Bioresource Technology Reports 28 (2024) 102000



Contents lists available at ScienceDirect

Bioresource Technology Reports

journal homepage: www.sciencedirect.com/journal/bioresource-technology-reports





Modelling and optimisation of low-indirect land used change biomass supply chains

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ARTICLE INFO

Keywords:
Biofuel
Mathematical modelling
Renewable energy directive II
Economic analysis
Biofuel value chain
Additionality

ABSTRACT

Biofuels derived from biomass feedstocks produced following the implementation of measures that avoid indirect land used change (ILUC) have the potential of reducing dependency on fossil-based fuels without competing with food value chain. This work develops a model- and optimisation-based methodologies that address challenges related to the production of low-ILUC biomass feedstocks. Case studies investigated include planning of low-ILUC biomass feedstock production, biomethane production using low-ILUC biomass feedstocks, integrated production of first generation (1G) and second generation (2G) bioethanol using Miscanthus, and production of hydrotreated vegetable oil (HVO) using castor seeds. Analysis of results show that farmers interested in these models are recommended to sell low-ILUC biomass such as soybean, wheat and brassica above the breakeven price to avoid losses. The estimated selling price for the three crops are 362 €/t, 321 €/t and 381 €/t respectively. To meet the demand of 40,000 t/yr of 2G bioethanol in the UK, approximately 17,094 ha of underutilised land is required. Policy makers should consider options to support alternatives such as retrofitting, and inter-cropping to avoid or mitigate ILUC.

1. Introduction

The increasing concerns over climate change and the commitments to reduce the use of fossil fuels have led to the search for alternative sources of energy that are both renewable and sustainable. Biofuels (such as hydrotreated vegetable oil, bioethanol, biomethane, etc.) derived from biomass feedstocks have been used for decades to power the transportation sector. Additionally, biofuel serves as energy sources for domestic usage, e.g., household heating, cooking, etc. Apart from providing a potentially sustainable energy source, the use of biofuels may also contribute significantly to decarbonisation of the transportation sector (Adamowicz, 2022; Capros et al., 2020; Chiaramonti et al., 2021; Vallejo et al., 2021), thus supporting the European Union's (EU) ambitious targets to reduce greenhouse gas emissions by at least 55 % by 2030 (IEA, 2021). Achieving the targets set by the EU has the potential to increase demand for land use to cultivate biorefinery feedstocks such as biomass for advanced biofuel production. To avoid competition with land used for food production, the EU has put in place policies that mandate sustainable biomass supply through introduction of low-indirect land use change (low-ILUC) feedstocks (Panoutsou et al., 2022). Low-ILUC risk biofuels are produced from feedstock that avoid food and feed crop displacement through (i) yield increases from improved agricultural practices or (ii) cultivation on areas not previously used for crop production, for example, unused, abandoned or severely degraded land or (iii) combining cover crop rotations with biomass feedstock production. To speed-up market uptake and certification by international sustainability and carbon certification (ISCC), there is a need for a systematic approach that can assess the benefit of both existing and emerging low-ILUC risk feedstocks, for example *Brassica carinata,* perennial crops such as *Miscanthus,* castor oil, etc.

In the past, research on modelling and optimization of biofuel supply chain focuses primarily on first generation (Akgul et al., 2012; Giarola et al., 2012; Kostin et al., 2012) and second generation (Dunnett et al., 2008; Neill et al., 2022; Panteli et al., 2018) biofuels. First generation biofuels derived from feedstocks such as wheat, soybean, sorghum, sugarcane, corn, etc. compete with food value chain, thus posing

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https://doi.org/10.1016/j.biteb.2024.102000
Received 8 February 2024; Received in revised form 13 November 2024; Accepted 18 November 2024
Available online 23 November 2024
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potential risk on food security. In this context, government and policy-makers have put in place policies that facilitate transition to second generation biofuel. On the other hand, supply chains for second generation biofuel utilizes non-food crops and agricultural wastes such as miscanthus, switch grass, wheat straw, castor seed, manure, etc. thus mitigating risk on food security. However, growing the aforementioned crops on existing agricultural lands could potentially displace food crops, causing indirect land use change. Avoiding indirect land use change requires the implementation of sustainable agricultural practices such as crop rotation, intercropping, cover cropping, sequential cropping, etc. A comprehensive review of opportunities for low-indirect land use biomass for biofuel production can be found in Panoutsou et al. (2022). Sumfleth et al. (2020) summarized a review of recent development in low-ILUC policies and certification in the EU bio-based economy while Balugani et al. (2022) developed an excel-based modelling tool that estimates the ILUC risk of bio-based material production and assesses how different additionality practices can reduce ILUC risk at all levels of the value chain. The developed tool does not include economic assessment of value chains. Khawaja et al. (2021) developed a webGIS decision-making tool that assesses the agronomic, techno-economic, and sustainability of low-ILUC value chains. The authors applied the tool to investigate the viability and sustainability of bioenergy value chains in Italy, Ukraine, and Germany. However, the proposed tool does not support optimization of value chain, thus solution could be sub-optimal. To the best of our knowledge, no study has incorporated sustainable agricultural practices, multi-echelon supply chain, and optimization methods in order to identify cost-optimal value chains of biofuel derived from low-ILUC risk biomass feedstocks.

This work proposes four systematic optimisation-based approaches that facilitate climate positive farming, which involves implementation of sustainable agricultural practices (such as crop rotation, cover cropping, intercropping, etc.) to produce additional biomass feedstock without displacing food and feed crops. The first approach comprises a mixed integer linear programming model for crop production that incorporates crop rotation. The inputs to the crop production model include a set of crops/crops sequence to be planted, a set of available land, fertiliser consumption, price of crops, production cost, average crop yield, time horizon, while the outputs include land allocated to each crop type, annual biomass produced and net farm income. The second approach comprises a mixed integer linear programming model developed following the principles of biogasdoneright® (BDR). The model estimates the biomethane potential of low-ILUC risk feedstocks produced using monocropping and sequential cropping systems. Input data includes feedstock rate, anaerobic digestion plant capacity, and biomass characteristics such as dry matter/total solid content, volatile solid content, volatile solid degraded in the digester, and yield of biomethane. Similarly, both third and fourth approaches comprise a mixed integer linear programming model developed following a multi-echelon supply chain concept. The models estimate the potential of producing bioethanol using Miscanthus cultivated on unused lands and the profitability of hydrotreated vegetable oil (HVO) production using castor seed cultivated on degraded lands respectively. The capabilities of the proposed systematic approaches were demonstrated using industrial case studies, aiming to facilitate market uptake of European feedstocks with low-ILUC risk status for use in biofuel from 2020 to 2030; inform primarily the bioenergy and biofuels but also other bioproduct sectors (biochemicals/biopolymers, chemical industry); support the sustainable conversion of the chemical industry; provide policy and market stakeholders with new knowledge; and to remove the most prominent barriers against the market uptake of low-ILUC risk biofuels, bioliquids and biomass fuels.

The remainder of this article is organised as follows. Section 2 presents the proposed framework for climate positive farming solutions and sources of information used in this work. Sections 3 presents the four case studies investigated in this work, i.e., planning of Brassica cultivation, BDR for biomethane production, Miscanthus for bioethanol production, and castor for HVO production. Lastly, Section 4 summarises the key findings and policy recommendations.

2. Methods

2.1. Modelling framework for climate positive farming solutions

Climate positive farming involves the implementation of sustainable agricultural practices (cover cropping, intercropping, rotational cropping, etc.) in order to avoid ILUC. In this section, a methodology is proposed to address challenges related to climate positive farming. As shown in Fig. 1, the methodology starts by gathering all information needed by the decision support models. This information can include farm-level datasets (e.g., land size and expected yield), economic data, type of technology used in converting biomass to biofuel, policy information, mode of transportation and agronomic data such as crop yield, date of establishment and harvest, fertiliser requirement, cultivation season, among others.

This work presents four mathematical models to support: (i) planning of low-ILUC biomass production, (ii) production of biomethane using low-ILUC biomass feedstocks, (iii) production of bioethanol using Miscanthus cultivated on unused lands, and (iv) production of HVO using castor seed cultivated on degraded lands. Lastly, a real-world dataset is applied to demonstrate the capabilities of the proposed models.

