Mohammadi, Maryam; Martín-Hernández, Edgar; Martín, Mariano; Harjunkoski, Iiro

Modeling and Analysis of Organic Waste Management Systems in Centralized and Decentralized Supply Chains Using Generalized Disjunctive Programming

Published in:
Industrial and Engineering Chemistry Research

DOI:
10.1021/acs.iecr.0c04638

Published: 03/02/2021

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Mohammadi, M., Martín-Hernández, E., Martín, M., & Harjunkoski, I. (2021). Modeling and Analysis of Organic Waste Management Systems in Centralized and Decentralized Supply Chains Using Generalized Disjunctive Programming. *Industrial and Engineering Chemistry Research*, *60*(4), 1719-1745. https://doi.org/10.1021/acs.iecr.0c04638

Modeling and analysis of organic waste management systems in centralized and decentralized supply chains using generalized disjunctive programming

Maryam Mohammadi [a], Edgar Martín-Hernández [b], Mariano Martín [b], Iiro Harjunkoski [a,c,*]
[a] Research Group of Process Control and Automation, Department of Chemical and Metallurgical Engineering, School of Chemical Engineering, Aalto University, FI-00076 Espoo, Finland
[b] Department of Chemical Engineering, University of Salamanca, Plz. Caídos 1-5, 37008 Salamanca, Spain
[c] Hitachi ABB Power Grids Research, Kallstadter Straße 1, 68309 Mannheim, Germany

Abstract
Although the decentralized and centralized strategies are widely known in today's supply chain realm, few studies have investigated their impacts on the bio-based waste management context. This study aims to formulate a multi-echelon structure for evaluating the influence of these supply chain strategies on optimal utilization of the biomass feedstocks. The proposed supply chain models, connecting the economic, social, and environmental aspects, tend to lower the total system costs, reduce the inadvertent effects of transportation and production processes, and respond to dynamic demands. The optimization problem is formulated as a mixed-integer linear programming model using generalized disjunctive programming to select the most robust integrated supply chain strategy. The results indicate that, although the centralized model leads to higher investment and operating costs than the decentralized model, centralization is still a more profitable alternative, as well as being capable of the production of a broader portfolio of bio-based products.

Keywords:
Biomass treatment, bio-based products, decentralization, centralization, integrated supply chain, sustainability.

1. Introduction

Waste generation is increasingly regarded as a serious worldwide public health concern and one of the leading causes of environmental damage to our contemporary era. Worldwide, bio-based waste such as biogenic fractions of municipal solid waste (MSW), agricultural waste, forestry waste, and energy crops sources comprises a substantial segment of the generated waste. Although the abundant generation of bio-waste and biomass is a continuing concern, it has also been viewed as a positive aspect, where they can be used in the production of value-added products and renewable energy, thereby improving financial and environmental sustainability. The plentiful availability of bio-waste and biomass can secure all year-round operations and energy supply, and thus, solving the dilemma of high consumption of natural resources and increasing energy demand.[1] Proper use of bio-based waste can also significantly reduce the illegal waste dumping in rural areas, especially in low- and middle-income countries,[2] in addition to supporting their economies by creating jobs and wealth.[3] Furthermore, energy recovery from bio-based waste materials has different circular economy potentials, as waste in this context is recognized as a valuable resource that contributes to the circular economy focus of creating self-sustaining production systems repeatedly.[4]

*Corresponding author
E-mail addresses: iiro.harjunkoski@aalto.fi, Iiro.Harjunkoski@hitachi-powergrids.com

Rural areas are characterized by the excessive production of, and accessibility to, biomass. Improper collection of biomass materials in rural areas leads to illegal disposal or backyard burning, deforestation, and land degradation.[5] In urban areas, bio-waste is also generated in massive quantities because of high population density and economic growth. Globally, the majority of this type of waste generally ends up in landfills, and a small portion of it is recovered, which results in losing valuable resources and nutrients.[6] Besides, it creates environmental damage such as the leaching of toxic compounds into soil and groundwater, as well as releasing an enormous amount of methane (CH_4) into the atmosphere.[7] This is mainly caused by lacking proper collection schemes and coordination on the supply chain levels.

