the maize grain. As for wheat, less than half of the whole wheat plant can be rescued as straw [22]. In the case of maize in the US (Scenarios 2 and 3), 50% of the stover was harvested, so the remaining stover will be left on the field as soil amendment. On the other hand, maize stover in Italy (Scenarios 4 and 5) was 100% harvested [23] while 30% of the wheat grain weight is harvested as straw from the wheat cultivation in France (Scenarios 7 and 8).

2.2 Inventory data collection

In this study, data for forest operations on hardwood stands have been obtained from the literature [20]. With regard to sawing activities, the Ecoinvent® database was managed in order to obtain representative results for the processes within SS2 [24]. These inventory data include consumption of electricity of the machinery, lubricant oil for maintenance activities, plastic and steel for packaging steps and chemicals for sawn timber finishing operations and pre-treatment of roundwood. As far as emissions are concerned, heat emission (from debarking machines and sawmills) is not recovered and is considered as direct discharge. Chipping activities were considered through inventory data from a bibliographic study [17], considering the pre-processing of residual wood. Table 1 presents a summary of the most relevant inventory data of forest and sawmill activities.

Table 1. Summarized inventory data detailed for forest activities (per kg of woodchips)

Inputs to SS1 - Forest activities	Amount	Unit
Diesel	$4.49 \cdot 10^{-3}$	kg
N-mineral fertilizer	$0.66 \cdot 10^{-3}$	kg
Outputs from SS1	**Amount**	**Unit**
Product		
Hardwood roundwood to SS2	$3.08 \cdot 10^{-3}$	m^3
Emissions to air		
N_2	$58.88 \cdot 10^{-3}$	g
NH_3	$8.04 \cdot 10^{-3}$	g
NOx	$10.86 \cdot 10^{-3}$	g
Inputs to SS2 - Sawmill		
Hardwood roundwood (from SS1)	$3.08 \cdot 10^{-3}$	m^3
Water (debarking)	$1.06 \cdot 10^{-3}$	m^3
Lubricating oil (machinery)	$0.39 \cdot 10^{-3}$	kg
Solvent (finishing steps)	$2.88 \cdot 10^{-3}$	g
Chemicals inorganic (roundwood pretreatment)	$96.13 \cdot 10^{-3}$	g
Steel (packaging)	$0.48 \cdot 10^{-3}$	kg
HDPE (packaging)	$0.71 \cdot 10^{-3}$	kg
Electricity (machinery)	$83.38 \cdot 10^{-3}$	kWh

Table 1 (cont). Summarized inventory data detailed for forest activities (per kg of woodchips)

Outputs from SS2		
Product and co-products		
Sawn timber	$1.80 \cdot 10^{-3}$	m^3
Bark chips	$0.45 \cdot 10^{-3}$	m^3
Residual wood to SS3	$1.28 \cdot 10^{-3}$	m^3
Emissions into air		
Heat (to be recovered in further subsystems)	1.84	MJ
CO_2	0.13	kg
CO	$68.13 \cdot 10^{-3}$	g
NOx	0.15	g
Particulates	$65.13 \cdot 10^{-3}$	g
SO_2	$3.55 \cdot 10^{-3}$	g
Waste to treatment		
Municipal solid waste to sanitary landfill	$6.50 \cdot 10^{-3}$	kg
Inputs to SS3 - Chipping		
Residual wood from SS2	$1.28 \cdot 10^{-3}$	m^3
Electricity	$2.3 \cdot 10^{-3}$	kWh
Outputs from SS3		
Residual wood chips	1	kg

Table 2 summarizes inventory data for agricultural activities. Data for maize, wheat and sugar beet crops were gathered from bibliography [19], [22], [23], [25]. The fertilization process makes an important contribution to the categories of climate change, eutrophication and the impact of acidification. However, the emission rate depends considerably on geoclimatic conditions and agricultural practices. In this study, the assessment of field emissions applied methodological guidelines to calculate the emission factors recommended by several authors [24]. The environmental burdens of machinery, agrochemical and seed production were also included in this study.