2.2. Decision-support models

2.2.1. Planning of low-ILUC biomass feedstock production

According to a review of the Renewable Energy Directive II (RED II) (Panoutsou et al., 2022), biomass feedstocks can be classified as low-ILUC risk if they are produced following the implementation of sustainable agricultural practices, i.e., (i) cultivation on unused, abandoned, and/or severely degraded land and (ii) productivity increases from improved agricultural practices. The agricultural practices include crop rotation, inter-cropping, cover cropping, etc. In this section, a model that incorporates sustainable agricultural practices is developed to support planning of low-ILUC biomass feedstock production. The model is build based on farm management system which consists of farmlands, crop management schemes and their corresponding crops, seasons of the year and biomass storage points.

On each piece of farmland, a crop rotation principle is implemented, i.e., alternating crops cultivated on a given piece of land over time. This practice enables farmers to improve crop yield, control crop specific pest and increase soil carbon (Panoutsou et al., 2022). The proposed farm planning model can be used to identify the best crop management practice and land allocation that improves total crop yield and/or net farm income. The model inputs include farmland size, crop yield, unit production cost, unit crop selling price, interest rate, crop rotation sequence and cropping calendar. With the aforementioned inputs, the model calculates outputs such as net farm income, total crop yield and net present value. A detailed description of the model can be found in Section S2.1 in the supplementary material. In Section 3.1, a case study is used to demonstrate the applicability of the proposed model.

2.2.2. Biomethane production using low-ILUC biomass feedstock

To meet government regulations on production of sustainable energy, this analysis implements the principles of biogasdoneright® (Dale et al., 2016) to produce biomethane using low-ILUC biomass feedstocks. Biogasdoneright®, originally developed by Consorzio Italiano Biogas (CIB), is a system in which energy crops (planted alongside food/feed) are converted into biogas and digestate. The biogas is either upgraded into biomethane and injected into the grid or utilised in a combined heat and power system to produce heat and electricity at efficiencies of approximately 30–37 % and 40–50 % respectively (Abanades et al., 2022; IEA, 2020; Omer, 2017). The digestate from the conversion

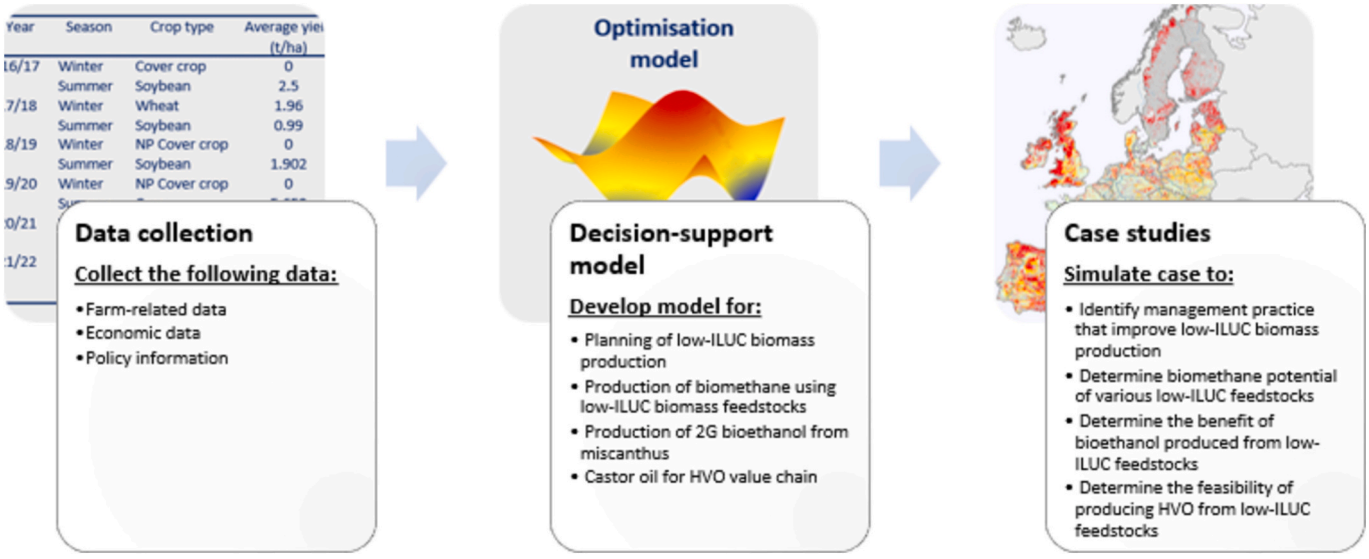


Fig. 1. Modelling framework for climate positive farming solutions. ILUC denotes indirect land use change.

process is used as organic fertiliser for both food/feed and energy crops.

In this analysis, biogas is converted to biomethane instead of heat and electricity in order to assess the biomethane potential of different types of low-ILUC biomass feedstocks. Fig. 2 shows the biomethane value chain considered in this work.

At the farm level, energy and food/feed crops are produced by implementing sequential cropping. The food/feed crops are used for consumption while the energy/sequential crops (e.g., cereal silage) and other feedstock types such as manure and agro-industrial waste are transported to the plant site and use as feedstock for anaerobic digestion process.

The plant level consists of an anaerobic digestion (AD) plant and a unit that upgrades biogas to biomethane. The plant converts feedstocks composed of organic matter (cellulose, hemicellulose, lignin, fats, etc.) into biogas and digestate (by-product). Since this work focuses on the biomethane supply chain, the biomass feedstock conversion at the plant level will be approximated using conversion factors, without detailed modelling of the digester. Similarly, the separation of biogas into biomethane and carbon dioxide will be estimated using recovery fractions without modelling the membrane unit or pressure swing adsorption unit (Calise et al., 2021).

Lastly, the distribution level injects biomethane directly into the grid for use as a supplement to natural gas. The proposed model takes the following inputs: feedstock rate, AD plant capacity and biomass characteristics such as biomass dry matter/total solid content, biomass volatile solid content, volatile solid degraded in the digester and yield of biomethane. Using the aforementioned inputs, the model calculates the biomethane potential of low-ILUC feedstocks. A detailed description of the model can be found in Section S2.2 in the supplementary material.

2.2.3. Integrated production of first generation & second generation bioethanol using low-ILUC biomass feedstock

In this section, a model is developed to support planning of low-ILUC biomass (Miscanthus) cultivation and production of second generation (2G) bioethanol. Fig. 3 shows the overall value chain of 2G bioethanol produced from low-ILUC feedstocks.

In Fig. 3, Miscanthus cultivated on underutilised lands is transported from farm level to plant level where the feedstock is converted to bioethanol. An underutilised piece of land can be defined as a piece of land that has not been in productive use for period of at least five years (Panoutsou et al., 2022), therefore biomass cultivated on this land can be classified as low-ILUC according to RED II.

At the plant level, the feedstock is first pre-treated followed by conversion to bioethanol. A detailed description of the production

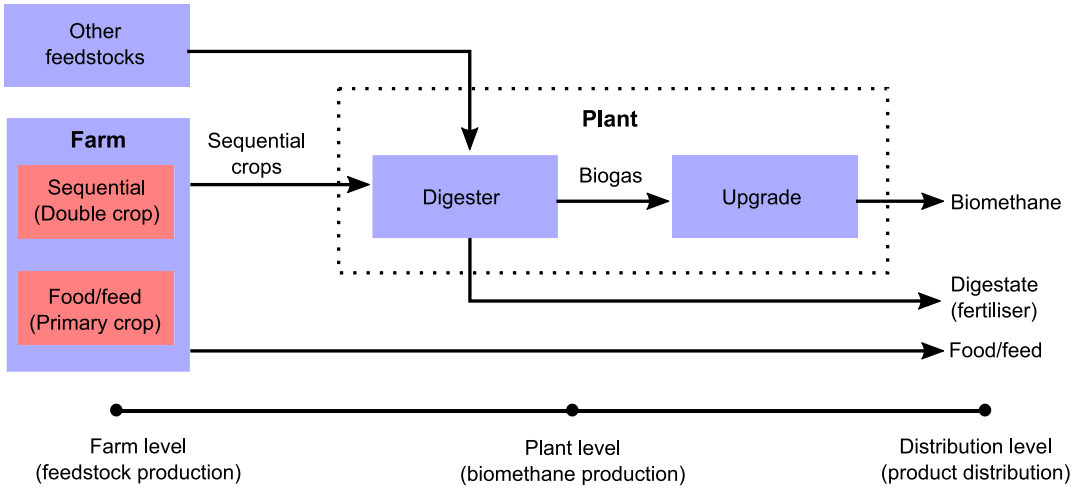


Fig. 2. Schematic representation of the three levels of biomethane value chain. In this analysis, biomethane is produce from low-ILUC biomass feedstocks.