In the new global economy, there has been a growing need and increasing interest in proximity between consumption, recovery, production, and distribution entities, which tremendously enhances the reuse of bio-based waste materials.[8] Recent studies on bio-based waste treatment show the importance of considering the collection, transport, storage, treatment, and distribution simultaneously to ensure the long-term viability of bio-based waste management systems.[9] The coordination between all entities of the supply chain has a substantial impact on the system performance by minimizing the overall costs while satisfying capacity restrictions existing in all levels of the network and fulfilling the demand requirements in time.[10]

Despite several advances in the field of bio-based waste supply chain management, there has been a lack of uniformity on integrating different concepts of supply chain design and planning, thus highlighting the need for further research that brings the models closer to reality. Furthermore, compared to the extensive research on economic and environmental issues of waste processing, little attention has been paid to the social aspects. Accordingly, this research aims to contribute to this growing realm of opportunity by exploring the organic waste utilization for generating biofuels and biopower, as well as measuring and evaluating their implications for sustainability. This study develops new models that optimally plan and integrate supply chain components of bio-based waste treatment into a coordinated system by combining strategic decisions with the tactical and operational decisions in centralized and decentralized networks. The proposed model analyzes the environmental and economic benefits derived from the production of value-added products from biomass and bio-waste streams. The model also measures the social impacts of the considered problem by determining to what extent the production of bioenergy leads to meeting the growing energy demand, the development of local communities, and the creation of employment opportunities.

This study examines two scenarios for assessing the potential of bio-based waste treatment in the small-scale decentralized and large-scale centralized production-distribution networks. The proposed models are formulated by considering various aspects of integrated supply chain networks. The strategic level (within a time frame of several years) of the integrated model involves decisions such as determining the number, location, and size of production facilities. The tactical level (a quarter to a year) of the model focuses on decisions related to manufacturing (production planning, workforce planning, demand forecasting, and capacity allocation) and logistics operations. This phase aims to maximize supply chain profit and optimize performance. The operational level (hourly-to-weekly time scales) covers decisions related to demand fulfillment and distribution planning. The model also aims at optimizing the choice between treatment technologies. Various biochemical (e.g., anaerobic digestion, fermentation) and thermochemical (e.g., pyrolysis, gasification, combustion) approaches are investigated to evaluate the potential for converting bio-based waste into solid fuels, liquid fuels, gaseous fuels, and electricity. Figure 1 illustrates a schematic of the considered bio-based supply chain.

The overall structure of this paper has been divided into six sections, including the introduction section. Section 2 gives a brief overview of bio-based waste treatment in centralized and decentralized production-distribution networks. Section 3 is concerned with the model formulation of the considered problem. Section 4 presents the utilized data, followed by the research findings and analysis of the obtained results in Section 5. Finally, Section 6 provides a summary of the study and analysis of the findings.