2.3. Allocation methods

In this assessment, the valuable fractions that must be further processed to obtain biochemicals are woodchip residues, maize grain, maize stover, sugar beet, wheat grain and sugar beet. The aim is to compare first- and second-generation raw materials from agricultural and forestry activities as raw materials to produce valuable chemicals. Since first-generation raw materials face competition between food and feed, it is interesting to find a viable application for the residual wood fraction of a sawmill and agricultural residues, such as wheat straw and maize straw. Although these residues play a less important role among the products obtained in a sawmill and in agricultural cultivation, this study explores a viable solution for their transformation into valuable chemical products.

Table 2. Summarized inventory data detailed for agricultural activities (per kg of feedstocks)

	Maize (US)	Maize (IT)	Sugar beet (UK)	Wheat (FR)
Agricultural inputs				
Occupation (m^2)	0.75	1.5	0.1	1.33
Irrigation (m^3)	-	0.12	8.10^{-4}	-
Seed (g)	1.95	1.64	0.02	14.1
Machinery (g)	3.8	1.35	1.07	3.22
Diesel (g)	13.9	10.5	3.76	13.71
Urea, as N (g)	-	4	-	-
Nitrogen, as N (g)	19.06	-	2.25	10.81
P, as P_2O (g)	7.87	-	0.83	24.75
K, as K_2O (g)	13.36	-	1.23	11.35
Pesticides (g)	0.30	0.4	0.17	1.77
Plant regulator (g)	-	-	-	0.27
Solid manure (g)	-	5.75	-	-
Lime (g)	37.03	-	22.17	-
Sodium (g)	-	-	1.81	-
Magnesium (g)	-	-	0.76	-
Agricultural outputs				
Maize grain (kg)	1	1	-	-
Maize stover (kg)	0.5	1.2	-	-
Beet root (kg)	-	1	1	-
Wheat grain (kg)	-	-	-	1
Wheat straw (kg)	-	-	-	0.3
Emissions to air				
NH_3 (g)	0.85	5.02	0.10	1.08
N_2O (g)	0.63	0.89	0.13	0.44
NO_2 (g)	1.62	3.12	0.19	0.92
Emissions to water				
NO_3^- (g)	5.34	7.91	1.35	1.08
PO_4^{3-} leaching (g)	0.007	0.006	0.001	0.009
PO_4^{3-} runoff (g)	0.019	0.023	0.003	0.030

In conducting the LCA of the systems presented above, the impacts obtained include all products leaving each of the subsystems (e.g., sawn timber, bark chips and wood chips). To estimate the percentage of impacts for which wood chips, maize straw and wheat straw are responsible, a volumetric, mass or economic allocation must be considered. Tables 3 and 4 show the allocation factors calculated on the basis of the quantity of co-products leaving the system, as well as their market prices [23], [26]–[28].

For forestry activities, mass allocation and economic factors were applied to subsystem SS2, which is the subsystem that deals with co-products within the boundaries included in the study. The impacts related to the SS3 subsystem were entirely assigned to the residual wood, since its function derives from the need to mechanically pre-treat it as a previous step to its subsequent exploitation in a biorefinery.

Table 3. Mass and economic allocation factors for wood chips

	Volume (m^3)	Volumetric allocation factor (%)	Market price (SEK m^{-3})	Economic allocation factor (%)
Sawn timber	1.8	51.0	246.7	72.9
Bark chips	0.45	12.8	130	9.5
Residual wood chips	1.28	36.2	90	18.6

Table 4. Mass and economic allocation factors for agricultural feedstocks

Case studies	Feedstock yield (t ha^{-1})	Mass allocation factor (%)	Feedstock price (€ kg^{-1})	Economic allocation factor (%)
Maize grain (US)	9.10	67	0.120	87
Maize Stover (US)	4.55	33	0.036	13
Maize grain (IT)	14.78	45	0.178	75
Maize stover (IT)	17.67	55	0.051	25
Wheat grain (FR)	7.40	79	0.189	95
Wheat straw (FR)	2.00	21	0.033	5