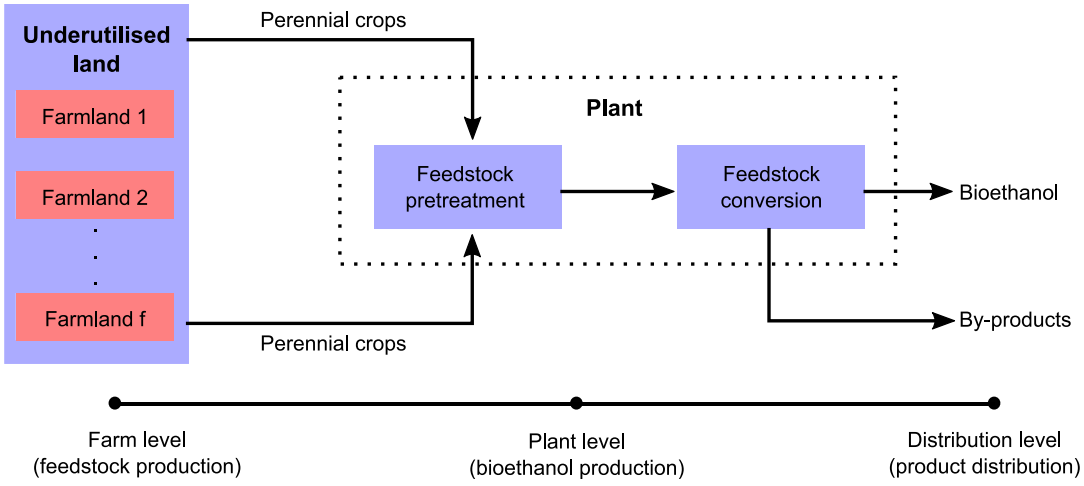


Fig. 3. Schematic representation of the proposed supply chain for 2G bioethanol produced using low-ILUC biomass feedstock.

process can be found elsewhere (Joelsson et al., 2016). The pre-treatment and ethanol production processes can be co-located or established in different geographical regions. In the current study, both pre-treatment and ethanol production facilities are located in the same place.

At the distribution level, fuel-grade ethanol is supplied and distributed to the EU energy market and sold as alternative to fossil-based gasoline or as blend, i.e., mixture of gasoline and ethanol at a ratio of 90:10 (E10) in the UK (GOV.UK, 2021). The proposed planning model, derived from Fig. 3, takes the following inputs: farmland size and geographical coordinates, crop yield, production capacity of 2G bioethanol plant, conversion factors for lignocellulosic biomass to ethanol and by-product (electricity), product demand, transportation modes and their associated cost, tortuosity, interest rate, unit transport cost, unit cultivation cost, unit production cost, and unit selling price of ethanol and electricity. Using the aforementioned inputs, the model calculates the quantity of Miscanthus produced per annum, net ethanol produced, electricity generated, total cost, revenue, and net present value. A detailed description of the model can be found in Section S2.3 in the supplementary material. In Section 3.3, a case study is used to demonstrate the applicability of the proposed model.

2.2.4. Production of hydrotreated vegetable oil using low-ILUC biomass feedstock

In this section, a model is developed to support planning of castor bean cultivation and production of hydrotreated vegetable oil. The value chain, as shown in Fig. 4, consists of four echelons and incorporates all essential features of a typical biofuel supply chain.

In Fig. 4, castor feedstock cultivated on degraded lands is transported from farm level to plant level 1. Plant level 1 comprises an oil mill which is used to extract vegetable oil from castor seeds while in plant level 2, the extracted oil is hydrotreated in a biorefinery to produce HVO, which is a substitute for fossil-based diesel. A detailed description of hydrogenation of vegetable oil can be found in Bellussi et al. (2016).

Lastly, the hydrotreated vegetable oil produced in the biorefinery is distributed and supplied to the EU energy market, thereby sold as alternative to conventional fossil-based diesel. The proposed model, derived from Fig. 4, takes the following inputs: farmland size and geographical coordinates, crop yield, production capacity of oil mill and biorefinery, conversion factors for castor seed to vegetable oil as well as castor cake and vegetable oil to HVO, product demand, transportation modes and their associated cost, travel distance between supply chain entities, tortuosity, interest rate, unit transport cost, unit cultivation cost, unit production cost, unit extraction cost and unit selling price of HVO and castor cake. Using the aforementioned inputs, the model calculates the quantity of castor seed produced per annum, castor oil produced, HVO produced, castor cake produced, total cost, revenues, and net present value. Total cost includes cultivation cost, transportation cost, and production cost. A detailed description of the model can be found in Section S2.4. In Section 3.4, a case study is used to demonstrate

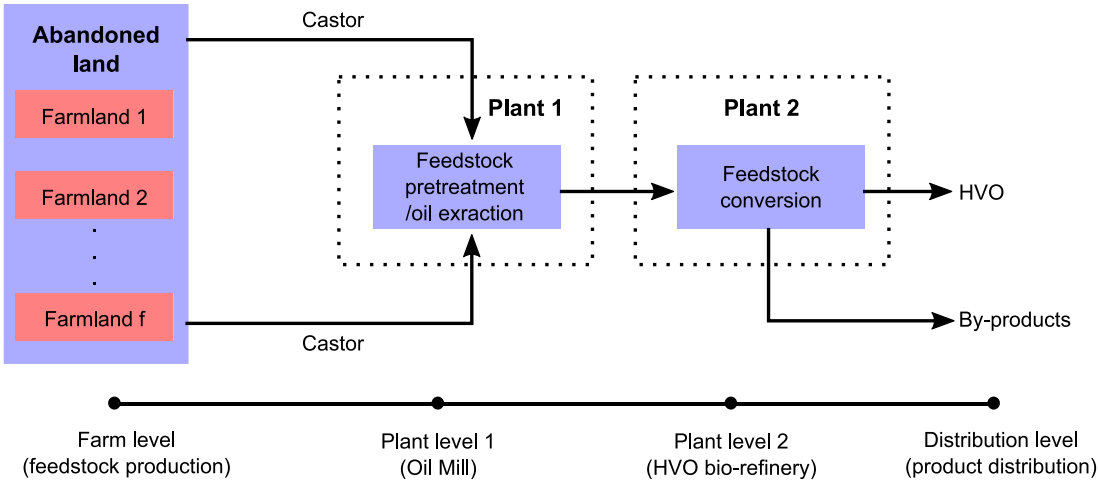


Fig. 4. Schematic representation of the proposed supply chain for HVO produced using low-ILUC biomass feedstock.

the applicability of the proposed model.

2.3. Data collection and assumptions

The farm-level information required can be grouped into geographic and agronomic datasets. Geographic data includes farmland location and land size while agronomic data includes crop specific information such as crop yield, cultivation season, date of establishment and harvest, fertiliser requirements, etc. For the majority of crop types cultivated across the globe, geographic and agronomic datasets can be collected from US Department of Agriculture (USDA, 2022). The case study data used in this work were provided by project industrial partners.

The estimation of farm profitability requires data for calculating crop production cost and net farm income. Crop production cost includes cost of all activities involve during cultivation, starting from establishment to harvest. Typical sources of crop production costs include historical data collected by farmers. This can be found in government sponsored websites (USDA, 2022) or in previous published papers (Mazzilli and Ernst, 2019). Alternatively, crop production cost can be estimated using the activity-based costing approach (Panoutsou and Alexopoulou, 2020), which takes into account the costs of all crop cultivation activities.

