*GCB Bioenergy*

WILEY

Global Change Biology Bioenergy
BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY

RESEARCH ARTICLE OPEN ACCESS

# Advanced Biofuel Value Chains Sourced by New Cropping Systems With Low iLUC Risk

Andrea Parenti[1] | Walter Zegada-Lizarazu[1] | Karla Dussan[2] | Ana M. López-Contreras[3] | Truus de Vrije[3] | Igor Staritsky[3] | Berien Elbersen[3] | Bert Annevelink[3] | Fulvio Di Fulvio[4] | Katja Oehmichen[5] | Niels Dögnitz[5] | Andrea Monti[1]

[1]DISTAL—Department of Agricultural and Food Sciences, University of Bologna, Bologna, Italy | [2]Biobased and Circular Technologies Group, Netherlands Organisation for Applied Scientific Research TNO, Petten, The Netherlands | [3]WUR—Wageningen Food & Biobased Research, Wageningen, The Netherlands | [4]Biodiversity and Natural Resources Program (BNR), International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria | [5]DBFZ Deutsches Biomasseforschungszentrum GmbH, Leipzig, Germany

**Correspondence:** Walter Zegada-Lizarazu (walter.zegadalizarazu@unibo.it)

**Received:** 31 March 2023 | **Revised:** 20 June 2024 | **Accepted:** 10 July 2024

**Funding:** This work was supported by Horizon 2020 Research and Innovation (744821).

**Keywords:** bioethanol | double cropping | feedstock | fermentation | lignocellulose | pretreatment | renewable fuel | residues | saccharification

## ABSTRACT

Increasing lignocellulosic feedstock for advanced biofuels can tackle the decarbonization of the transport sector. Dedicated biomass produced alongside food systems with low indirect land use change (iLUC) impact can broaden the feedstock availability, thus streamlining the supply chains. The objective of this study was the design and evaluation of advanced ethanol value chains for the Emilia-Romagna region based on low iLUC feedstock. Two dedicated lignocellulosic crops (biomass sorghum and sunn hemp) were evaluated in double cropping systems alongside food crop residues (corn stover and wheat straw) as sources to simulate the value chains. A parcel-level regional analysis was carried out, then the LocaGIStics2.0 model was used for the spatial design and review of the biomass delivery chain options regarding cost and greenhouse gas (GHG) emissions of the different feedstock mixes. Literature data on bioethanol production from similar feedstocks were used to estimate yields, process costs, and GHG emissions of a biorefinery process based on these biomasses. Within the chain options, GHG emissions were overly sensitive to cultivation input, mostly N-fertilization. This considered, GHG emissions resulted similar across different feedstock with straw/stover (averaging 13 g $CO_2$eq $MJ^{-1}$ fuel), sunn hemp (14 g $CO_2$eq $MJ^{-1}$ fuel), and biomass sorghum (16 g $CO_2$eq $MJ^{-1}$ fuel). On the other hand, the bioethanol produced from biomass sorghum (608 € $Mg^{-1}$ of bioethanol) was cheaper compared with straw (632 € $Mg^{-1}$), sunn hemp (672 € $Mg^{-1}$), and stover (710 € $Mg^{-1}$). The bioethanol cost ranged from 0.0017 to 0.020 € $MJ^{-1}$ fuel depending on the feedstock, with operations and maintenance impacting up to 90% of the final cost. In summary, a single bioethanol plant with an annual capacity of 250,000 Mg of biomass could replace from 5% to 7% of the Emilia-Romagna's ethanol fuel consumption, depending on the applied sourcing scenario.

## 1 | Introduction

Policies on bioenergy expansion in the European Union (EU) paved the way for an increased contribution of biomass sources for advanced biofuels towards the net zero carbon emission target set by the Green New Deal (European Commission 2019). According to Andrés and Padilla (2018) between 1990 and 2014 greenhouse gas (GHG) emissions decreased by 22% in all EU-28 sectors, with the exception of transport which increased by 13% (IRENA 2019). The share of transport before the pandemic raised up to 28% (IRENA 2019) of which 72% accounted for road transport (56% share to trucks and 44% to passenger cars, National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism: https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-17). In 2022, biofuels accounted for more than 3.5% of the global demand for transport energy, primarily in road transportation. In the NZE Scenario, the role of biofuels in the transport sector is projected to more than double by 2030, reaching 9% of total demand, which is a similar proportion to that for road vehicles alone (IEA 2023). Within biofuels, first-generation liquid biofuels are still predominant (European Parliament 2018), despite the fact that they have to be phased out by 2030 (EU Directive 2023/2413), due to the "food versus fuel" competition and the related indirect land use change (iLUC). In this light, the revised Renewable Energy Directive III 2023/2413 (EU Directive 2023/2413), defined the advanced biofuels as non-food/feed energy crops and listed dedicated lignocellulosic crops as possible feedstock sources, when they do not decrease food production. Bioethanol produced via saccharification and fermentation of lignocellulosic biomass is therefore an important alternative for transitioning out of fossil-based transportation fuels. In the Net Zero Emissions Scenario, biofuel production is projected to exceed 10 EJ by 2030, necessitating an annual growth rate of approximately 11%. Moreover, there is a need for expanded utilization of advanced feedstocks, such as biofuels derived from waste, residues, and non-food energy crops. By 2030, these advanced feedstocks are expected to account for over 40% of total biofuel demand, a significant increase from their 9% share in 2021 (IEA 2023).

While the supply chain refers to the multitude of suppliers contributing to the final product (Bassett and Horne 2008), the value chain approach also incorporates socioeconomic and environmental sustainability perspectives within the analysis (Kaplinsky and Morris 2000). The biofuel's value chain structure is pyramidal hierarchically (Lazzarini, Chaddad, and Cook 2001; Singh 2008) in which the key apical position is held by the long-term policy framework together with fuel producers (Traverso et al. 2020). Previously reported studies on the implementation of cellulosic bioethanol value chains in Europe highlighted that feedstock choice, logistics, and regional income level are contributing factors that greatly influence the sustainability and economic viability of the value chain (Dautzenberg and Hanf 2008; Gabrielle et al. 2017; Traverso et al. 2020, 2021). In this light, Traverso et al. (2020) showed that in a post-mining area in Italy, 7000 ha of cultivated irrigated giant reed could produce 40,000 $\mathrm{Mg\,year^{-1}}$ of advanced ethanol with a positive GHG reduction ($-69\%$ $CO_2$eq $\mathrm{MJ^{-1}}$ fuel compared with oil), but with negative profit of 4 million €$\mathrm{year^{-1}}$. Conversely, the same methodology was applied to a 33,000 $\mathrm{Mg\,year^{-1}}$ willow plantation in Ukraine, which generated similar positive sustainability results coupled with 10 million €$\mathrm{year^{-1}}$ of GVA. In 2007, Germany produced about 1511 million $\mathrm{L\,year^{-1}}$ of bioethanol with the opportunity to increase its advanced biofuel share by exploiting set-aside agricultural land at feedstock prices between 40 and 80 €$\mathrm{Mg^{-1}}$ dry matter (d.m.) (Dautzenberg and Hanf 2008). These considerations suggest that the performance of biofuel value chains is strictly site-specific. More comprehensive studies, such as Vera Concha et al. (2021), which consider the supply potential of lignocellulosic energy crops on marginal land in the EU, highlight that perennial lignocellulosic crops only under certain conditions can meet the 50% GHG saving compared with fossil fuel required in the RED III (EU Directive 2023/2413). The reason for this is the high GHG emissions related to the LUC from the current condition into cultivated land. However, the majority of advanced ethanol value chains were sourced from marginal, underutilized and/or contaminated (MUC) lands with dedicated perennial energy crops (Dahmen et al. 2019), i.e. short rotation coppice (Khawaja, Janssen, and Elbersen 2014; Mergner et al. 2017) or from food crop residues on productive arable lands (Hortsch and Corvo 2020). The contribution of such MUC areas has to be significantly increased to approach the European target, but realistically it will not be enough (Phillips et al. 2018). Moreover, MUC lands are often scattered, characterized by low yield or contaminated biomass that could require expensive removal and logistical operations. Remote areas are flawed by scarce infrastructure, limitations to the use of heavy transport, a general low feedstock density per hectare, and hampered access to the market (Zegada-Lizarazu et al. 2013; Zegada-Lizarazu and Monti 2012).

Even though residues are generally highly available, they are characterized by an unstable market price due to existing competing markets such as bedding for livestock, other non-fuel biorefineries (Gauder, Graeff-Hönninger, and Claupein 2011) or the need to maintain soil organic carbon (SOC) through straw incorporation (Anderson-Teixeira et al. 2009; Parenti et al. 2022). The mentioned feedstock shortage can be mitigated by adopting new cropping schemes with dedicated annual high lignocellulose yielding crops in intensive agricultural context. Dedicated energy crops do not have to replace food/feed crops, and thereafter could be double-cropped after a main crop thus avoiding competition for land (Feyereisen et al. 2013; Heggenstaller et al. 2008; Zegada-Lizarazu et al. 2022). Such schemes can significantly consolidate the feedstock availability thus shortening the supply distance and taking advantage of the high organizational level of the transportation network in such areas. In temperate areas of the EU, there are many opportunities for double cropping, and therefore the development of advanced biofuels (Eurostat 2021; Perpiña Castillo et al. 2018). In particular, Emilia-Romagna has 212 biogas plants that account for 18% of the overall existing small-scale bioenergy value chains in Italy (Tamburini et al. 2020). Emilia-Romagna is the biggest and most fertile floodplain of Italy, where the farm acreage is large and intensive management is prevailing. The average farm area of 15 ha is almost double that of the Italian national average (8 ha), and a large portion of Emilia-Romagna's arable land can benefit from irrigation. The agricultural area covers 50% of the regional surface (ISTAT 2022), whereas the arable crops represent 35% of this regional surface, accounting for about 790,000 ha in 2019 (ISTAT 2019). The potential for double cropping in Emilia-Romagna is therefore high. In addition to that, production systems such as double cropping can help reduce the use of fertilizers and pesticides (Khanh et al. 2005; Willis et al. 1997; Zegada-Lizarazu et al. 2022), raising interest in the light of agricultural sustainability for the ecological transition. There is growing evidence that double cropping with appropriate crops (rich in carbohydrates and with high biomass yields) can lead to increased yield stability (Graß et al. 2013; Zegada-Lizarazu et al. 2022), complementary to food/energy production with no land competition, and a significant GHG emission reduction compared with fossil sources (Dong et al. 2009; Parenti et al. 2022). Among the warm-season annual lignocellulosic crops, biomass sorghum, and sunn hemp have great potential yields in the temperate climate zones. These crops are drought-tolerant and fast-growing (Mansoer, Reeves, and Wood 1997; Schomberg et al. 2007) in temperate environments (Zegada-Lizarazu, Parenti, and Monti 2021) and can represent a valuable option in the light of climate change. Fallow soil is uncovered and subjected to harsh conditions such as soil erosion, which increases $CO_2$ emissions (Lal 2004). The prolonged soil cover can improve soil water retention, reduce water runoff, and several other ecosystem services that are positive with respect to climate change-related events such as floods. Furthermore, biomass sorghum is a well-known crop in Emilia-Romagna in that it is already utilized as feedstock for first-generation and advanced biofuels (Zegada-Lizarazu and Monti 2012).

The present study aims to evaluate a potential advanced ethanol value chain sourced through dedicated energy crops and residues integrated with existing cropping schemes, without competing with food crops or existing markets. The innovations rely on a holistic approach based on: (i) the use of data from the testing of innovative cropping systems to produce food and feedstocks for advanced bioethanol production; (ii) the use of experimental data on the biochemical composition of the considered feedstocks and literature data on bioethanol production on similar feedstocks; (iii) the design of a regional supply chain for the Emilia-Romagna region; and (iv) the environmental and economic evaluation of the defined supply chain.