3. Results and discussion

The impact assessment phase was undertaken using the ReCiPe 1.1 hierarchist method [29] at midpoint level and software SimaPro 9.1. The chosen impact categories are climate change (CC - kg CO_2-eq), particulate matter (PM - kg PM2.5-eq), acidification (AC - kg SO_2-eq), freshwater eutrophication (FE - kg P-eq), human toxicity (HT - kg 1,4-DCB), land use (LU - m_2a crop-eq) and fossil depletion (FD). To translate the inventories, only the classification and characterization phases were selected, and normalization was not taken into consideration. The comparative environmental profile is displayed in Fig.2 and Fig.3 for mass and economic allocation, respectively.

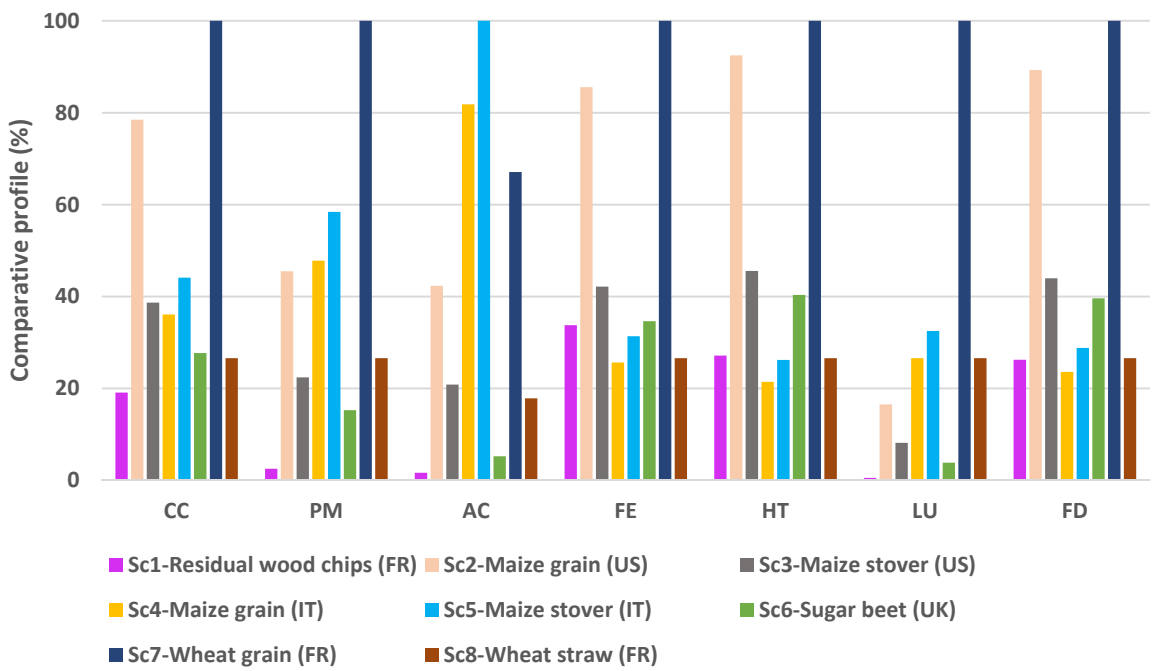

Fig.2. Comparative profiles for 1 kg of feedstock (mass allocation)

The environmental outcomes in Fig.2 (mass allocation) show that the production of 1 kg of residual wood chips (Scenario 1) is the best scenario, with the lowest contribution for CC, PM, AC and LU. On the other hand, Scenario 4 has the lowest values for FE, HT and FD. Scenario 7 performs the worst for almost all environmental impact categories, except for AC, with Scenario 5 representing the worst scenario for AC. Despite the fact that maize stover is a residue of agricultural activities, in Scenario 5 stover is 100% removed and shows a higher yield than maize grain. Since the outcomes in Fig.2 are based on a mass allocation, it is not surprising that the environmental impact is greater for the stover than for the maize grain.