Furthermore, net farm income can be estimated using the current market value of farm products and by-products. The prevailing price of products can be found in commodity price index (Insider, 2022; Mundi, 2022) and government sponsored websites (USDA, 2022).

The production of low ILUC biomass must be carried out in accordance with renewable energy directives II. This work considers productivity increases from improved agricultural practices and cultivation on unused, abandoned and/or severely degraded land.

3. Case study

3.1. Case study 1: Brassica for HVO production

3.1.1. Cultivation of Brassica

The cultivation of Brassica in Uruguay is one of four case studies described here to demonstrate the benefits of sustainable agricultural practices. The data for this case study can be classified into two categories: reference case and improved case. The reference case is the conventional crop rotation practice using non-productive cover crops, see Table S1 in the supplementary material. In the improved case, Brassica replaces the non-productive cover crops, as shown in Table S2 in the supplementary material.

In both cases, cultivation is carried out on 110 ha farmland over a period of six years (2016 to 2022). The length of summer and winter seasons is four months (January to April) and eight months (May to December) respectively. It takes three years to complete a rotation. Soybean and maize are cultivated in the summer while wheat and Brassica during the winter. Tables S1 and S2 show the rotation sequence and average crop yields for the reference and improved cases. The unit production cost and selling price of crops included in the rotation are summarized in Table S3. The unit production costs were collected from (Mazzilli and Ernst, 2019) and the crop selling price were collected from a commodity price index (Insider, 2022; Mundi, 2022; YCHARTS, 2022).

In addition to the current crop selling price in Table S3, Fig. S1 shows the selling price for both summer and winter crops over a period of five years (2018 to 2022). The crop price distribution is applied in Section 3.2 to investigate the effects of fluctuation in crop price on net farm income. The lowest and highest selling prices for each crop, indicated by the whiskers in Fig. S1, are used to define high crop price scenario and low crop price scenario respectively.

3.1.2. Results and discussions

The case study information presented in Section 3.1.1 is applied in the model described in Section 2.2.1 and Section S2.1 to investigate the impact of crop management practices on total crop produced and net farm income.

For the two crop management practice (reference and improved), the net crop production is equivalent to 1930 ton and 2312 ton (difference ≅ 382), corresponding to net present value of € 320,211 and € 383,159 (difference ≅ 62,948) respectively.

From the results, introduction of Brassica as a winter crop in place of non-productive cover crop leads to additional biomass of 382 t per rotation, emphasising the importance of implementing sustainable agricultural practices. Fig. 5 shows the breakdown of total crop produced per annum for reference and improved cases.

In Fig. 5, soybean is cultivated in all summer seasons except 2019/2020 where maize is used. This follows the common practice of introducing a “break crop” into a cropping systems to enable weed and disease control (Angus et al., 2011; Dolye, 2021). From the results, the introduction of Brassica as winter crop does not affect the yield of summer crop as indicated by the total yield of maize and soybean in 2019/2020 and 2021/2022. Comparing winter wheat in the first rotation (2016 to 2019) and Brassica in the second rotation (2019 to 2022), it can be seen that winter wheat leads to decrease in soybean yield of approximately 60 % while Brassica increases soybean yield by 19 % (calculated relative to the previous year). Mazzilli and Ernst (2019) reported approximately 11 % increase in soybean yield when Brassica is cultivated instead of winter wheat. The positive effect of Brassica as winter crop can be attributed to increased nutrient availability for crop cultivated in upcoming season, biofumigant effects of brassica, and improved soil structure (which reduces soil penetration resistance) among other factors (Mazzilli and Ernst, 2019).

In the improved case, the total yield of winter crop (wheat) in the first rotation is 216 t per rotation while in the second rotation the yield of winter crop (Brassica) increases to 382 t per rotation because Brassica is cultivated in two winter seasons. Therefore, in addition to crop yield increase, the improved case leads to higher land utilisation during winter seasons. In Fig. 5, the 110 ha cropland is utilised once over six years in the reference case and three times in the improved case.

The increase in crop yield leads to a corresponding increase in net present value of € 62,948, calculated over a period of six years and interest rate of 10 %. Fig. S2 shows the annual cash flow over six-year period. As can be seen, the annual revenue is greater than the production cost throughout the planning horizon of both reference case and improved case, indicating a positive cash flow. The relatively large revenue in 2019/2020 and 2021/2022 results from the sales of additional biomass (Brassica). Also, the gross margins per hectare for wheat-soybean double (2017/2018), Brassica-soybean (2021/2022) and Brassica-maize (2019/2020) correspond to 150 €/ha•yr, 1260 €/ha•yr and 1417 €/ha•yr respectively. Overall, the introduction of Brassica increases the gross margin per hectare from 877 €/ha•yr to 1417 €/ha•yr in 2019/2020 and 900 €/ha•yr to 1260 €/ha•yr in 2021/2022. Similarly, the yield increase corresponds to 1.88 t/ha•yr and 1.59 t/ha•yr, see Fig. 5. Apart from having a positive effect on summer crops, Brassica cultivated as winter crop is more profitable compared to winter wheat in a double cropping system. This economic advantage results from the fact that Brassica has slightly low production cost and sold at almost double the price of wheat.

The results and analysis presented so far focus on the current market price of crops included in the two management practices. However, crop price is subject to change caused by many factors, for example, demand-supply variability (Patterson, 2022), changes in government regulations/policies (Eardley, 2022), regional conflict (EMEDIEGWU, 2022), etc. To account for the effect of crop price fluctuation on crop management practice, a sensitivity analysis is carried out using high and low values for crop price collected from Fig. S1 in the supplementary material.

Results from this analysis show that the net present value of high crop price scenario of the reference case and improved case correspond to € 459,595 and € 636,194 respectively (difference ≅ € 176,599). Similarly, the net present value for low crop price scenario corresponds

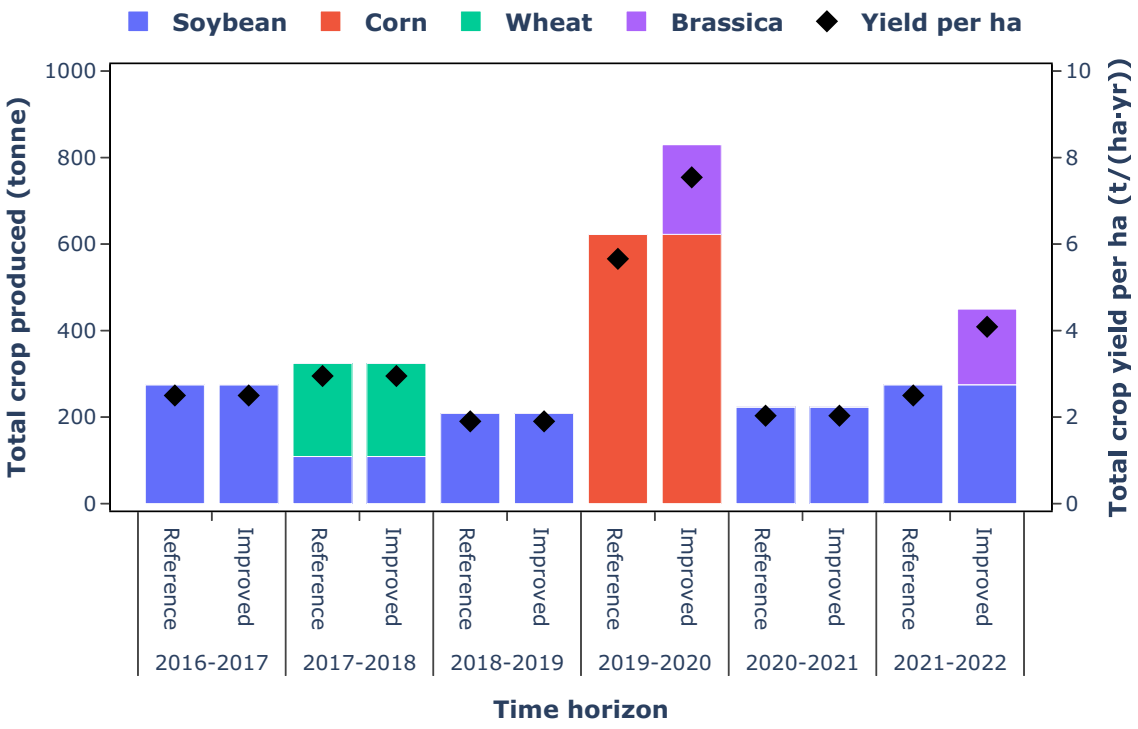


Fig. 5. Annual crop produced over the entire planning horizon. Vertical bars with two crop types indicate cover crop during winter, where either wheat or Brassica is cultivated.

to € 35,416 and € 30,582 (difference ≅ € -4834) respectively.