## 2 | Materials and Methods

### 2.1 | Experimental Methods

#### 2.1.1 | Field Determinations

Site characteristics, experimental layout, and cultivation of wheat (*Triticum* spp.) and dedicated lignocellulosic crops such as sunn hemp (*Crotalaria juncea* L.) and biomass sorghum (*Sorghum bicolor* L.) were described in Parenti et al. (2020). Wheat and maize (*Zea mais* L.) were planted at the end of October and March, respectively, and harvested in mid-June and mid-August with a combine harvester. The theoretical grain and straw yields were determined by manual sampling of an area of 8 $m^2$, and then the technical yield was determined by weighing the grain and straw that resulted from the mechanical harvest of the whole parcel area (231 $m^2$). As far as four reps were set each rotation, the overall harvested area to assess the crop yield was about 1000 $m^2$. The d.m. was determined by oven-drying a sub-sample of the fresh mass at 105°C to constant weight. The same methodology was used for sorghum and sunn hemp at the end of September. The aboveground portion of the plants was cut/chopped at the soil level, windrowed twice to obtain uniform dry biomass, and then round-baled when biomass humidity decreased below 30%. The technical yield shown in Table 3 is the result of the rotations including the selected crops in the framework of the BECOOL project and published in Parenti et al. (2020). These data were then compared with other studies on long-term yield simulation in Emilia-Romagna (Parenti et al. 2021; Serra, Colauzzi, and Amaducci 2017) to check their consistency across multiple years and locations. The sustainability of such systems was proved by Parenti et al. (2022), where the selected crop rotation did not deplete the soil's organic carbon, but rather showed an increasing trend over 6 years of monitoring.

To correctly simulate the double crop yield of the lignocellulosic crops a yield reduction coefficient was applied depending on the double cropping scheme (Table S1): (i) 0% reduction coefficient is applied when the double crop is planted in their optimal planting period; (ii) 25% when we have a slightly delayed period of planting (hence a shorter growing season); and (iii) 50% with a marked delayed planting compared with optimal. The yield reduction coefficient is based on crop yield simulations derived from the literature (caption Table 1). Finally, each yield value was attributed to the parcels detected from the spatial analysis.

### 2.2 | Value Chains

The Emilia-Romagna land availability was selected from the Land Parcel Identification System (LPIS) for 2020. The LPIS parcel data provides information on land use at a 1 $m^2$ resolution level. Among the available attributes, three were selected and used for the spatial analysis and allocation of potential feedstock: (i) dimension of agricultural plot; (ii) crop type and use; and (iii) irrigation.

Three land allocation scenarios ranging from baseline to high biomass productivity were investigated at a regional level. The intention was to study the possibility of increasing feedstock availability by double cropping and to reduce dependency on fossil fuels. Each allocation scenario was built by selecting the parcels with a dimension $\geq$10,000 $m^2$. Then the crop type and use of interest were selected and assigned to the scenario accounting for the potential irrigation availability.

The biomass yield value was adjusted (Table 1) depending on the simulated double crop rotation. The in-field technical biomass yield measurements were compared with a range from other studies (Table 3) and the values were used to assign each parcel a new attribute dealing with the potential harvestable biomass on an annual basis.

The baseline is Scenario 1 (S1), in which the actual maize stover and wheat straw will be intended for bioethanol production without double cropping. According to the assessment of Dees et al. (2017), which accounted for SOC maintenance and the competing uses of biomass in Emilia Romagna, 60% and 79% of removal was considered sustainable for wheat straw and maize stover, respectively. The acreage for maize stover and wheat straw was limited to the current grain production locations of such crops because the silage production of fodder/energy maize and wheat leaves no residue.

Scenario 2 (S2) foresees a low input crop intensification in which sorghum and sunn hemp are double-cropped after an early winter harvest of cereal forage crops such as Italian ryegrass, oats, and rye. When used as forages, such crops are cut at the

**TABLE 1** | Selected food crops and acreage from LPIS in Emilia-Romagna (year 2020) to build the double cropping system with biomass sorghum and sunn hemp. Most of the parcels without irrigation were excluded in S3; otherwise, when the main crop is harvested early (Italian ryegrass, oat and rye) parcels without irrigation availability were included because realistically the double crop will benefit from seasonal rainfall. YR is the yield reduction applied to the optimal yield due to the double crop delayed sowing.

| | | | | | | Double crop | |
|---|---|---|---|---|---|---|---|
| Main crop | Acreage (ha) | Use | Harvest time | Scenario | Irrigation | Biomass sorghum YR (%)[a] | Sunn hemp YR (%)[b] |
| Barley | 217 | Forage | May to June | S3 | Y | 25 | 25 |
| | 9361 | Grain | June | S3 | Y | 25 | 50 |
| Italian ryegrass | 6136 | Forage | April to May | S2, S3 | Y + N | 0 | 0 |
| | 1724 | Seed | June | S3 | Y | 25 | 50 |
| Maize | 69,313 | Grain | August | S1, S2, S3 | Y + N | / | / |
| Oat | 299 | Forage | April to May | S2, S3 | Y + N | 0 | 0 |
| Rapeseed | 468 | Oil | June | S3 | Y | 25 | 50 |
| Rye | 143 | Forage | April to May | S2, S3 | Y + N | 0 | 0 |
| | 263 | Seed | June | S3 | Y | 0 | 50 |
| Wheat | 5260 | Forage | May to June | S3 | Y | 0 | 25 |
| | 200,257 | Grain | June | S1, S2, S3 | Y + N | 25 | 50 |
| Triticale | 1142 | Forage | May to June | S3 | Y | 25 | 25 |

[a]Amaducci et al. (2000), Amaducci et al. (2016), Fazio and Barbanti (2014), Colauzzi, Serra, and Amaducci (2018), Zegada-Lizarazu et al. (2010), Zegada-Lizarazu and Monti (2012), Zegada-Lizarazu, Parenti, and Monti (2021), Zegada-Lizarazu et al. (2022), Serra, Colauzzi, and Amaducci (2017).
[b]Parenti, Lambertini, and Monti (2018), Parenti et al. (2021), Zegada-Lizarazu, Parenti, and Monti (2021), Zegada-Lizarazu et al. (2022).

beginning of May, since in mid-May the sowing of a double crop in the warm season dedicated to energy production is feasible without irrigation. To estimate S2, S1 parcels were added to those of sorghum and sunn hemp.

Scenario 3 (S3) was defined to express the maximum biomass yield potential for the selected crops in Emilia-Romagna. These are established in late May or June after the harvest of main crops and also involve double cropping practice. Given the relatively late planting date, the energy crop considered in this study requires irrigation, hence only irrigable lands were considered in this scenario (Table 1) and added to the acreage from S1 and S2.

The LocaGIStics2.0 model (Annevelink et al. 2021) was used for the spatial design and review of the biomass delivery chain options with regard to cost and emissions. LocaGIStics2.0 is a regional biomass supply chain assessment tool that simulates the supply of biomass from the fields to a conversion plant. It consists of a group of modules that can be connected to form a complete biomass supply chain. Each module represents an operation or process (e.g. transport, drying, or harvesting) and is independently constructed with a set of inputs and outputs. Costs, energy use, and GHG emission are common to all operations and processes.

In this assessment, a biomass delivery chain was designed where LocaGIStics2.0 was used to simulate the forwarding of the harvested biomass from the roadside of the field to the final conversion point in which the bioethanol conversion installation would hypothetically be based. For this purpose, the feedstocks were represented at a grid level of 2.5 $km^2$ on a GIS map in LocaGIStics2.0. The mapped biomass creates an overview of biomass density in the Emilia-Romagna region. In addition to the three sourcing scenarios, different mobilization levels were assumed. For the logistical chain assessment, the assumption was that the bioethanol plant would have been located where the highest biomass density within a 50 km circle was found, since the bioethanol plant could be sourced most easily in that area; this was more applying a heuristical rule than an actual optimization. From that chosen position of the bioethanol plant the total biomass demand can be sourced with the shortest distance to the conversion point (Figure 1). The actual maximum distance could even be greater than 50 km in certain scenarios.

The amount of biomass required for one bioethanol plant per year was set at 250,000 Mg d.m. $year^{-1}$ as a predetermined choice based on the size of similar power plants in the EU (Hortsch and Corvo 2020). This follows from the process design of the ethanol production presented in the value chain (Figure 2) with input levels between 171,000 and 242,000 Mg d.m. depending on the type of biomass. The logistical optimization concentrated on supplying the optimal feedstock mix given the size of this bioethanol plant and not on choosing the size of the plant. The value chain includes cultivation and harvesting, transport, biomass milling and further biomass pretreatment, fermentation, distillation, and downstream processes like stillage separation, evaporation, and wastewater treatment. Lignin and biogas co-products are combusted to generate the heat and power required for processing. Surplus electricity is fed into

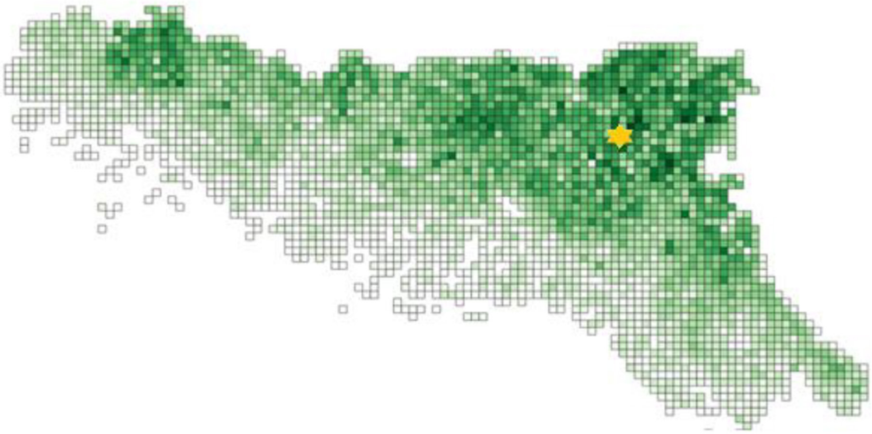

**FIGURE 1** | Map of Emilia-Romagna showing the biomass concentration for S1 in a 2.5 km$^2$ grid. The darker color represents higher concentration. The yellow star identifies the bioethanol plant location.

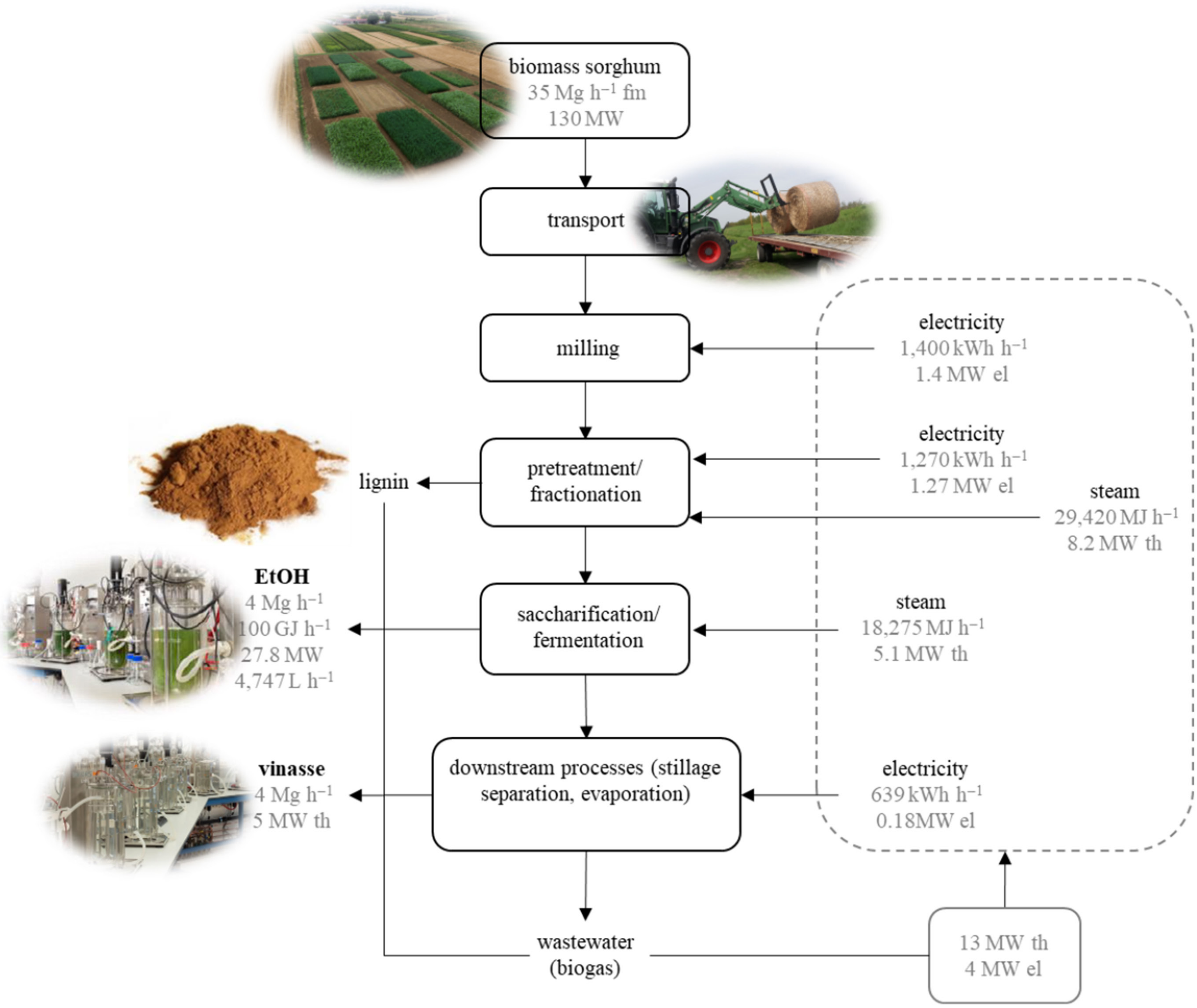


**FIGURE 2** | Process flow chart and energy balance of the biochemical advanced biofuel chain specific to the use of biomass sorghum. Two by-products such as lignin and biogas are used to provide heat (th) and electricity (el) needed for the bioethanol (EtOH) production process.