Scenario 7 presents the worst environmental profile because wheat grain has a high allocation factor (95%), due to low residual straw yields compared to other residues, such as maize stover. In addition, the wheat grain has a lower yield when related to the scenarios for maize and sugar beet. Sugar beet (Scenario 6) does not show very high impacts, because sugar beet yield can be particularly high, around 40 t per hectare, compared to 9.1 t per hectare for maize grain. Since the functional unit is per kg of raw materials, higher yielding crops will benefit from the environmental results.

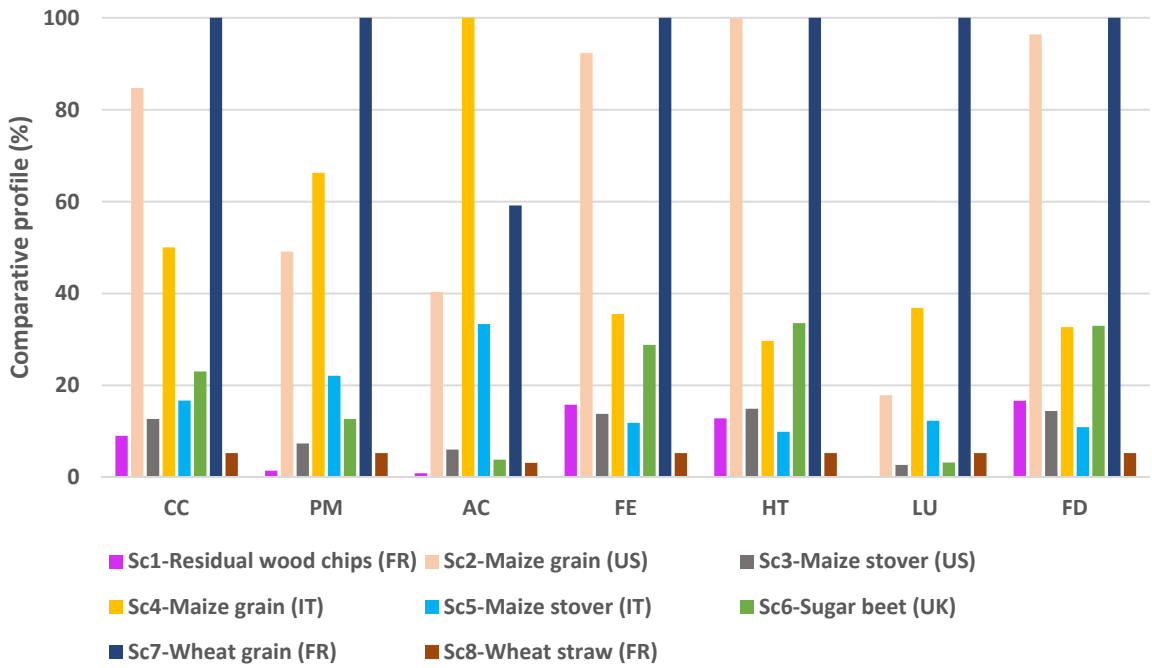

Fig.3. Comparative profiles for 1 kg of feedstock (economic allocation)

As regards the environmental results for the production of 1 kg of raw material, it is clear that the economic allocation benefits second-generation feedstocks, reducing their environmental impact. This is due to the low value of forest and agricultural residues on the market. First-generation raw materials (grain maize, grain wheat and sugar beet) have the worst environmental profiles. When making the economic allocation, Scenario 8 now shows the lowest values for FD, HT, FE and CC, while Scenario 1 performs better for PM, AC and LU.