In the high crop price scenario, the improved case is more profitable than the reference case as indicated by the increase in net present value. Conversely, the improved case is less profitable in low crop price scenario. This is caused by the decrease in gross margin per hectare, see Figs. S3 and S4.

Figs. S3 and S4 can be used alongside Figs. S4 and S5 to identify the crops leading to decreases in gross margin per hectare. In all crop price scenarios, only the crop selling price is varied using the information in Fig. S1.

In the three crop price scenarios, the gross margin per season is positive except Year 2017/2018 of the low crop price scenario. The negative gross margin during winter (wheat) and summer (soybean) seasons results from low revenue due to low selling price. Similar trend is observed in the improved case shown in Fig. S6, which also shows that cultivation of Brassica in Year 2021/2022 leads to negative gross margin. The negative gross margin can be attributed to the drop in Brassica yield from 1.88 t per hectare in 2019/2020 to 1.59 t per hectare in 2021/2022.

In the low crop price scenario, the crop yield per hectare needs to improve in order to avoid operating at loss. In Table S2, soybean cultivated in the summer of 2017/2018 has the lowest yield per hectare (0.99 t per hectare) compared to other seasons (range: 1.90 to 2.50 t per hectare). Likewise, the yield of wheat is 1.96 t per hectare in 2017/2018. For farmers to avoid operating at loss, it is necessary to identify the breakeven point for each crop, i.e., the minimum price to sell crops. At the breakeven point, the selling price of soybean, wheat and Brassica correspond to 362 €/t, 321 €/t and 381 €/t respectively. Clearly, the minimum selling price for wheat, soybean and Brassica are well above the values used in the low crop price scenario, see Fig. S1.

3.2. Case study 2: biomethane production via anaerobic digestion

In this section, the benefit of climate positive farming is demonstrated using two case studies, depending on whether the biomass feedstock is produced based on a monocropping system or sequential cropping (aka double cropping) system. The two case studies (collected from Valli et al. (2017)) focus on the production of biomethane and organic fertiliser (aka digestate) using low-ILUC biomass feedstocks. Sections 3.2.1 and 3.2.2 present the two case studies and Section 3.2.3 presents the results and discussions. Note that both case studies take into account weed management and/or weed control during cropping cycle.

3.2.1. AD plant feedstock produced using monocropping system

This case study is a biogas plant (aka AD plant 1) with capacity of 1000 kW located in Northern Italy (the Lombardy region). The plant is fed with maize silage cultivated on 285 ha of cropland located 2.5 km away from the plant. There is no food/feed as the whole crop is used for bioenergy. The digestate is used as fertiliser to supplement chemical fertiliser. Table S4 summarises the information related to anaerobic digestion of feedstock to products.

3.2.2. AD plant feedstock produced using sequential cropping system

Similar to the case study in Section 3.2.1, the 1000 kW biogas plant (aka AD plant 2) considered here is located in Northern Italy (also the Lombardy region) at a 600-head dairy cattle farm, including 280 lactating cows, see Valli et al. (2017). However, the plant is fed with a variety of feedstocks including cattle slurry, by-products from agro-industry (cereal grain and potato scrap), and energy crops which are mostly maize silage produced as sequential crops. The silage/energy crops are produced on 255 ha of cropland divided into seven plots, see Fig. S7 in the supplementary material.

In Fig. S7, 160 ha is dedicated to sequential cropping with winter cereal (triticale or ryegrass) used as forage for animal while 15 ha is used to grow perennial forage (alfalfa) for cattle, see Valli et al. (2017). The remaining 80 ha is used for monocropping to produce maize silage of which 50 % is used as animal feed and 50 % as feedstock for bioenergy, see Valli et al. (2017). Table S7 presents information on conversion of various feedstocks into biogas, biomethane and digestate.

3.2.3. Results and discussion

The information presented in Sections 3.2.1 and 3.2.2 is applied in

the model described in Section 2.2.2 and Section S2.2 in order to assess the biomethane potential of various low-ILUC risk feedstocks. Tables 1 and 2 summarise the products from AD plants 1 and 2 respectively.

The anaerobic digestion of biomass to produce biogas is an important step toward biomethane production. Table 1a shows the quantity of biomethane produced using biomass feedstock from monocropping system. Out of 17,945 t/y of maize silage, only 30 % (*w*/w) is converted to biogas and subsequently to biomethane which constitute 53 % (*v*/v) of biogas in this case study. Similarly, the quantity of biomethane produced from biomass feedstocks mainly from sequential cropping system is shown in Table 1b. Unlike the previous case, the feedstock here consists of cattle slurry, potato scrap, and cereal by-product in addition to maize and triticale silage. The total biomass feedstock rate is 31,937 t/y, of which 17 % (w/w) is converted to biogas (contains 53 % v/v biomethane). The biogas and biomethane yields from AD plant 2 are slightly lower than AD plant 1 despite having a larger total biomass feedstock rate. The low biogas and biomethane yields could be attributed to low total solid content of cattle slurry (8 % total solid content and constitute 46 % w/w of total feedstock rate). Recall, biogas yield obtained following the four steps (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) in anaerobic digestion strongly depends on the amount of volatile solid, which is a fraction of total solid content of biomass.

The by-product (digestate) from anaerobic digestion is used as fertiliser for food/feed and energy crop, following the principle of biogasdoneright®. In Tables 1a and 2b, the digestate produced by AD plants 1 and 2 corresponds to 12,579 t/y and 26,679 t/y respectively. The digestate produced by AD plant 1 is not sufficient to satisfy cropland requirements, therefore chemical fertiliser is used as supplement. By contrast, AD plant 2 generates sufficient digestate to satisfy demand, hence no chemical fertiliser is needed. Note that the use of chemical fertiliser is likely to increase total production cost.

Typically, the application of digestate on cropland is carried out in accordance with government regulations and in-line with standard practice to avoid the spread of pathogens present in digestates. The rules and regulations mandatory to all EU members Countries include (EC) No. 208/2006 and (EC) No. 1774/2002 (Gebrezgabher et al., 2010). According to Valli et al. (2017), digestate can be applied at three distinct stages of cropping cycles using unique equipment: (i) before sowing the next crop, (ii) at weed control stage, and (iii) at crop growth stage.

The feedstocks for AD plants 1 and 2 are cultivated on 285 ha and 255 ha using monocropping and sequential cropping respectively. In the latter, 55 ha is dedicated to feed crop production while 200 ha is used for feed and AD plant feedstock production, see Fig. S7. In order to compare biogas and biomethane yield per hectare of cropland, only 200 ha used for feed and AD plant 2 feedstock is considered. Also, biogas and biomethane produced using cattle slurry, potato scrap, and cereal by-product are excluded in this analysis. For AD plant 1, the biogas and biomethane yield correspond to 12,785 m^3/ha•yr and 6776 m^3/ha•yr respectively. Similarly, AD plant 2 generates 12,451 m^3/ha•yr and 6599 m^3/ha•yr of biogas and biomethane. Despite having larger land size, the biogas and biomethane yields from AD plant 1 is similar in magnitude to AD plant 2. Without winter crops, the biogas and biomethane yield from AD plant 2 drops to 10,012 m^3/ha•yr and 5306 m^3/ha•yr respectively.

Biogas and biomethane yield per hectare for various crop types can be found in literature. For example, the yield of biomethane per hectare of maize and triticale ranges between 3573 and 18,540 m^3/ha•yr and 1112 to 6604 m^3/ha•yr respectively (Braun et al., 2011).