the power grid. The biochemical composition of the feedstocks in scope was determined experimentally following an adapted protocol described in Smit et al. (2022) (Table S2). From this analysis, two hydrocarbon fractions are quantified, namely C5 sugars such as xylan and arabinan, and C6 sugars such as glucan, mannan, galactan, and rhamnan, from both hemicellulose and cellulose fractions in the feedstocks. It is assumed that 90% w/w of the C5 and C6 sugars are released through acid pretreatment and enzymatic hydrolysis in the combined pretreatment, saccharification, and fermentation processes (Humbird et al. 2011). Furthermore, conversion efficiencies of C5 and C6 sugars through ethanol fermentation are assumed to be 85% and 95%, respectively, from the theoretical maximum achievable yield (0.51 g ethanol per g of sugar) (Batog et al. 2020; Novy et al. 2014; Novy, Longus, and Nidetzky 2015; Paul and Chakraborty 2019; Zhao, Damgaard, and Christensen 2018).

The three defined scenarios base feedstock potential on the unrealistic hypothetical assumption that 100% of farmers would be willing to adopt the double cropping systems with sorghum and sunn hemp cultivated at a share of 50% each. Therefore, to simulate feasible value chains, four different chain organization cases were defined and combined with the scenarios (Table 2). These cases complied with two mobilization levels and two collection principles, which were defined as follows: (i) 25% mobilization level and collection according to lowest cost (c25); (ii) 25% mobilization level and collection according to lowest GHG (g25); (iii) 50% mobilization level and collection according to lowest cost (c50); and (iv) 50% mobilization level and collection according to lowest GHG (g50). In consequence, the feedstock from double cropping (sorghum and sunn hemp) contributes to varying shares to the overall stock for the conversion plant. At this point, the LocaGIStics2.0 model selects the available feedstock in the nearby area of the conversion plant which can optimize alternatively cost or GHG performances given two mobilization levels (25% or 50%).

#### 2.2.1 | Assessment of GHG Emissions

The life cycle assessment (LCA) method was used for the GHG balance. The requirements for conducting an LCA are set out in the international standards ISO 14040 and ISO 14044 for quantifying the environmental impacts of products and services (ISO 14040; ISO 14044).

The LCA tool focuses on analyzing the entire life cycle of the product under investigation, from cultivation to production and use and ultimately to disposal, in order to capture as fully as possible, the potential GHG emissions associated with this product.

**TABLE 2** | Three scenarios and four sourcing cases: (i) 25% mobilization level and collection according to lowest cost; (ii) 25% mobilization level and collection according to lowest GHG; (iii) 50% mobilization level and collection according to lowest cost; and (iv) 50% mobilization level and collection according to lowest GHG.

| | Mobilization level | | | |
|---|---|---|---|---|
| | 25% | | 50% | |
| | Optimized by lowest | | | |
| Scenario | Cost | GHG | Cost | GHG |
| S1 | S1_c25 | S1_g25 | S1_c50 | S1_g50 |
| S2 | S2_c25 | S2_g25 | S2_c50 | S2_g50 |
| S3 | S3_c25 | S3_g25 | S3_c50 | S3_g50 |

All auxiliary and operating materials used at any point within the life cycle were also considered. The following conditions and parameters were defined in order to carry out the GHG balance properly. The Umberto software (ifu Hamburg GmbH 2018) was leveraged for LCA tool and the internationally recognized ecoinvent database was employed as the life cycle inventory database for the purpose of the assessment (Simons 2016). The most important GHGs that are relevant for the calculation of GHGs are $CO_2$, $CH_4$, and nitrous oxide ($N_2O$). The global warming potential (GWP), which describes the potential to change global temperatures through GHG emissions, is expressed in kg of carbon dioxide equivalents ($CO_2$eq). To convert a given $CH_4$ mass into kg $CO_2$eq, the $CH_4$ weight is multiplied by 25 and the $N_2O$ mass is multiplied by 298 (based on a period of 100 years, according to IPCC 2007). $CO_2$ emissions from $CH_4$ use were not included in the calculation of GHG emissions. According to the IPCC, it is assumed that biogenic $CO_2$ emissions are offset by $CO_2$ sequestration during plant growth (IPCC 2007). Surplus electricity was considered using the credit method. The credit method assumes that the co-product produced can replace other products and that the other products therefore no longer need to be manufactured. The emissions avoided as a result are credited to the product system. The use of abandoned land, and thus possible SOC recovery due to re-cultivation has been assumed for the cultivation of sorghum and sunn hemp. The resulting GHG emissions from form direct land use change have been calculated according to the European Commission's guidelines (Commission decision on guidelines for the calculation of land carbon stocks for the purpose of Annex V of Directive 2009/28/EC) (European Commission 2010).

The results of the assessment are related to 1 MJ Ethanol.

I. System boundaries. The assessment of the advanced biofuels based on lignocellulosic biomass covers the entire supply chain, from biomass production, biomass logistics, and conversion processes through to distribution of the bio-ethanol. The biomass production process includes the cultivation and supply processes for the use of cultivated biomass. If residues and waste are used for biofuel production, the assessment starts with the collection and transport of the feedstock to the conversion plant, where upstream emissions are not included.
II. The functional unit has been defined as 1 MJ bio-ethanol. The functional unit is the reference value for the presentation of results.
III. Impact assessment. The GWP, describes the potential to change global temperatures through GHG emissions. The relevant GHGs, $CO_2$, $CH_4$, and $N_2O$, are presented as $CO_2$-equivalents using characterization factors according to IPCC (2007). Biogenic $CO_2$ emissions were not included in the calculation of GHG emissions but were considered to be offset by $CO_2$ sequestration during plant growth according to the IPCC (2007).
IV. Consideration of by-products. Surplus electricity was considered using a credit. The credit method assumes that the produced co-product can replace other products and therefore the other products no longer need to be produced. The emissions thereby avoided are credited to the product system.

V. Assumptions for the calculation of emissions from LUC. The use of abandoned land, and thus possible SOC recovery due to re-cultivation has been assumed for the cultivation of sorghum and sunn hemp. The resulting GHG emissions from direct land use change has been calculated according to the European Commission's guidelines (Commission decision on guidelines for the calculation of land carbon stocks for the purpose of Annex V of Directive 2009/28/EC) (European Commission 2010).

The mass and energy flows for the assessment of the advanced biofuel value chains are based on actual data, information from the literature and own assumptions.

### 2.2.2 | Lifecycle Costs

Manufacturing costs were addressed by setting a system boundary, which contains all the available facilities at the production site, in particular those needed for conversion and storage. The methodology illustrated in Figure 3 was used to calculate the production costs.

Each component was assessed over a period corresponding to the time horizon of the useful life or depreciation period of the conversion asset. All payments for the cost calculation were considered over a period of 20 years, without considering the start-up costs and a rough estimate of the plant costs. Both the start-up costs and the dismantling of the plant are not considered in the calculation, as this is not done in the based analysis (De Jong et al. 2015) and these would only be in the low single-digit percentage range.

The employee-hours per day were multiplied by the operator's rate per hour and the single operations time consumption (hours). The operator rate was assumed at 28.5 €$h^{-1}$ according to Turton et al. (2018). Additionally, an operating supervision rate (15%) (Peters, Timmerhaus, and West 2004) and two administrations cost components were added. The first administration payments were calculated from fixed capital investment (FCI) (0.5%),

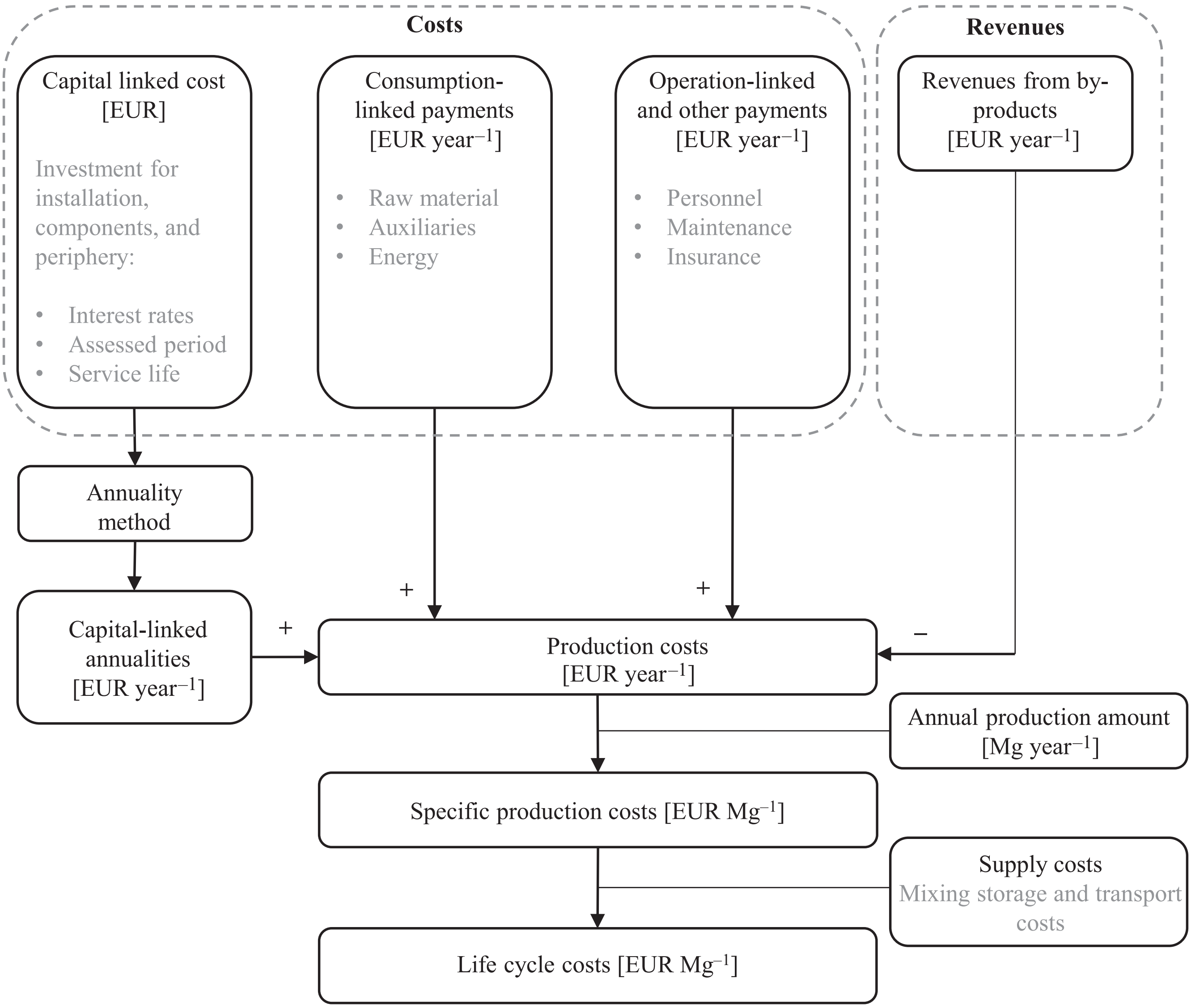


**FIGURE 3** | Schematic representation of the methodology used in the calculation of yearly based (year) production costs, which is then used to obtain the final LCC according to VDI-Richtlinie 6025 (2012).