Comparison with other studies is not straightforward, as many differ in terms of system boundaries, impact assessment methods and type of indicators, as well as the methodology used to calculate emissions on the field. In the study by Achten and Van Acker (2016) on European wheat grain production, it was concluded that the production of 1 kg of wheat grain in Europe varies between 0.30-1.07 kg CO_2-eq and 1.95-6.35 g SO_2-eq for CC and AC, respectively. Without performing allocation, this present study accounts for 0.54 kg CO_2-eq and 4.83 g SO_2-eq for CC and AC per kg of wheat gain, being in the range of the study mentioned above.

Results for sugar beet can vary considerably from one bibliographical reference to another. That is, 1 kg of sugar beet in the report of Garcia et al. (2016) [30] presents a range of 0.196 – 0.234 kg CO_2-eq, while the present study considers a value of 0.11 kg CO_2-eq. In the work of Alexiades et al. (2018) [31], the results showed 0.023 kg CO_2-eq per kg of sugar beet. As aforementioned, the yield of sugar beet is especially high compared to starch crops. In addition, the yields may vary from about 40 t ha^{-1} up to 90 t ha^{-1}. Therefore, the results per kg of feedstocks are very sensitive for sugar beet.

In the research of Murphy and Kendall (2013)[32], the functional unit is 1 hectare of maize grain and stover production, which makes comparison with the present study difficult. However, they used different allocation methods (economic, energy and subdivision) to compare these two raw materials, demonstrating that the subdivision and economic allocation benefit the stover results, as compared to the energy allocation. The

economic allocation also benefits the second-generation feedstocks in this present study, due to the low market value. However, it must be borne in mind that the prices of such residues (wheat straw, maize stover and forest residues) are not well established in the market, thus, economic allocation presents considerable uncertainty.

Linking the results of forest residues with other studies is even more difficult, as most focus on the evaluation of residues for bioenergy systems. Therefore, most functional units are in terms of energy, such as kWh or MJ [33]–[35]. However, the research developed by Moon et al. (2015) [36] assessed GHG emissions from forest residues from logging and milling operations in Japan using mass as a functional unit. The results showed a range of 28.7 to 47.5 g CO_2-eq per kg of forest residues using the economic allocation method. In the present study, when considering price allocation, the results show 46.5 g CO_2-eq per kg of residual wood chips. It is important to understand that geoclimatic conditions, tree type and forest management affect environmental outcomes.

This present study assumes that about 50% of residues are disposed of in Scenarios 2 and 3 for maize in the United States and in Scenarios 7 and 8 for wheat in France [37]. However, for Scenarios 4 and 5, which is maize cultivation in Italy, 100% manure removal was considered [23]. Residues disposal also involves additional fertilization, as they are natural soil conditioners. It should be borne in mind that enough field residues must be left in the field to present soil erosion and not endanger soil quality. In addition, the disposal of agricultural residues affects soil carbon stocks. More research in this field is advisable to assess whether the disposal of such waste on a large scale would not lead to a rebound effect, which may damage soil quality.

4. Conclusions

The comparison of different case studies makes it possible to assess the environmental advantages and disadvantages of using first and second generation feedstocks as biomass for the production of bioproducts. The results of this study show that, when mass assignment is performed, Scenario 1 for residual wood chips has the lowest environmental values for CC, PM, AC and LU, while Scenario 4 has the best results for FD, HT and FE. If an economic allocation is applied, Scenario 8 (wheat straw) has the lowest environmental loads for FD, HT, FE and CC and Scenario 1 (residual wood chips) is the best scenario for PM, AC and LU. The use of the economic allocation benefits the environmental profile of second-generation raw materials. In general, it can be observed that wheat grain in France (Scenario 7) has worse environmental performance, regardless economic or mass allocation. This is due to the low yield of the straw being removed, and therefore almost all the impact is allocated to the wheat grain. In addition, wheat grain has more commercial value than straw. The future trend is an increase in second-generation feedstocks as possible substitutes for fossil fuels to produce bioproducts from fermentable sugars. It is therefore interesting to compare different farming systems in order to understand which raw materials to use and/or which process should be improved to reduce (in the production process) the environmental impacts of the whole life cycle of a bioproduct.

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