Table 1
(a) biomethane produced via anaerobic digestion of maize cultivated using monocropping system; (b) biomethane produced via anaerobic digestion of manure, agro-industry waste and silages cultivated using sequential cropping system.

Feedstock type	Value	Digestate	Biogas
(a) AD Plant 1			
Feedstock conversion			
Maize	17,945 t/y	12,579 t/y	5366 t/y
Product (biogas) upgrade	3.64×10^6 m^3/y		
Biomethane	1.93×10^6 m^3/y		
Carbon dioxide	1.71×10^6 m^3/y		
(b) AD Plant 2			
Feedstock conversion			
Cattle slurry	14,600 t/y	14,067 t/y	533 t/y
Potato scraps	1825 t/y	1703 t/y	122 t/y
Cereal by-product	913 t/y	277 t/y	636 t/y
Maize silage I (monocrop)	2522 t/y	1768 t/y	754 t/y
Maize silage II (sequential crop)	1746 t/y	1265 t/y	481 t/y
Maize silage II (sequential crop)	6936 t/y	5025 t/y	1911 t/y
Triticale silage (sequential crop)	3395 t/y	2574 t/y	821 t/y
Total	31,937 t/y	26,679 t/y	5258 t/y
Product (biogas) upgrade	3.19×10^6 m^3/y		
Biomethane	1.709×10^6 m^3/y		
Carbon dioxide	1.482×10^6 m^3/y		

Table 2
Miscanthus supplied, bioethanol and energy generated (by-product produced), and net present value of bioethanol value chain comprising underutilised lands within 50 km radius to an existing plant.

Item	6.5 t/ha	9 t/ha	Difference	Unit
Feedstock supplied	535.48	741.43	205.95	t/yr
Bioethanol produced	139.22	192.77	53.55	t/yr
Energy generated	267,759.09	370,743.36	102,984.27	kWh
Overall cost	148,560.54	190,126.76	41,566.22	euro/yr
Revenue	251,662.03	348,455.12	96,793.09	euro/yr
Net present value	93,728.63	143,934.87	50,206.24	euro

3.3. Case study 3: Miscanthus for bioethanol production

This case study assesses the potential of producing 2G bioethanol using Miscanthus cultivated on underutilised lands in the UK. To make use of existing resources and avoid large capital investment related to building a new plant, this work analyses the retrofit of an existing 1G bioethanol plant to allow production of 2G bioethanol using Miscanthus as feedstock. Two cases were analysed depending on target area for feedstock cultivation, i.e., cultivation on underutilised lands within 50 km and 100 km radius to an existing biorefinery.

3.3.1. Cultivation of Miscanthus

The farmlands used for cultivation of Miscanthus in the UK were identified using the BIOPLAT-EU web GIS tool developed by the Food and Agriculture Organisation (FAO). The tool identifies only lands not currently in use and excludes areas not suitable for bioenergy feedstock production as a result of various reasons such reserve forest area, water and wetland areas, settlement areas, protected areas such as national parks, steep slope areas, partly agriculturally used areas, and lastly unusable areas such as beach, bare rock and glacier. In the accompanied supplementary material, Tables S6 and S7 show the summary of underutilised farmlands within 50 km and 100 km radius to an existing biorefinery in the UK.

In the UK, the establishment and harvest date of Miscanthus correspond to November/January and November/February respectively (Panoutsou and Alexopoulou, 2020), with life span of up to 20 years as reported by Miscanthus Nursery Limited. Table S8 shows the characteristics of Miscanthus used in this analysis.

3.3.2. Integrating 2G to an existing 1G bioethanol plant

This work presents the analysis to retrofit an existing 1G bioethanol plant instead of constructing a new plant in order to convert Miscanthus into 2G bioethanol. The existing plant, located in England, converts wheat into 1G bioethanol. To process Miscanthus, pre-treatment and enzymatic hydrolysis units were installed to enable the conversion of

lignocellulosic biomass into simple sugars which can be fed to the existing fermenter unit. The retrofitted plant can produce up to 40,000 t per annum of 2G bioethanol. By-product (lignin) is utilised in a combined heat and power (CHP) unit to generate electricity. Table S9 shows the parameters of the retrofitted plant.

The transportation of Miscanthus from farmland to biorefinery is carried out using trailers with a maximum capacity of 15.50 t per trip (Caslin et al., 2015). It costs approximately € 1.34 to transport feedstock over 1 km (Caslin et al., 2015). Transportation cost considers fuel cost, driver wages, maintenance cost, and capital cost. In this case study, travel distance is estimated assuming straight line between supply chain entities. To account for the nonlinear nature of real travel distance, a tortuosity factor of 1.80 is applied. Tables S10 and S11 show the summary of distance from farmland to biorefinery.

3.3.3. Results and discussion

The case study information presented in Sections 3.3.1 and 3.3.2 is applied in the model described in Section 2.2.3 and Section S2.3 to assess the potential of producing 2G bioethanol using Miscanthus cultivated on underutilised lands within the UK. Results for the two cases considered are presented as follows, i.e., Miscanthus cultivated on land within 50 km and 100 km to an existing biorefinery.

(a) Bioethanol produced from Miscanthus cultivated on land within 50 km radius to an existing biorefinery

The total amount of Miscanthus produced on land within a 50 km radius to an existing biorefinery is shown in Figs. S8 and S9 in the supplementary information. As can be seen, only four farmlands are available within this target area and the total biomass produced is 536 t/yr and 741 t/yr at crop yield equivalent to 6.5 t/ha and 9 t/ha respectively. As expected, increase in crop yield per ha is accompanied by a net increase total Miscanthus produced (206 t/yr). The cultivation cost is € 492 per hectare in both cases.

Table 2 shows the amount of 2G bioethanol produced from Miscanthus and associated cost. The total revenue is the sum of revenue generated from the sale of 2G bioethanol and electricity generated from by-product.

For the same land size, the amount of 2G bioethanol produced increases by 39 % as crop yield per hectare increase from 6.5 to 9.0. Similarly, the net present value increases by 54 %. The overall cost includes the cost of cultivation, production of 2G bioethanol, and transportation of feedstock from farmland to biorefinery. Despite an increase in overall cost, there is no significant change in cost distribution (see Fig. S10) when crop yield increases from 6.5 to 9.0 t per hectare. Fig. S11 shows the structure of value chain for 2G bioethanol produced from Miscanthus cultivated on underutilised lands in the UK. The value chain indicates the locations of the biorefinery and all farmlands, links between farmlands and the biorefinery, and lastly the amount of Miscanthus produced on each piece of land.

(b) Bioethanol produced from Miscanthus cultivated on land within 100 km radius to an existing biorefinery

The amount of Miscanthus produced on farmlands within 100 km radius to an existing biorefinery is shown in Figs. S12 and S13 in the supplementary material. For crop yields of 6.5 t/ha and 9.0 t/ha, the feedstock produced corresponds to 5577 t/yr and 7722 t/yr respectively. Cultivation cost is approximately € 492 per hectare in both cases.

In Table 3, increase in crop yield from 6.5 t/ha to 9.0 t/ha results to 39 % increase in bioethanol produced. The net present value increased by 55 %.

As shown in Fig. S14, the cost of bioethanol production dominates the overall cost in both cases. In addition, the cost of transporting biomass increases slightly with increase crop yield. This results from the fact that more trips will be required to convey additional biomass from farmland to biorefinery.

Table 3
Miscanthus supplied, bioethanol and energy generated (by-product produced), and net present value of bioethanol value chain comprising underutilised lands within 100 km radius to an existing plant.