**TABLE 3** | Crop yields for food and biomass components assessed by manual harvest (theor.) and by mechanical harvest (tech.) to calculate the theoretical and technical yields.

| | Food ($Mg\,ha^{-1}$) | | Biomass ($Mg\,ha^{-1}$) | | Food ($Mg\,ha^{-1}$) | Biomass ($Mg\,ha^{-1}$) | |
|---|---|---|---|---|---|---|---|
| **Crop** | **Theor.** | **Tech.** | **Theor.** | **Tech.** | **Literature (theor.)** | | **References** |
| Maize | 7.6 | 7.4 | 9.9 | 8.7 | 3.5–10 | 3.0–8.0 | Schils et al. (2018) |
| Wheat | 9.9 | 8 | 12.2 | 5.2 | 1.2–8.9 | 3.0–7.0 | |
| Biomass sorghum | | | 31.2 | 21.5 | | 10.9–38.4 | Amaducci et al. (2000), Amaducci et al. (2016), Colauzzi, Serra, and Amaducci (2018), Dou et al. (2014), Fazio and Barbanti (2014), Hassan et al. (2020), Hoffmann and Rooney (2014), Martinez Uribe et al. (2020), Serra, Colauzzi, and Amaducci (2017), Sun et al. (2020), Zegada-Lizarazu et al. (2010), Zegada-Lizarazu and Monti (2012), Zegada-Lizarazu, Parenti, and Monti (2021), Zegada-Lizarazu et al. (2022) |
| Sunn hemp | | | 15.2 | 9.8 | | 6.6–17 | Balkcom et al. (2011), Cantrell, Bauer, and Ro (2010), Cherr, Scholberg, and McSorley (2006), Parenti, Lambertini, and Monti (2018), Parenti et al. (2021), Zegada-Lizarazu, Parenti, and Monti (2021), Zegada-Lizarazu et al. (2022), Schomberg et al. (2007) |

whereas the second was taken from an operating cost calculated with additional 20% (Peters, Timmerhaus, and West 2004).

Within other cost, items related to maintenance are worth being included. Assuming a process under normal conditions, the 7% from the payments for FCI was calculated. Within the other costs related to maintenance, assuming a process under normal conditions, the 7% was calculated from the payments for FCI. Furthermore, additional insurance and uncertainties costs were set at 1% and 0.5% of FCI, respectively (Peters, Timmerhaus, and West 2004).

## 3 | Results and Discussion

### 3.1 | Feedstock

#### 3.1.1 | Biomass Yields of the Double Cropping Systems

The measured food and biomass yield outcoming from double cropping experiments were within comparable range of other studies, (Table 3) with the exception of maize stover and wheat straw which resulted as slightly higher compared with Schils et al. (2018) assessment. The conservative technical biomass yield outcoming from multi-year and multi-location experiments in the Emilia-Romagna area resulted in 8.7, 5.2, 21.5, and 9.8 $Mg\,ha^{-1}$, for maize stover, wheat straw, sorghum and sunn hemp, respectively. These values were allocated to the selected parcels in the regional assessment.

The 'in house' (Parenti, Lambertini, and Monti 2018; Parenti et al. 2021; Zegada-Lizarazu, Parenti, and Monti 2021; Zegada-Lizarazu et al. 2022) double cropping experimental yield values were actually used as input data for the simulation since they were considered more reliable than those taken from the literature. The reason for this is that most of the previously published studies present yields based on conventional farming systems (Gautam et al. 2020; Schomberg et al. 2007; Rotar and Joy 1983) or in different environments (Mansoer, Reeves, and Wood 1997; Enciso et al. 2015). However, a sensitivity analysis on the feedstock sourcing was conducted by creating different scenarios and sourcing cases and not by varying the crop yield values.

#### 3.1.2 | Biomass Composition and Estimated Bioethanol Production

The composition of cultivated and residue feedstock was consistent with data reported in literature for these biomasses (Table 4, Kamireddy et al. 2013; Stefaniak et al. 2012; Zhao et al. 2009). Biomass sorghum showed the lowest C6 sugars content of the biomasses analyzed (27.8% d.m.), being the total sugar content lower than typically observed for this

**TABLE 4** | Total bioethanol yield of sugars in cellulose and hemicellulose hydrolysate fermented separately.

| | Biochemical composition | | Sugar hydrolysate[a] | | Bioethanol production[b] | | |
|---|---|---|---|---|---|---|---|
| Feedstock | C5 sugars (% of d.m.) | C6 sugars (% of d.m.) | c5 sugars ($kg\,Mg^{-1}$ d.m.) | C6 sugars ($kg\,Mg^{-1}$ d.m.) | c5 sugars ($kg\,Mg^{-1}$ d.m.) | C6 sugars ($kg\,Mg^{-1}$ d.m.) | Total sugars ($kg\,Mg^{-1}$ d.m.) |
| Maize stover | 19.7 | 31.4 | 177.3 | 282.6 | 76.9 | 136.9 | 213.8 |
| Wheat straw | 22.7 | 36.0 | 204.3 | 324.0 | 88.6 | 157.0 | 245.5 |
| Biomass sorghum | 20.6 | 27.8 | 185.4 | 250.2 | 80.4 | 121.2 | 201.6 |
| Sunn hemp | 11.7 | 36.4 | 105.3 | 327.6 | 45.6 | 158.7 | 204.4 |

[a]Conversion efficiencies of acid pretreatment (C5 sugars) and acid pretreatment and enzymatic hydrolysis (C6 sugars) of 90% (Batog et al. 2020; Humbird et al. 2011; Novy et al. 2014; Novy, Longus, and Nidetzky 2015; Paul and Chakraborty 2019; Zhao, Damgaard, and Christensen 2018).
[b]Assumed conversion efficiencies of fermentation of 85% and 95% for C5 and C6 sugars, respectively. Assumed bioethanol yield of 0.51 g of ethanol per g of sugar (C5 and C6).

specific biomass (35%–40% d.m.) (Gomes et al. 2019; Phyllis2 Database, n.d.). These biomasses are rich in hemicellulosic sugars that can also be utilized as feedstock for yeast fermentation to bioethanol. In order to make these sugars available for the fermenting microorganisms, pretreatment and hydrolysis steps are needed. The most studied processing methods for lignocellulosic biomasses are based on a pretreatment under aqueous acidic conditions to disrupt the macrostructure of the biomass and make it accessible to saccharifying enzymes that can depolymerise cellulose and hemicellulose into monomeric sugars (Figure 2). Bioethanol production from both glucose and xylose from maize stover, wheat straw, sunn hemp and sorghum biomasses after acid pretreatment and enzymatic hydrolysis has been reported previously (Batog et al. 2020; Humbird et al. 2011; Novy et al. 2014; Novy, Longus, and Nidetzky 2015; Paul and Chakraborty 2019; Zhao, Damgaard, and Christensen 2018). The data reported on conversion yields have been used to estimate the production of bioethanol from the specific biomasses used in this study, based on their respective biochemical analysis (Table 4). Therefore, the data used as basis for the sustainability analysis of the value chains defined for bioethanol production are based on experimental data on chemical composition for each biomass and on literature data of experimental work on pretreatment and fermentation of similar biomasses. Using this approach, the resulting estimations are representative for processes for bioethanol production using these feedstocks.

### 3.2 | Value Chain Evaluation

Wheat and maize resulted as the crops with the greatest acreage in Emilia-Romagna. In 2020, they were cultivated on about 270,000 ha, representing 24% of the utilized agricultural area (UAA). The potential main feedstock source contributor in S1 (Figure 4) is wheat straw (416,534 $Mg\,year^{-1}$ d.m. of feedstock), whereas maize stover could only deliver 301,512 $Mg\,year^{-1}$ d.m. of feedstock due to a lower acreage.

S2 foresees the intensification of the traditional cropping systems with sorghum and sunn hemp on 6578 ha currently cultivated with italian ryegrass, oats and rye (Figure 4). These cereals cultivated for forage purposes become ready for harvest early in the season and they can be double cropped with sorghum and sunn hemp without irrigation. S2 could produce an additional 85,944 $Mg\,year^{-1}$ d.m. of feedstock compared with S1.

S3 is characterized by a higher level of intensification where the irrigated areas were all considered for double cropping even with late planting in summer (Table 1). The calculated additional land availability for S3 in Emilia-Romagna was 165,602 ha, considering that wheat acreage was accounted both for the straw and for the double cropping on irrigated lands (140,590 ha). The feedstock availability (Figure 4) in S3 is higher for sorghum (1,803,260 $Mg\,year^{-1}$ dw of feedstock), then for sunn hemp (557,546 $Mg\,year^{-1}$ dw of feedstock), wheat straw (416,534 $Mg\,year^{-1}$ dw of feedstock) and maize stover (301,512 $Mg\,year^{-1}$ dw of feedstock).

The productivity map (Figure 4) displays a higher feedstock density in the plain areas in the northern part of Emilia-Romagna where agriculture is intensive and most profitable, whereas the gray hexagons in the southern part correspond to the hilly areas, which offer a lower amount of feedstock.

The comparison of the different sourcing scenarios (Table 5) shows that GHG emissions related to feedstock production, storage, transport, and unloading were found to be lowest in S1_g50 (3906 Mg $CO_2$eq $year^{-1}$), whereas the highest emissions were found in S3_c50 reaching 5341 Mg $CO_2$eq $year^{-1}$. This difference in range is relatively larger (37%) than the difference found between the highest and lowest cost levels. In S1, entirely based on straw and stover, 3% lower emission levels can be reached by increasing the mobilization level from 25% to 50%, thanks to the optimisation of the collection efforts (transport). Similarly, in S2, an 11% GHG emission reduction is obtained by increasing the mobilization level from 25 to 50% coupled with a higher share of straw and stover and a reduced share of sorghum. In S3, the gain in GHG efficiency is the largest with −22% moving from c25 to g50. This is particularly caused by the fact that LocaGIStics2.0 adapts the collection strategy to prioritize the lowest emissions