Item	6.5 t/ha	9 t/ha	Difference	Unit
Feedstock supplied	5576.96	7721.94	2144.98	t/yr
Bioethanol produced	1450.01	2007.71	557.70	t/yr
Energy generated	2,788,702.82	3,861,280.82	1,072,578.01	kWh
Overall cost	1,636,594.69	2,103,867.62	467,272.93	euro/yr
Revenue	2,621,052.39	3,629,149.47	1,008,097.07	euro/yr
Net present value	894,961.55	1,386,619.86	491,658.31	euro

The structure of the value chain for 2G bioethanol is presented in Fig. S15. Unlike the 50 km case with only four underutilised farmlands (total size ≅ 82 ha), this case study contains 45 underutilised farmlands with total size of 858 ha. Each piece of land supplies Miscanthus directly to the biorefinery, see Fig. S15. By increasing the target area coverage from 50 to 100 km radius, the total Miscanthus supply increases by 5042 t/yr and 6981 t/yr at crop yield of 6.5 t/ha and 9.0 t/ha respectively.

At a crop yield of 9 t/ha, the quantity of Miscanthus produced on farmland within 50 km and 100 km correspond to 741 t/yr and 7722 t/yr resulting to 2G bioethanol yield of 193 t/yr and 2008 t/yr respectively. In both cases, the bioethanol yield is lower than the planned capacity of the biorefinery, which is ≅ 40,000 t/yr. The quantity of Miscanthus needed to produce 40,000 t/yr of 2G bioethanol is ≅ 153,846 t/yr (at conversion efficiency equal to 0.26 t/t DM), requiring a cultivation land equivalent to 17,094 ha (calculated assuming crop yield is approximately 9 t/ha). This land size is larger than the total underutilised lands within 100 km radius (i.e., 858 ha) to the existing biorefinery. Therefore, to satisfy the plant capacity, underutilised land beyond a 100 km radius should be considered. According to BIOPLAT EU web GIS tool, there are 7748 underutilised land parcels in the UK with a total size of ≅ 301,797 ha, distributed across England (61,988 ha), Wales (21,660 ha), Scotland (196,591 ha) and Northern Ireland (21,559 ha). Therefore, there are sufficient underutilised lands in the UK to produce feedstock for the biorefinery.

3.4. Case study 4: castor seed for HVO production

This case study evaluates the profitability of HVO production using castor seed cultivated on abandoned or degraded farmland. According to the existing HVO value chain, cultivation of castor seed and extraction of castor oil are carried out in Kenya while conversion of castor oil to hydrotreated vegetable oil is carried out in Italy. The datasets for this analysis are presented in Sections 3.4.1 and 3.4.2.

3.4.1. Cultivation of castor seed

The cultivation of castor seed (*Ricinus communis*) for HVO production is carried out on 3000 ha farmland located in Kenya, where about 6000 farmers were involve in land preparation as well as planting and harvesting of castor seed; see Table S12 for additional details.

The cultivation of castor seed in Kenya is in line with Eni's goal to expand feedstock sources for the Gela biorefinery and to support decarbonisation of the transportation sector (AOGR, 2021). In July 2021, Eni signed a memorandum of understanding with Kenya's Ministry of Petroleum and Mining to expands its HVO value chain through the production of castor seed on degraded land, croton trees in agroforestry systems, etc. (Scaramuzza, 2023). The first cargo of castor oil was delivered to Gela biorefinery in October 2022 (Scaramuzza, 2023).

In Kenya, castor is grown on arid and semi-arid land during the rainy season, i.e., October–November (short rain season) and March–April (long rain season). The full details of crop variety, soil quality requirements, water requirements and other agronomic information can be found in report by Alexopoulou (2023). Table S13 presents the yield

per hectare of castor seed in addition to cultivation cost and market selling price.

3.4.2. Oil mill and HVO biorefinery

After harvest, castor seed is transported to the oil mill located in Kwa Kathoka, Wote within Makueni county. Extraction of castor oil is carried out using a mechanical press and the parameters of the plant are presented in Table S14. Currently, the plant processes 24,000 t of castor seed per annum (equivalent to 10,800 t/yr of castor oil), but there is a plan to scale-up to 30,000 t/yr of castor oil through the construction of a second agri-hub (ENI, 2022).

The extracted oil is pre-treated and converted to hydrotreated vegetable oil in the Gela biorefinery located in Sicily, Italy. The parameters of the biorefinery are presented in Table S15. Note that these parameters were provided by industrial partners except unit production cost and HVO market price which were collected from literature.

The movement of castor seed, castor oil and hydrotreated vegetable oil along the supply chain is shown in Fig. S16. A truck is used to transport castor seed harvested from all farmlands to oil mill where extraction of castor oil takes place. The extracted oil is transported to a departing port in Mombasa using a tanker truck. Note that the port in Mombasa has an intermediate storage facility. Lastly, a ship is used to deliver the castor oil to the Gela biorefinery. Tables S16 and S17 present travel distance between supply chain entities and parameters of each transport type considered in the analysis.

3.4.3. Results and discussion

The case study information presented in Sections 3.4.1 and 3.4.2 are applied in the model described in Sections 2.2.4 and Section S2.4 to evaluate the profitability of producing hydrotreated vegetable oil from castor seeds cultivated on abandoned or degraded lands.

As shown in Table 4, the total quantity of castor seed produced is 4500 t per annum which contains about 45 % (2025 t/yr) of extractable oil. The revenue generated from the sale of hydrotreated vegetable oil and castor cake outweighs total cost over the entire planning horizon, leading to a positive net present value. Therefore, in this study, the production of hydrotreated vegetable oil using low-ILUC risk feedstocks (castor seed) is profitable.

The cost distribution shown in Fig. S17 indicates that transportation cost constitutes the smallest fraction of total cost. The transport cost is estimated over the travel distance (see Fig. S18) between supply chain entities: Farmland – Oil mill – Departure port – Biorefinery.

The structure of the HVO value chain presented in Fig. S18 shows the geographical location of all supply chain entities such as farmland, oil mill, departing seaport and biorefinery. Looking at the supply chain structure, the longest distance is along Departure port – Biorefinery route. Hence total cost can be improved by minimising shipping cost.

3.5. Case studies summary

This section summarises and discusses the key results from the four case studies investigated and analysed in this work. Recall, this work focuses on the development of decision-support models that address challenges related to climate positive farming solutions. The decision models were developed for two value chain optimisation types relevant to the concept on low ILUC as defined in the Renewable Energy Directive: (i) productivity increases from improved agricultural practices and (ii) cultivation on abandoned or degraded land. In each case, two alternative cases were investigated. The first investigated *Brassica* for HVO production and Biogas Done Right for biomethane production, while the latter focused on Miscanthus for bioethanol production and castor for HVO production. Table 5 summarises the key findings from this work.

Analysis of the case studies on production of low-ILUC biomass feedstock indicates that introduction of Brassica as cover crop during winter leads to additional usable biomass feedstock, consequently increasing net farm income. Here net farm income is estimated as the gap between revenue generated from the sales of farm products and the total cost incurred during crop production. The improved case leads to better gross margin per hectare in both current crop price scenario and high crop price scenario, while the reference case is better at low crop price. The breakeven selling price of soybean, wheat and Brassica correspond to 362 €/t, 321 €/t and 381 €/t respectively.

The production of biomethane via an anaerobic digestion process indicates that biomass feedstocks from sequential cropping leads to better biogas and biomethane yield per hectare compared to monocropping. Furthermore, an AD plant fed with sequential crops and other feedstock types (cattle slurry, potato scrap and waste from agro-industry) generates sufficient digestate that covers cropland

Table 4
Products and key performance indicators.

Item	Value	Unit
Products		
Castor seed produced	4500	t/yr
Castor oil produced	2025	t/yr
Castor cake produced	2475	t/yr
HVO produced	1620	t/yr
Performance indicators		
Overall cost	4,038,017	euro/yr
Revenue	5,058,000	euro/yr
Net present value	927,257	euro

Table 5
Key findings from case studies on production of biofuels using low-ILUC biomass feedstocks.

Case study	*Brassica* for HVO	BDR for Biomethane	Miscanthus for bioethanol	Castor for HVO
Location	Uruguay	Italy	United Kingdom	Kenya and Italy
Industrial partner	UPM	CIB	Miscanthus Nursery Ltd	ENI
Low ILUC value chain type	Productivity increases from improved practices	Productivity increases from improved practices	Cultivation on underutilised and abandon land	Cultivation on underutilised and abandon land
Land type	Existing farmland	Existing farmland	Unused land	Degraded land
Agricultural practice	Crop rotation/ cover cropping	Crop rotation	Cultivation on unused land	Cultivation on degraded land
Crop type	*Brassica*	Maize & triticale	Miscanthus	Castor
Crop yield	1.6–1.9 t/ha/yr	NA	9.0 t/ha/yr	1.5 t/ha/yr
Land size	110 ha	200 ha	858 ha	3000 ha
Additional biomass	382 t *Brassica* straw	14,569 t maize & triticale silage	7722 t Miscanthus	4500 t castor straw
Total biofuel & bioenergy yield	138 t HVO[a] ≅ 6.1×10^6 MJ[b]	1,319,800 m^3 (989 t) $bioCH_4$ ≅ 47.5×10^6 MJ[c]	2008 t $bioC_2H_5OH$ ≅ 54.2×10^6 MJ[d]	1620 t HVO ≅ 71.3×10^6 MJ[b]
Biofuel yield per hectare	0.572–0.678 t/ha/yr	6599 m^3/ha•yr or 4.9 t/ha/yr[e]	2.34 t/ha/yr	0.54 t/ha/yr

[a] Calculated assuming 45 % extractable oil (Cartea et al., 2019) and Oil to HVO conversion factor of 0.80 (Bellussi et al., 2016).
[b] Conversion factor: 1 l HVO = 34.4 MJ (DEFRA, 2021).
[c] Conversion factor: 1 m^3 biomethane = 36 MJ Ref (IEA, 2018).
[d] Conversion factor: 1 l bioethanol = 23.6 MJ (DEFRA, 2021).
[e] Density of biomethane = 0.75 kg/m^3 (Banu, 2018).

requirements.

The retrofit of an existing 1G plant to allow the production of 2G bioethanol reduces capital investment cost and enables utilisation of existing infrastructure, for example, fermenter, distillation units, CHP unit, etc. The production of 2G bioethanol using Miscanthus cultivated on underutilised lands in the UK is economically feasible as indicated by a positive net present value. At maximum expected crop yields per hectare (9 t/ha), the total Miscanthus produced on underutilised lands within 100 km radius to an existing biorefinery is 95 % lower than the amount needed to satisfy the capacity (40,000 t/ha) of the selected retrofitted plant. Consequently, target area must be expanded beyond 100 km radius to meet plant capacity.

The production of HVO in the Gela biorefinery (located in Italy) using castor seed cultivated on degraded land in Makueni (located in Kenya) is economically feasible and generates income to both local farmers and industrial stakeholders. Analysis of results indicates that cultivation cost dominates overall production cost of HVO. Hence, the profitability of the value chain can be improved by implementing measures that can minimise total cultivation cost.

Most supply chain optimisation models available in the literature focus on the optimal generation of bioethanol using annual or multi-annual crops. Dunnett et al. (2008) developed a model for the optimal bioethanol production in the UK from lignocellulosic feedstocks, investigating the effects of a centralised/decentralised configuration on the system costs. Giarola et al. (2012) developed a supply chain optimisation model where hybrid (corn and corn stover-fed) supply chains were simultaneously optimised from the economic and environmental side for the production of bioethanol in northern Italy. Akgul et al. (2012) developed a supply chain model where wheat, wheat straw, miscanthus, and short rotation coppice were used to produce bioethanol in the UK. Kostin et al. (2012) developed a sugarcane to bioethanol supply chain model in Argentina. Panteli et al. (2018) modelled a supply chain for ethanol production in West Hungary where multiple feedstocks could be mixed such as wheat straw, barley straw, and corn stover. Finally, Neill et al. (2022) modelled a switchgrass to-bioethanol supply chain in southern Michigan.

Compared to the existing literature, the modelling framework here proposed targets multiple products, such as biogas, biomethane, biofertilizer (digestate), hydrotreated vegetable oil, and bioethanol. In addition, multiple feedstocks (e.g., maize, cattle slurry, potato scraps, maize silage, triticale silage, cereal by-products, miscanthus castor seed, etc.) are modelled, using measured crop yield data from cover crops. The approach is highly generalisable to different geographical regions (South America – Uruguay; Europe – UK and Italy; and Africa – Kenya). A key feature of the modelling approach here proposed is that low ILUC agricultural practices are optimised within the supply chain. This includes rotational cropping, intercropping, sequential cropping, and cover cropping. The approach here proposed, based on a full system optimisation where real-world case studies are modelled, differentiates this contribution from the literature on ILUC where top-down statistical estimations are used (such as the work proposed by Balugani et al. (2022) and Khawaja et al. (2021)).

The current model has the key features of flexible analysis of different approaches to ensuring good economic performance and productivity while also respecting the low ILUC considerations. These two features are illustrated by (a) the flexibility to capture different case studies in different regions and (b) to constrain the system to ensure that the overall outcome corresponds to a low ILUC solution.

4. Conclusions

This work develops optimisation-based decision support models that facilitate climate positive farming solutions. Key findings from this work indicates that introducing brassica as winter cover crop in place of non-cash cover crops leads to additional biomass feedstock without affecting the yield of summer crops. Sequential cropping together with biogasdoneright© model produces biomethane and sufficient amount of digestate that meets cropland requirements, therefore avoiding the need to use chemical fertiliser derived from fossil fuel. Miscanthus produced on farmland within 100 km to an existing biorefinery satisfies only 5 % of the 2G plant capacity. Therefore, to satisfy the plant capacity, underutilised land beyond 100 km radius should be considered. The existing value chain for HVO production is profitable, providing income to both local farmers and industrial stakeholders. However, profitability can be improved by implementing measures that minimises transport cost between departing port (in Mombasa, Kenya) and biorefinery (in Gela, Italy). One element that probably influences profitability is the scale of cultivation - so castor is at much larger cultivated area than the Uruguay and Italian cases. Policy makers should consider options to support alternatives such as retrofitting, and inter-cropping to avoid or mitigate ILUC. The private sector looking for raw or limited processing of crops need to consider sustainability issues and standard certifications for the implementation of these models. Overall, our take-home message is that a range of creative options for increased biomass for bioenergy production are available, depending on the geography and expected end uses, and that these can be developed as part of an integrated land management strategy which avoids indirect land use change. Additionally, this assessment also demonstrated the economic benefits for the farmers and its feasibility compared to other crops and other farming systems. Overall, our recommendation is to review the range of options for increased biomass production for bioenergy, depending on the geography and expected end uses, these can be developed as part of an integrated land management strategy which avoids indirect land use change.

Abbreviations

AD	Anaerobic digestion
ASALS	Kenyan State Department for the arid and semi-arid lands
BDR	biogas done right
BR	Brassica
CC	cover crop
CIB	Consorzio Italiano Biogas
CN	corn
DM	dry matter
ENI	Ente Nazionale Idrocarburi
EU	European Union
FAO	food and agriculture organisation
FL	fallow
GIS	geographic information system
1G	first generation
2G	second generation
ha	hectare
HVO	hydrotreated vegetable oil
I-LUC	Low-Indirect Land Use Change
ISCC	international sustainability and carbon certification
km	kilometre
kt	kilo tonne
kWh	kilo watt hour
L	litre
MJ	mega joule
NCP	net crop produced
NPV	net present value
RED II	renewable energy directive II
SB	soybean
t	tonne
WH	wheat
yr	year

CRediT authorship contribution statement

Dauda Ibrahim: Writing – review & editing, Writing – original draft,

Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sara Giarola:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Calliope Panoutsou:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Rocio Diaz-Chavez:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Nilay Shah:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Calliope Panoutsou and Nilay Shah reports financial support was provided by European Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

In this section, you can acknowledge any support given which is not covered by the author contribution or funding sections. This may include administrative and technical support, or donations in kind (e.g., materials used for experiments).

Funding

This research was funded by the European Commission grant number: 952872—BIKE. Biofuels production at low—Iluc risK for European sustainable bioeconomy (2020−2023).

Appendix A. Supplementary data

The following supporting information can be downloaded at: www.xxx.com/xxx/s1, Section S1: Supplementary results; Section S2: Model description. Supplementary data to this article can be found online at doi:https://doi.org/10.1016/j.biteb.2024.102000.

Data availability

Data will be made available on request.

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