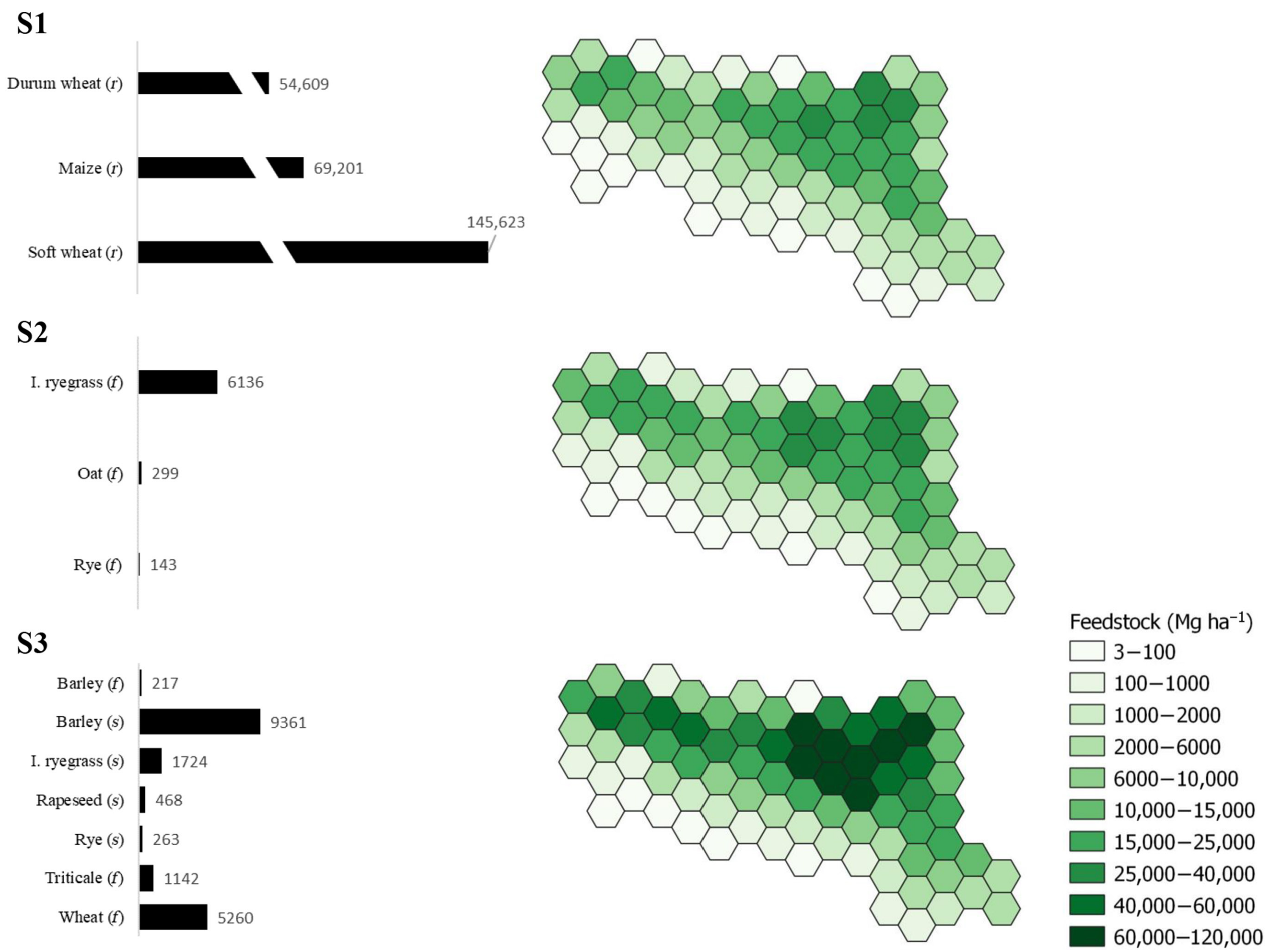


**FIGURE 4** | Left side: Emilia-Romagna acreage (ha) for food land which was considered for implementation with the double-cropped biomass sorghum and sunn hemp, for S1, S2, and S3, respectively. The acreage is cumulated as follows: S1 = S1; S2 = S1 + S2; S3 = S1 + S2 + S3. On the right-hand side, the availability of sustainable food residues removal and double crop feedstock is discretized in hexagons for S1, S2, and S3, respectively; (*r*) abbreviation for residues; (*f*) abbreviation for forage production; (*s*) abbreviation for seed production.

and is able to significantly reduce the cultivation emissions by prioritizing the collection of sunn hemp over sorghum. Higher shares of sunn hemp can only be reached with higher mobilisation levels as is applicable to g50. Even though GHG emissions are relatively low for sunn hemp, the lower spatial distribution may cause the transport emissions of sunn hemp to be relatively higher than that of crop residues (Figure 5b). Indeed, leveraging residual biomass as the sole source for the value chain is always the most GHG efficient option as in S1. Overall, it is crystal clear that GHG emissions can be reduced significantly by basing the bioethanol chains on a combination of straw, stover and efficiently produced sunn hemp where possible. Cost differences are not that significant between the different biomass sourcing mixes, as cost of residues and crops does not differ greatly and the final cost level is determined by the combination of biomass and transport cost.

Overall, the biomass sourcing cost range was not broader than 10% of total sourcing costs across the different cases and sourcing scenarios. In this light, the lowest average sourcing cost (Table 5) was 92 €Mg$^{-1}$ d.m. (S1_c50), whereas the highest cost was at 100.7 €Mg$^{-1}$ d.m. (S2_g25).

In S2, the lowest sourcing costs are reached with a biomass crop mix in which sorghum and straw/stover shares are as low and as high as possible, respectively. In S3, to reach the best costing performance the model selected a high share of sunn hemp and no straw. Sunn hemp is the cheapest biomass resource, but it has lower spatial density and therefore the cost of collecting it may be relatively higher than for other crops or residues. Therefore, LocaGIStics2.0 chooses the locations where sunn hemp is grown in combination with sorghum, which has a high spatial concentration due to high yields per hectare. The biomass sourcing cost for maize stover was double that of Becerra-Pérez, Rincón, and Posada-Duque (2022), although the mobilization scenarios are a marked difference in methodology between the two studies. Traverso et al. (2020) calculated a biomass sourcing cost of 71 €Mg$^{-1}$ for dedicated perennial energy crop more aligned with the present study, but still about 25% lower. In this case, giant reed was produced in a post-mining area contaminated with heavy metals that are not constraining to giant reed yield, but conversely the area turned out to be unsuitable for food production. Heavy metals in the aboveground biomass could, however, increase the advanced bioethanol conversion post-production costs for metal removal.

**TABLE 5** | Feedstock contribution to each scenario, biomass collection, biomass cost and GHG emissions for the four sourcing cases: c25, 25% mobilization level and collection according to lowest cost; g25, 25% mobilization level and collection according to lowest GHG; c50, 50% mobilization level and collection according to lowest cost; g50, 50% mobilization level and collection according to lowest GHG.

| Scenario | ID | Food residues (%) | Biomass sorghum (%) | Sunn hemp (%) | Cost (€ $Mg^{-1}$ of feedstock) | GHG (Mg $CO_2$eq $year^{-1}$) |
|---|---|---|---|---|---|---|
| 25% lowest cost | | | | | | |
| S1 | S1_c25 | 100 | 0 | 0 | 97.0 | 4020 |
| S2 | S2_c25 | 36 | 24 | 40 | 99.1 | 4945 |
| S3 | S3_c25 | 0 | 37 | 63 | 96.0 | 5341 |
| 25% lowest GHG | | | | | | |
| S1 | S1_g25 | 100 | 0 | 0 | 97.0 | 4020 |
| S2 | S2_g25 | 43 | 15 | 42 | 100.7 | 4383 |
| S3 | S3_g25 | 0 | 22 | 78 | 97.2 | 4170 |
| 50% lowest cost | | | | | | |
| S1 | S1_c50 | 100 | 0 | 0 | 92.0 | 3906 |
| S2 | S2_c50 | 36 | 24 | 40 | 99.1 | 4945 |
| S3 | S3_c50 | 0 | 37 | 63 | 96.0 | 5341 |
| 50% lowest GHG | | | | | | |
| S1 | S1_g50 | 100 | 0 | 0 | 92.0 | 3906 |
| S2 | S2_g50 | 43 | 15 | 42 | 99.1 | 4383 |
| S3 | S3_g50 | 0 | 22 | 78 | 96.0 | 4170 |

### 3.2.1 | GHG Emission Components

The value chain assessment of sorghum, sunn hemp, straw, and maize stover (Figure 6) revealed different GHG emissions between the use of dedicated crops (sorghum and sunn hemp) and the use of agricultural residues (like straw and maize stover), with advantages for the latter (−10%). In particular, for dedicated lignocellulosic crops there are additional emissions due to the input of fertilizer and the use of fossil diesel for cultivation and harvesting processes of sorghum and sunn hemp. The emissions from demand and use of fertilizer, such as N-fertilizer, are caused by energy intensive fertilizer production and $N_2O$ field emission from N-application. By contrast, the assessment of value chains based on straw/stover starts with the biomass collection. Upstream emissions and expenditures from cultivation are not included, whereas compensatory fertilization for straw removal was. A further difference is associated with the improvement of SOC and the credits given for the carbon accumulation. However, the carbon credits cannot offset the higher emissions associated with cultivation and harvesting of sorghum and sunn hemp. In this regard, overall GHG emissions for the residue-based value chains are slightly lower compared with value chains using double cropping. The emissions associated with conversion are similar across the different feedstocks (Figure 6). Since the required process energy is provided internally using lignin and biogas, the emissions are largely related to the use of auxiliary and operating materials. In the present study, the GHG emissions associated with double cropping systems are in the range of 0 – 50 g $CO_2$eq $MJ^{-1}$ of fuel as assessed in a comprehensive European study for perennial energy crops on marginal land (Vera Concha et al. 2021). In this light, the double cropping systems were surprisingly well performing even though they resulted slightly higher (15 g $CO_2$eq $MJ^{-1}$ of fuel) compared with residues (13.5 g $CO_2$eq $MJ^{-1}$ of fuel). This is due to a high biomass yield and broad feedstock availability per unit of land, offsetting the crop cultivation input with regard to N-fertilization compared with marginal areas.

### 3.2.2 | Cost Components

The biomass supply operation showed a different impact on the final bioethanol costs (Figure 7). As the costs are presented proportionally to the total costs, the influence of different steps in one chain is illustrated. The production costs are compared for the individual production processes, and the total cost ranges between 608 and 710 € $Mg^{-1}$ of bioethanol corresponding to 0.52 to 0.60 € $L^{-1}$ for sorghum and corn stover, respectively. Intermediate values were found for sunn hemp (672 € $Mg^{-1}$) and straw (632 € $Mg^{-1}$). Biomass production (cultivation and harvesting) represents the major driver influencing the overall manufacturing costs. Disposal costs play no role in this context. The dependence of the production costs on the operation and maintenance is clear. In each case, these account for more than 90% of the overall production costs. The costs are reduced in part by profits from surplus electricity, which has a relevant impact because they can offset about 1/3 of the overall costs. Even if these calculations were primarily

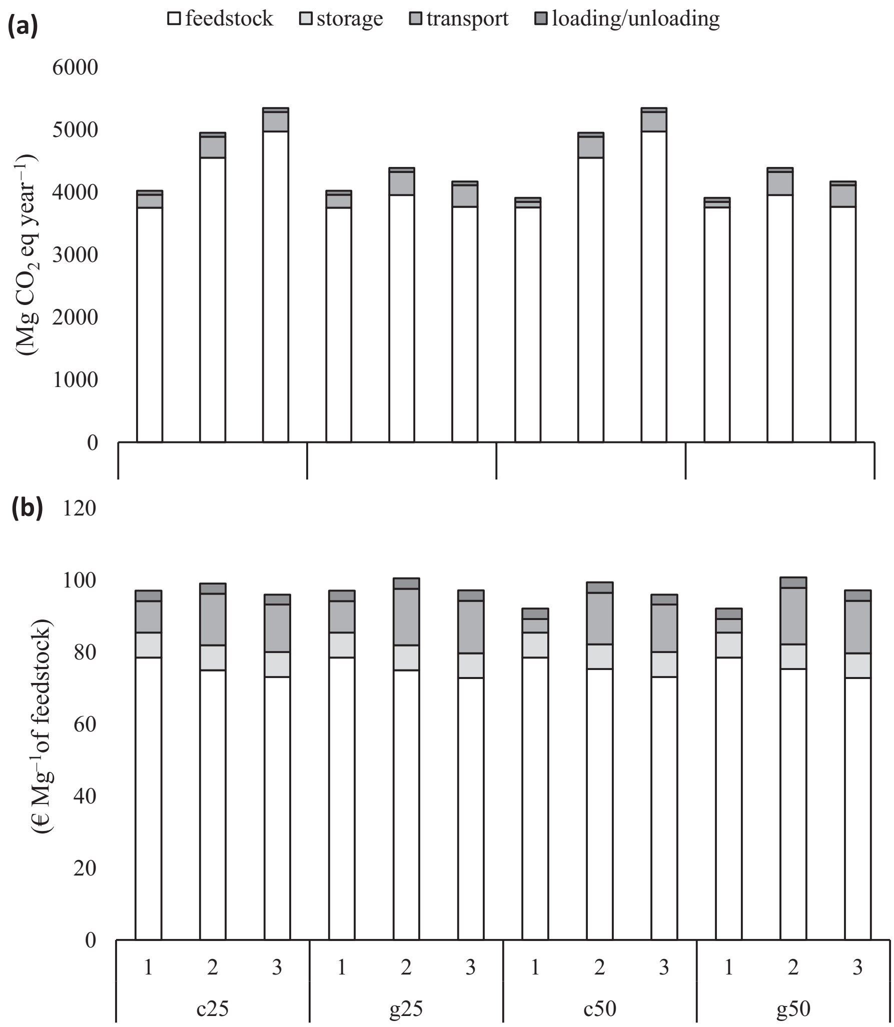


**FIGURE 5** | (a) GHG emissions and (b) Cost structure of feedstock production and delivery, in three scenarios for the four sourcing cases: c25, 25% mobilization level and collection according to lowest cost; g25, 25% mobilization level and collection according to lowest GHG; c50, 50% mobilization level and collection according to lowest cost; g50, 50% mobilization level and collection according to lowest GHG.

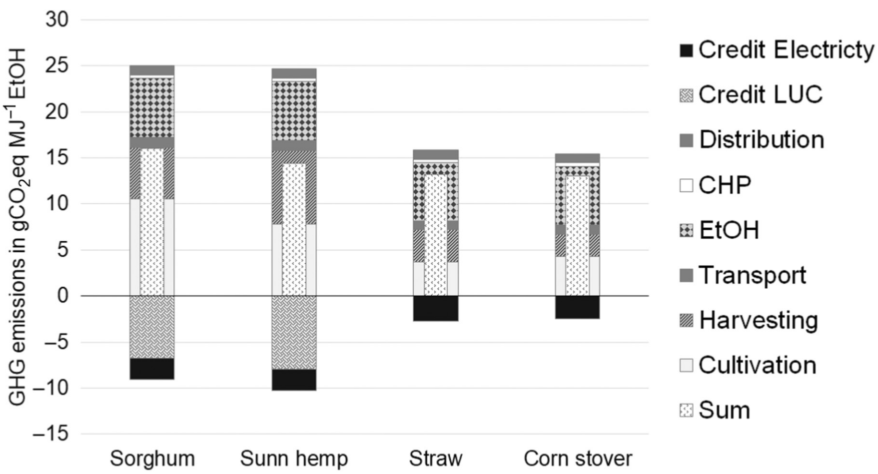


**FIGURE 6** | GHG emissions in $gCO_2eq\,MJ^{-1}$ of bioethanol for biomass sorghum, sunn hemp, straw and maize stover. These results are compliant with ISO 14040 methodology. The figure shows the results as a stacked bar chart. The resulting GHG emissions are superimposed on the individual GHG where CHP stands for 'Combined Heat and Power'. Credits are shown as "negative" in the bar chart.

made for the comparability of the different raw materials, the result is relatively comparable costs for all raw materials. For a commercial use, these costs are to be compared in particular with conventional bioethanol and are already in the range of scale (around 500 € $Mg^{-1}$) (Dögnitz, Etzold, and Meisel 2023). Commercialization would therefore be conceivable, especially

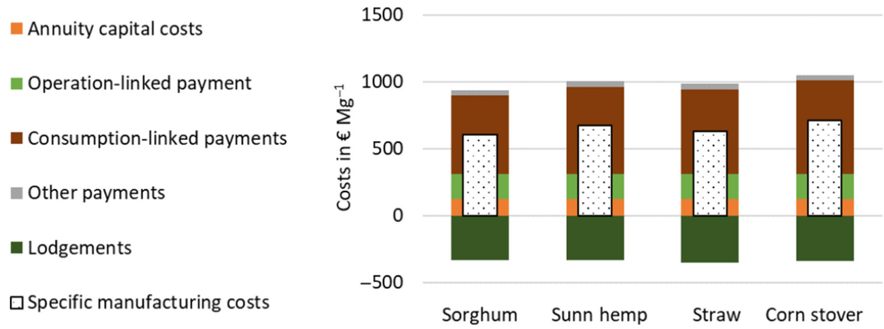


**FIGURE 7** | Results for different feedstock for specific manufacturing costs. The figure shows the results as a stacked bar chart. Resulting production costs are superimposed on the individual cost items. The costs are expressed as €$Mg^{-1}$ of bioethanol. Revenues are shown as "negative" costs in the bar chart.

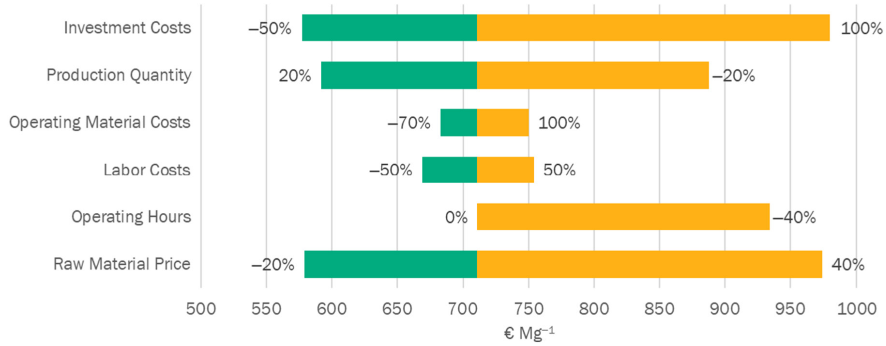


**FIGURE 8** | Sensitivity analysis, examples for corn stover. In green and yellow colors are represented the decrease and increase in feedstock price, respectively, due to the change of the parameters in the *y*-axis.

when considering possible support under the Renewable Energy Directive.

A sensitivity study of the life cycle costs was carried out selecting corn stover as the reference, although the other feedstock behavior was similar. Figure 8 shows the variation in the key input variables from ±50% and the relevant percentile effect on the life cycle costs of the bioethanol costs. The sensitivity analysis highlights that feedstock price has the greatest influence on total production costs. With a 50% increase of the feedstock price, production costs rise by 47%, demonstrating a high positive correlation between the two variables. An increase and reduction of investment costs and surplus energy (electricity) by 50% leads to about 18% (investment) and 15% (energy) increase and decrease, respectively, in the overall manufacturing costs. A great impact was also found in the operating grade of the plant. If the operating hours are lowered, for instance when influenced by a non-continuous feedstock supply, the costs increase significantly. Conversely, variation of the remaining inputs such as labor or operating hours only lead to a marginal increase or reduction in the life cycle costs of the final product.

Figure 8 shows the variation of key input variables at different levels and the corresponding impact on the cost of bioethanol production. The sensitivity analysis shows that the feedstock price and investment costs have the greatest impact on total production costs. A 40% increase in the feedstock price or a 100% increase in the investment cost increases the production cost by 37%, demonstrating a high correlation between the two variables. Similarly, an increase or decrease in production volume (−20%) or operating hours (−40%) leads to an increase or decrease in total manufacturing costs of around 25% (volume) and 31% (hours), respectively. If the operating hours are reduced, for example, due to a discontinuous supply of raw materials, the costs increase significantly. Conversely, variations in the other inputs, such as labor or operating hours, only marginally increase or decrease the life cycle costs of the final product.

### 3.3 | Final Remarks and Areas of Improvements

Advanced biofuel value chains sourced by lignocellulosic biomasses are strongly dependent on the site-specific characteristics of the plant surroundings. Crop production inputs such as soil till and N-fertilization have been demonstrated to directly impact the value chain GHG emissions and cost (Becerra-Pérez, Rincón, and Posada-Duque 2022), thus the comparison of the presented results with those of other studies that focus on different feedstock should be done with this in mind. The presented cropping systems were challenged and hampered somewhat by a lack of dedicated farm machinery, a lack of structured value chain, and limited crop variety availability, although they demonstrated to be promising (Berti et al. 2015) and are currently adopted in small-scale Biogas-Done-Right concept (Tamburini et al. 2020) in Emilia-Romagna. In this light, agronomists and researchers are working to increase double cropping feasibility. A lack of an advanced biofuel value chain is acknowledged as a serious barrier, in particular, the main weaknesses identified by the IRENA (2019) report, were: stability of regulation, availability, and cost of financing, conversion efficiency, technology risk, and process reliability, level of subsidies, level of blending mandates, feedstock price and availability, ranked from the most to least important, respectively.

A methodological tradeoff of GHG emissions was, however, necessary due to the intrinsic nature of the assessment. The GHG emissions are calculated as individual balances that are highly dependent on process-specific characteristics, methodological assumptions, and data availability. Thus, the GHG emissions of the present study are, therefore, only valid under the specified framework conditions. Value chain cost assessments (Table S5) were primarily calculated for the purpose of comparing internal raw materials, enabling the comparison of different results. Assumptions were made for non-established process routes, and these specifically relate to the key figures which resulted from the BECOOL project and which were reported in Table S3. A comparison and classification with other studies is hardly applicable in this case, as these highly specific routes can only be grouped within a broader overview of routes that lead to very different outcomes. Nonetheless, the findings align well with the ranges of previous research.

## 4 | Conclusions

A holistic approach was used to design an advanced bioethanol value chain that combined conceptually innovative cropping systems, design of a regional supply chain for the Emilia-Romagna region, GHG emissions, economic evaluations and validation of the potential bioethanol production from dedicated energy crops based on literature. Sourcing a bioethanol plant with an annual capacity of 250,000 Mg of biomass entirely on wheat straw is the most attractive option in terms of GHG efficiency and is also relatively feasible given the large amount of residue availability in Emilia-Romagna, although biomass sorghum is the most attractive with regard to costs. The produced bioethanol could replace from 5% to 7% of Emilia-Romagna's fuel consumption, depending on the applied sourcing scenario. The cost analysis showed, however, that the difference between the explored cultivation scenarios and feedstock mobilization level is low (10%), although the differences increase when accounting for GHG (37%).

Overall, lowest emissions were found from wheat straw and maize stover but also sunn hemp can be produced at relatively low emission levels. High spatial concentration of feedstocks particularly of sunn hemp, by increasing the mobilization levels, will make the sourcing of biomass significantly more GHG efficient. Concentrating on double cropping of sunn hemp in certain Emilia-Romagna districts could increase feedstock availability with low GHG emissions and secure the supply chain. However, despite the highest mobilization per unit of land, sorghum is the cheapest feedstock, although with the slightly higher GHG emissions. The emission differences between dedicated crops (sorghum and sunn hemp) and crop residues (straw and stover) are mainly caused by demand and use of fertilizer, in particular N based, due to energy intensive production processes and $N_2O$ field emissions. Part of these emissions are offset by the increment of SOC which provides carbon credits. However, the carbon credits cannot offset the higher emissions associated with cultivation and harvesting of sorghum and sunn hemp. Emissions in the conversion process are partly balanced by the provision of process energy from internal sources such as lignin and biogas.

Biomass production (cultivation and harvesting) costs represent a relatively high share of the total LCC cost. However, there are no major differences between the individual feedstock options in price and conversion costs. The costs are reduced in part by profits from surplus electricity (i.e. internal sources from lignin and biogas internally provided in the process), which is highly relevant for cost reduction.

Besides feedstock cost, the operating grade of the plant also has a large influence on the LCC. The sensitivity analysis showed that if the operation hours are lowered, for instance when influenced by a noncontinuous feedstock supply, the costs rise sharply. Variation of the remaining input variables such as labor or operating materials only lead to a marginal increase or reduction in the life cycle costs of the final product. In this light, the feedstock diversification becomes crucial in order to secure a constant flow of supply to the plant, even in the case of harsh cultivation seasons.

### Author Contributions

**Andrea Parenti:** conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft, writing – review and editing. **Walter Zegada-Lizarazu:** conceptualization, funding acquisition, investigation, project administration, supervision, writing – review and editing. **Karla Dussan:** conceptualization, data curation, formal analysis, investigation, visualization, writing – original draft, writing – review and editing. **Ana M. López-Contreras:** data curation, funding acquisition, investigation, project administration, writing – original draft, writing – review and editing. **Truus de Vrije:** data curation, formal analysis, investigation, writing – original draft, writing – review and editing. **Igor Staritsky:** formal analysis, investigation, methodology, software, writing – review and editing. **Berien Elbersen:** conceptualization, data curation, formal analysis, funding acquisition, project administration, software, writing – original draft. **Bert Annevelink:** conceptualization, data curation, formal analysis, software, writing – original draft, writing – review and editing. **Fulvio Di Fulvio:** data curation, formal analysis, investigation, writing – original draft, writing – review and editing. **Katja Oehmichen:** data curation, methodology, validation, visualization, writing – original draft, writing – review and editing. **Niels Dögnitz:** data curation, methodology, software, validation, visualization, writing – original draft, writing – review and editing. **Andrea Monti:** conceptualization, funding acquisition, project administration, resources, supervision.

### Acknowledgements

This work was supported by the European Union's Horizon 2020 Research and Innovation Programme (grant agreement 744821—BECOOL project: https://www.becoolproject.eu/).

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are openly available at Zenodo at https://doi.org/10.5281/zenodo.13169149.

## References


Amaducci, S., M. T. Amaducci, R. Benati, and G. Venturi. 2000. "Crop Yield and Quality Parameters of Four Annual Fibre Crops (Hemp, Kenaf, Maize and Sorghum) in the North of Italy." *Industrial Crops and Products* 11: 179–186.

Amaducci, S., M. Colauzzi, F. Battini, A. Fracasso, and A. Perego. 2016. "Effect of Irrigation and Nitrogen Fertilization on the Production of Biogas From Maize and Sorghum in a Water Limited Environment." *European Journal of Agronomy* 76: 54–65. https://doi.org/10.1016/j.eja.2016.01.019.

Anderson-Teixeira, K. J., S. C. Davis, M. D. Masters, and E. H. Delucia. 2009. "Changes in Soil Organic Carbon Under Biofuel Crops." *GCB Bioenergy* 1, no. 1: 75–96. https://doi.org/10.1111/j.1757-1707.2008.01001.x.

Andrés, L., and E. Padilla. 2018. "Driving Factors of GHG Emissions in the EU Transport Activity." *Transport Policy* 61, no. November 2017: 60–74. https://doi.org/10.1016/j.tranpol.2017.10.008.

Annevelink, B., B. Elbersen, M. Essers, et al. 2021. *BECOOL Project D2.2: Tools (BeWhere, LocaGIStics and Bioloco) Adapted to Be Tested in the Selected Case Studies (Issue 744821)*. https://www.becoolproject.eu/.

Balkcom, K. S., J. M. Massey, J. A. Mosjidis, A. J. Price, and S. F. Enloe. 2011. "Planting Date and Seeding Rate Effects on Sunn Hemp Biomass and Nitrogen Production for a Winter Cover Crop." *International Journal of Agronomy* 2011: 1–8. https://doi.org/10.1155/2011/237510.

Bassett, R., and R. Horne. 2008. "Unchaining Value. Innovative Approaches to Sustainable Supply." https://ysrinfo.files.wordpress.com/2012/06/unchaining-value-final-report.pdf.

Batog, J., J. Frankowski, A. Wawro, and A. Lacka. 2020. "Bioethanol Production From Biomass of Selected Sorghum Varieties Cultivated as Main and Secon Crop." *Energies* 13: 6291. https://doi.org/10.3390/en13236291.

Becerra-Pérez, L. A., L. E. Rincón, and J. A. Posada-Duque. 2022. "Logistics and Costs of Agricultural Residues for Cellulosic Ethanol Production." *Energies* 15, no. 12: 1–18. https://doi.org/10.3390/en15124480.

Berti, M., R. Gesch, B. Johnson, Y. Ji, W. Seames, and A. Aponte. 2015. "Double- and Relay-Cropping of Energy Crops in the Northern Great Plains, USA." *Industrial Crops and Products* 75: 26–34. https://doi.org/10.1016/j.indcrop.2015.05.012.

Cantrell, K. B., P. J. Bauer, and K. S. Ro. 2010. "Utilization of Summer Legumes as Bioenergy Feedstocks." *Biomass & Bioenergy* 34, no. 2: 1961–1967. https://doi.org/10.1016/j.biombioe.2010.08.005.

Cherr, C. M., J. M. S. Scholberg, and R. McSorley. 2006. "Green Manure as Nitrogen Source for Sweet Corn in a Warm-Temperate Environment." *Agronomy Journal* 98, no. 5: 1173–1180. https://doi.org/10.2134/agronj2005.0036.

Colauzzi, M., P. Serra, and S. Amaducci. 2018. "Variety Earliness Effect on Field Drying of Biomass Sorghum." *Biomass and Bioenergy* 115: 160–173. https://doi.org/10.1016/j.biombioe.2018.04.011.

Dahmen, N., I. Lewandowski, S. Zibek, and A. Weidtmann. 2019. "Integrated Lignocellulosic Value Chains in a Growing Bioeconomy: Status Quo and Perspectives." *GCB Bioenergy* 11, no. 1: 107–117. https://doi.org/10.1111/gcbb.12586.

Dautzenberg, K., and J. Hanf. 2008. "Biofuel Chain Development in Germany: Organisation, Opportunities, and Challenges." *Energy Policy* 36, no. 1: 485–489. https://doi.org/10.1016/j.enpol.2007.08.010.

De Jong, S., R. Hoefnagels, R. Slade, R. Mawhood, and M. Junginger. 2015. "The Feasibility of Short-Term Production Strategies for Renewable Techno-Economic Comparison." *Biofuels, Bioproducts and Biorefining*: 778–800. https://doi.org/10.1002/bbb.1613.

Dees, M., M. Hohl, P. Datta, et al. 2017. "S2Biom Project D1.6—A Spatial Data Base on Sustainable Biomass Cost-Supply of Lignocellulosic Biomass in Europe—Method and Data Source." https://zenodo.org/record/1478483.

Dögnitz, N., H. Etzold, and K. Meisel. 2023. "Economic Aspects of Sustainability." In *Monitoring Renewable Energies in Transport (DBFZ Report No. 44)*, edited by J. Schröder and K. Naumann, 57–91. Leipzig: DBFZ.

Dong, W., C. Hu, S. Chen, and Y. Zhang. 2009. "Tillage and Residue Management Effects on Soil Carbon and $CO_2$ Emission in a Wheat-Corn Double-Cropping System." *Nutrient Cycling in Agroecosystems* 83, no. 1: 27–37. https://doi.org/10.1007/s10705-008-9195-x.

Dou, F., J. P. Wight, L. T. Wilson, J. O. Storlien, F. M. Hons, and U. M. Sainju. 2014. "Simulation of Biomass Yield and Soil Organic Carbon Under Bioenergy Sorghum Production." *PLoS One* 9, no. 12: 1–15. https://doi.org/10.1371/journal.pone.0115598.

Enciso, J., J. Jifon, L. Ribera, S. D. Zapata, and G. K. Ganjegunte. 2015. "Yield, Water Use Efficiency and Economic Analysis of Energy Sorghum in South Texas." *Biomass and Bioenergy* 81: 339–344. https://doi.org/10.1016/j.biombioe.2015.07.021.

European Commission. 2010. "Guidelines for the Calculation of Land Carbon Stocks for the Purpose of Annex V to Directive 2009/28/EC." https://doi.org/10.18356/7b0a64c4-en.

European Commission. 2019. "The European Green Deal." http://eur-lex.europa.eu/resource.html?uri=cellar:208111e4-414e-4da5-94c1-852f1c74f351.0004.02/DOC_1&format=PDF.

European Parliament. 2018. "Directive (EU) 2018/2001 of the European Parliament and of the Council on the Promotion of the Use of Energy From Renewable Sources." *Official Journal of the European Union* 2018, no. 328: 82–209.

Eurostat. 2021. "Eurostat Regional Yearbook 2021 Edition." https://doi.org/10.2785/762788.

Fazio, S., and L. Barbanti. 2014. "Energy and Economic Assessments of bio-Energy Systems Based on Annual and Perennial Crops for Temperate and Tropical Areas." *Renewable Energy* 69: 233–241. https://doi.org/10.1016/j.renene.2014.03.045.

Feyereisen, G. W., G. G. T. Camargo, R. E. Baxter, J. M. Baker, and T. L. Richard. 2013. "Cellulosic Biofuel Potential of a Winter Rye Double Crop Across the U.S. Corn-Soybean Belt." *Agronomy Journal* 105, no. 3: 631–642. https://doi.org/10.2134/agronj2012.0282.

Gabrielle, B., A. Bispo, M. El Akkari, et al. 2017. "Biomass, Land-Use Changes and Environmental Impacts: A Qualitative and Quantitative Review of Scientific Literature." 25th European Biomass Conference and Exhibition, 12–15 June 2017, Stockholm, Sweden.

Gauder, M., S. Graeff-Hönninger, and W. Claupein. 2011. "Identifying the Regional Straw Potential for Energetic Use on the Basis of Statistical Information." *Biomass and Bioenergy* 35, no. 5: 1646–1654. https://doi.org/10.1016/j.biombioe.2010.12.041.

Gautam, S., U. Mishra, C. D. Scown, and Y. Zhang. 2020. "Sorghum Biomass Production in the Continental United States and Its Potential Impacts on Soil Organic Carbon and Nitrous Oxide Emissions." *GCB Bioenergy* 12, no. 10: 878–890. https://doi.org/10.1111/gcbb.12736.

Gomes, L., F. De Almeida, R. Augusto, et al. 2019. "Biomass and Bioenergy Composition and Growth of Sorghum Biomass Genotypes for Ethanol Production." *Biomass and Bioenergy* 122: 343–348. https://doi.org/10.1016/j.biombioe.2019.01.030.

Graß, R., F. Heuser, R. Stülpnagel, H. P. Piepho, and M. Wachendorf. 2013. "Energy Crop Production in Double-Cropping Systems: Results From an Experiment at Seven Sites." *European Journal of Agronomy* 51: 120–129. https://doi.org/10.1016/j.eja.2013.08.004.

Hassan, M. U., M. U. Chattha, L. Barbanti, et al. 2020. "Cultivar and Seeding Time Role in Sorghum to Optimize Biomass and Methane Yield

Under Warm Dry Climate." *Industrial Crops and Products* 145: 111983. https://doi.org/10.1016/j.indcrop.2019.111983.

Heggenstaller, A. H., R. P. Anex, M. Liebman, D. N. Sundberg, and L. R. Gibson. 2008. "Productivity and Nutrient Dynamics in Bioenergy Double-Cropping Systems." *Agronomy Journal* 100, no. 6: 1740–1748. https://doi.org/10.2134/agronj2008.0087.

Hoffmann, L., and W. L. Rooney. 2014. "Accumulation of Biomass and Compositional Change Over the Growth Season for six Photoperiod Sorghum Lines." *Bioenergy Research* 7, no. 3: 811–815. https://doi.org/10.1007/s12155-013-9405-5.

Hortsch, R., and P. Corvo. 2020. "The Biorefinery Concept: Producing Cellulosic Ethanol From Agricultural Residues." *Chemie-Ingenieur-Technik* 92, no. 11: 1803–1809. https://doi.org/10.1002/cite.202000203.

Humbird, D., R. Davis, L. Tao, et al. 2011. *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol. Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover.* Golden, CO: National Renewable Energy Lab (NREL).

IEA. 2023. *Tracking Clean Energy Progress 2023*. Paris: IEA. https://www.iea.org/reports/tracking-clean-energy-progress-2023.

ifu Hamburg GmbH. 2018. "Umberto LCA+." https://www.ifu.com/umberto/lca-software/.ISO.

IPCC. 2007. "Climate Change 2007: The Physical Science Basis." In *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, 996. Cambridge, UK and New York, NY: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/05/ar4_wg1_full_report-1.pdf.

IRENA. 2019. "Advanced Biofuels. What Holds Them Back?" https://www.irena.org/publications/2019/Nov/Advanced-biofuels-What-holds-them-back.

ISTAT. 2019. Italian Institute of Statistics. https://www.istat.it/en/.

ISTAT. 2022. Italian Institute of Statistics. https://www.istat.it/en/.

Kamireddy, S. R., J. Li, S. Abbina, M. Berti, M. Tucker, and Y. Ji. 2013. "Converting Forage Sorghum and Sunn Hemp Into Biofuels Through Dilute Acid Pretreatment." *Industrial Crops and Products* 49: 598–609. https://doi.org/10.1016/j.indcrop.2013.06.018.

Kaplinsky, R., and M. Morris. 2000. *A Handbook for Value Chain*. Institute for Development Studies: Brighton, UK.

Khanh, T. D., M. I. Chung, T. D. Xuan, and S. Tawata. 2005. "The Exploitation of Crop Allelopathy in Sustainable Agricultural Production." *Journal of Agronomy and Crop Science* 191, no. 3: 172–184. https://doi.org/10.1111/j.1439-037X.2005.00172.x.

Khawaja, C., R. Janssen, and B. S. Elbersen. 2014. "Sustainable Supply of Non-Food Biomass for a Resource Efficient Bioeconomy. A Review Paper on the State-Of-The-Art." S2Biom. https://edepot.wur.nl/517819.

Lal, R. 2004. "Agricultural Activities and the Global Carbon Cycle." *Nutrient Cycling in Agroecosystems* 70: 103–116. https://doi.org/10.1023/B:FRES.0000048480.24274.0f.

Lazzarini, S. G., F. R. Chaddad, and M. L. Cook. 2001. "Integrating Supply Chain and Network Analyses: The Study of Netchains." *Journal on Chain and Network Science* 1, no. 1: 7–22. https://doi.org/10.3920/JCNS2001.x002.

Mansoer, Z., D. W. Reeves, and C. W. Wood. 1997. "Suitability of Sunn Hemp as an Alternative Late-Summer Legume Cover Crop." *Soil Science Society of America Journal* 61: 246–253. https://doi.org/10.2136/sssaj1997.03615995006100010034x.

Martinez Uribe, R. A., P. C. Silvério, G. H. Gravatim Costa, L. C. Nogueira, and L. A. Rosa Leite. 2020. "Chloride Levels in Biomass Sorghum due to Fertilization Sources." *Biomass and Bioenergy* 143: 105845. https://doi.org/10.1016/j.biombioe.2020.105845.

Mergner, R., R. Janssen, D. Rutz, et al. 2017. "Fostering Sustainable Feedstock Production for Advanced Biofuels on Underutilised Land in Europe." In *European Biomass Conference and Exhibition Proceedings*, 125–130.

Novy, V., S. Krahulec, M. Wegleiter, et al. 2014. "Process Intensification Through Microbial Strain Evolution: Mixed Glucose-Xylose Fermentation in Wheat Straw Hydrolyzates by Three Generations of Recombinant Saccharomyces Cerevisiae." *Biotechnology for Biofuels* 7, no. 46: 1–12.

Novy, V., K. Longus, and B. Nidetzky. 2015. "From Wheat Straw to Bioethanol: Integrative Analysis of a Separate Hydrolysis and Co-Fermentation Process With Implemented Enzyme Production." *Biotechnology for Biofuels* 8, no. 46: 1–12. https://doi.org/10.1186/s13068-015-0232-0.

Parenti, A., G. Cappelli, W. Zegada-Lizarazu, et al. 2021. "SunnGro: A New Crop Model for the Simulation of Sunn Hemp (*Crotalaria juncea* L.) Grown Under Alternative Management Practices." *Biomass and Bioenergy* 146: 105975. https://doi.org/10.1016/j.biombioe.2021.105975.

Parenti, A., C. Lambertini, and A. Monti. 2018. "Areas With Natural Constraints to Agriculture: Possibilities and Limitations for the Cultivation of Switchgrass (*Panicum virgatum* L.) and Giant Reed (*Arundo donax* L.) in Europe." In *Land Allocation for Biomass Crops*, edited by R. Li and A. Monti, 39–63. Cham: Springer. https://doi.org/10.1007/978-3-319-74536-7_3.

Parenti, A., W. Zegada-Lizarazu, A. Borghesi, and A. Monti. 2020. "Lignocellulosic Crops in Rotation With Food Crops." In *European Biomass Conference and Exhibition Proceedings, July, 2018–2020*.

Parenti, A., W. Zegada-Lizarazu, E. Pagani, and A. Monti. 2022. "Soil Organic Carbon Dynamics in Multipurpose Cropping Systems." *Industrial Crops and Products* 187: 115315. https://doi.org/10.1016/j.indcrop.2022.115315.

Paul, S., and S. Chakraborty. 2019. "Mixing Effects on the Kinetics of Enzymatic Hydrolysis of Lignocellulosic Sunn Hemp Fibres for Bioethanol Production." *Chemical Engineering Journal* 377: 120103. https://doi.org/10.1016/j.cej.2018.10.040.

Perpiña Castillo, C., B. Kavalov, V. Diogo, et al. 2018. "Trends in the EU Agricultural Land Within 2015–2030." https://ec.europa.eu/jrc/sites/jrcsh/files/jrc113718.pdf.

Peters, M. S., K. D. Timmerhaus, and R. E. West. 2004. *Plant Design and Economics for Chemical Engineers*. 5th ed. Boston: McGraw-Hill Chemical Engineering Series. http://journal.um-surabaya.ac.id/index.php/JKM/article/view/2203.

Phillips, S., B. Flach, S. Lieberz, J. Lappin, and S. Bolla. 2018. "EU Biofuels Annual." https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=BiofuelsAnnual_TheHague_EU-28_7-3-2018.pdf.

Phyllis2 Database. n.d. "Biomass, Algae, Feedstocks for Biogas Production and Biochar." TNO Biobased and Circular Technologies. https://phyllis.nl/.

Rotar, P. P., and R. J. Joy. 1983. *"Tropic Sun" Sunn Hemp, Crotalaria juncea L*. Vol. 36. Univ. of Hawaii, College of Tropical Agr. and Human Resources, Institute of Tropical Agr. and Human Resources Research Extension Series. https://core.ac.uk/download/5103695.pdf.

Schils, R., J. E. Olesen, K. C. Kersebaum, et al. 2018. "Cereal Yield Gaps Across Europe." *European Journal of Agronomy* 101, no. September: 109–120. https://doi.org/10.1016/j.eja.2018.09.003.

Schomberg, H. H., N. L. Martini, J. C. Diaz-Perez, S. C. Phatak, K. S. Balkcom, and H. L. Bhardwaj. 2007. "Potential for Using Sunn Hemp as a Source of Biomass and Nitrogen for the Piedmont and Coastal Plain

Regions of the Southeastern USA." *Agronomy Journal* 99, no. 6: 1448–1457. https://doi.org/10.2134/agronj2006.0294.

Serra, P., M. Colauzzi, and S. Amaducci. 2017. "Biomass Sorghum Production Risk Assessment Analysis: A Case Study on Electricity Production in the Po Valley." *Biomass and Bioenergy* 96: 75–86. https://doi.org/10.1016/j.biombioe.2016.10.016.

Simons, A. 2016. "Road Transport: New Life Cycle Inventories for Fossil-Fuelled Passenger Cars and Non-Exhaust Emissions in Ecoinvent v3." *International Journal of Life Cycle Assessment* 21, no. 9: 1299–1313. https://doi.org/10.1007/s11367-013-0642-9.

Singh, N. 2008. "A Model for Supply Chain Networks." *International Journal of Value Chain Management* 2, no. 4: 487–507. https://doi.org/10.1504/IJVCM.2008.019853.

Smit, A. T., A. Van Zomeren, K. Dussan, et al. 2022. "Biomass Pre-Extraction as a Versatile Strategy to Improve Biorefinery Feedstock Flexibility, Sugar Yields, and Lignin Purity." *ACS Sustainable Chemistry and Engineering* 10: 6012–6022. https://doi.org/10.1021/acssuschemeng.2c00838.

Stefaniak, T. R., J. A. Dahlberg, B. W. Bean, N. Dighe, E. J. Wolfrum, and W. L. Rooney. 2012. "Variation in Biomass Composition Components Among Forage, Biomass, Sorghum-Sudangrass, and Sweet Sorghum Types." *Crop Science* 52, no. 4: 1949–1954. https://doi.org/10.2135/cropsci2011.10.0534.

Sun, F., S. C. Sarin, J. S. Cundiff, and I. O. Sert. 2020. "Design of Cost-Effective Sorghum Biomass Feedstock Logistics-A Comparison of Different Systems." *Biomass and Bioenergy* 143: 105823. https://doi.org/10.1016/j.biombioe.2020.105823.

Tamburini, E., M. Gaglio, G. Castaldelli, and E. A. Fano. 2020. "Is Bioenergy Truly Sustainable When Land-Use-Change (LUC) Emissions Are Accounted For? The Case-Study of Biogas From Agricultural Biomass in Emilia-Romagna Region, Italy." *Sustainability* 12, no. 8: 3260. https://doi.org/10.3390/SU12083260.

Traverso, L., M. Colangeli, M. Morese, G. Pulighe, and G. Branca. 2020. "Opportunities and Constraints for Implementation of Cellulosic Ethanol Value Chains in Europe." *Biomass and Bioenergy* 141: 105692. https://doi.org/10.1016/j.biombioe.2020.105692.

Traverso, L., E. Mazzoli, C. Miller, et al. 2021. "Cost Benefit and Risk Analysis of Low Iluc Bioenergy Production in Europe Using Monte Carlo Simulation." *Energies* 14, no. 6: 1–18. https://doi.org/10.3390/en14061650.

Turton, R., J. A. Shaeiwitz, D. Bhattacharyya, and W. B. Whiting. 2018. *Analysis, Synthesis, and Design of Chemical Processes*. 5th ed. Boston: Prentice Hall.

VDI-Richtlinie 6025. 2012. "Betriebswirtschaftliche Berechnungen für Investitionsgüter und Anlagen."

Vera Concha, I., R. Hoefnagels, M. Junginger, and F. van der Hilst. 2021. "Supply Potential of Lignocellulosic Energy Crops Grown on Marginal Land and Greenhouse Gas Footprint of Advanced Biofuels—A Spatially Explicit Assessment Under the Sustainability Criteria of the Renewable Energy Directive Recast." *GCB Bioenergy* 13, no. 9: 1425–1447. https://doi.org/10.1111/gcbb.12867.

Willis, T. M., D. J. M. Hall, D. C. McKenzie, and I. Barchia. 1997. "Soybean Yield as Affected by Crop Rotations, Deep Tillage and Irrigation Layout on a Hardsetting Alfisol." *Soil and Tillage Research* 44, no. 3–4: 151–164. https://doi.org/10.1016/S0167-1987(97)00049-4.

Zegada-Lizarazu, W., J. L. N. Carvalho, A. Parenti, et al. 2022. "The Effects of Integrated Food and Bioenergy Cropping Systems on Crop Yields, Soil Health, and Biomass Quality: The EU and Brazilian Experience." *GCB Bioenergy* 14: 522–538. https://doi.org/10.1111/gcbb.12924.

Zegada-Lizarazu, W., H. W. Elbersen, S. L. Cosentino, A. Zatta, E. Alexopoulou, and A. Monti. 2010. "Agronomic Aspects of Future Energy Crops in Europe." *Biofuels, Bioproducts and Biorefining* 4, no. 6: 674–691. https://doi.org/10.1002/bbb.242.

Zegada-Lizarazu, W., and A. Monti. 2012. "Are We Ready to Cultivate Sweet Sorghum as a Bioenergy Feedstock? A Review on Field Management Practices." *Biomass and Bioenergy* 40: 1–12. https://doi.org/10.1016/j.biombioe.2012.01.048.

Zegada-Lizarazu, W., A. Parenti, and A. Monti. 2021. "Intercropping Grasses and Legumes Can Contribute to the Development of Advanced Biofuels." *Biomass and Bioenergy* 149: 106086. https://doi.org/10.1016/j.biombioe.2021.106086.

Zegada-Lizarazu, W., D. Parrish, M. Berti, and A. Monti. 2013. "Dedicated Crops for Advanced Biofuels: Consistent and Diverging Agronomic Points of View Between the USA and the EU-27." *Biofuels, Bioproducts and Biorefining* 7, no. 6: 715–731. https://doi.org/10.1002/bbb.1430.

Zhao, Y., A. Damgaard, and T. H. Christensen. 2018. "Bioethanol From Corn Stover—A Review and Technical Assessment of Alternative Biotechnologies." *Progress in Energy and Combustion Science* 67: 275–291. https://doi.org/10.1016/j.pecs.2018.03.004.

Zhao, Y. L., A. Dolat, Y. Steinberger, X. Wang, A. Osman, and G. H. Xie. 2009. "Biomass Yield and Changes in Chemical Composition of Sweet Sorghum Cultivars Grown for Biofuel." *Field Crops Research* 111, no. 1–2: 55–64. https://doi.org/10.1016/j.fcr.2008.10.006.

## Supporting Information

Additional supporting information can be found online in the Supporting Information section.