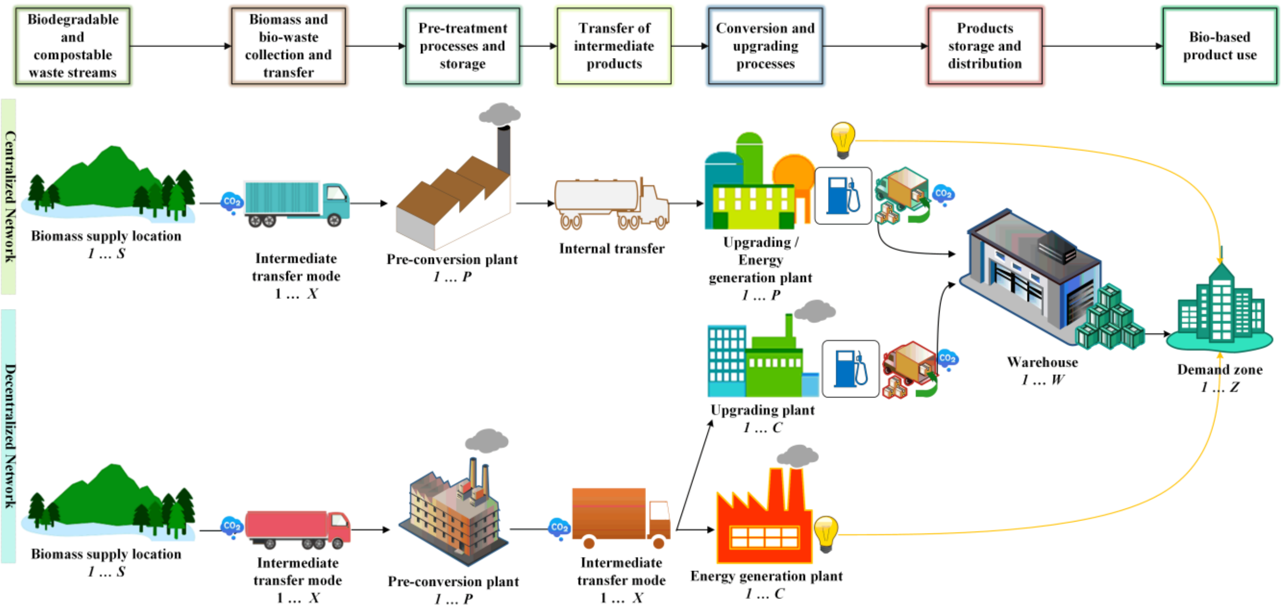

Figure 1. A centralized and decentralized supply chain network for bio-based waste processing

2. Literature Review

2.1. Bio-based waste materials

Bio-based waste refers to biological and renewable materials and can be classified as biomass and bio-waste. Biomass is commonly used to reference biodegradable rural waste components and is defined as the decomposable fraction of biological-origin materials that can be utilized as an energy source. The diverse types of biomass include crops and residues from agriculture harvesting or processing, forestry crops and residues, animal residues, and wood pellets. Since biomass absorbs carbon dioxide (CO_2) when it grows and emits it when consumed for energy production purposes, its cycle can be considered carbon-neutral, and therefore deemed as not increasing the concentration of greenhouse gases (GHGs) in the atmosphere.[11] Bio-waste refers to organic matter and nutrients in urban waste, such as food waste, kitchen waste, green garden waste, and sewage sludge. Several factors, including the culture, climate, economic development, income levels of the inhabitants, geographical location, and consumption level, affect the waste composition and the amount of waste collected.[12]

Increasing the amount of generated waste by anthropogenic activities, and accordingly, the amount of bio-based waste will have profound consequences if not managed properly, and thus, serving as a significant threat to public health and the environment. Dumping the bio-based waste materials in uncontrolled landfills causes their decomposition anaerobically, and hence, leading to releasing CH_4, CO_2, and other harmful gases into the air.[13] Recent developments in the waste management sector highlight the need for evaluating the efficacy and impacts of the treatment of bio-based waste materials on social, economic, and environmental growth.[14,15]

2.2. Overview of bio-based waste treatment technologies

There are three main categories for converting biomass and biowaste materials (also classified as renewable resources) into solid fuels (e.g., biochar), liquid fuels (e.g., bioethanol, biomethanol, bio-oil), and gaseous fuels (e.g., syngas, biomethane, biogas), namely thermochemical, biochemical, and physicochemical conversion techniques. These fuel sources can then be converted to biofuels (transportation fuels), synthetic natural gas (SNG), chemicals, and electricity. Figure 2 illustrates a summary of bio-based waste treatment technologies and their resulting value-added products.

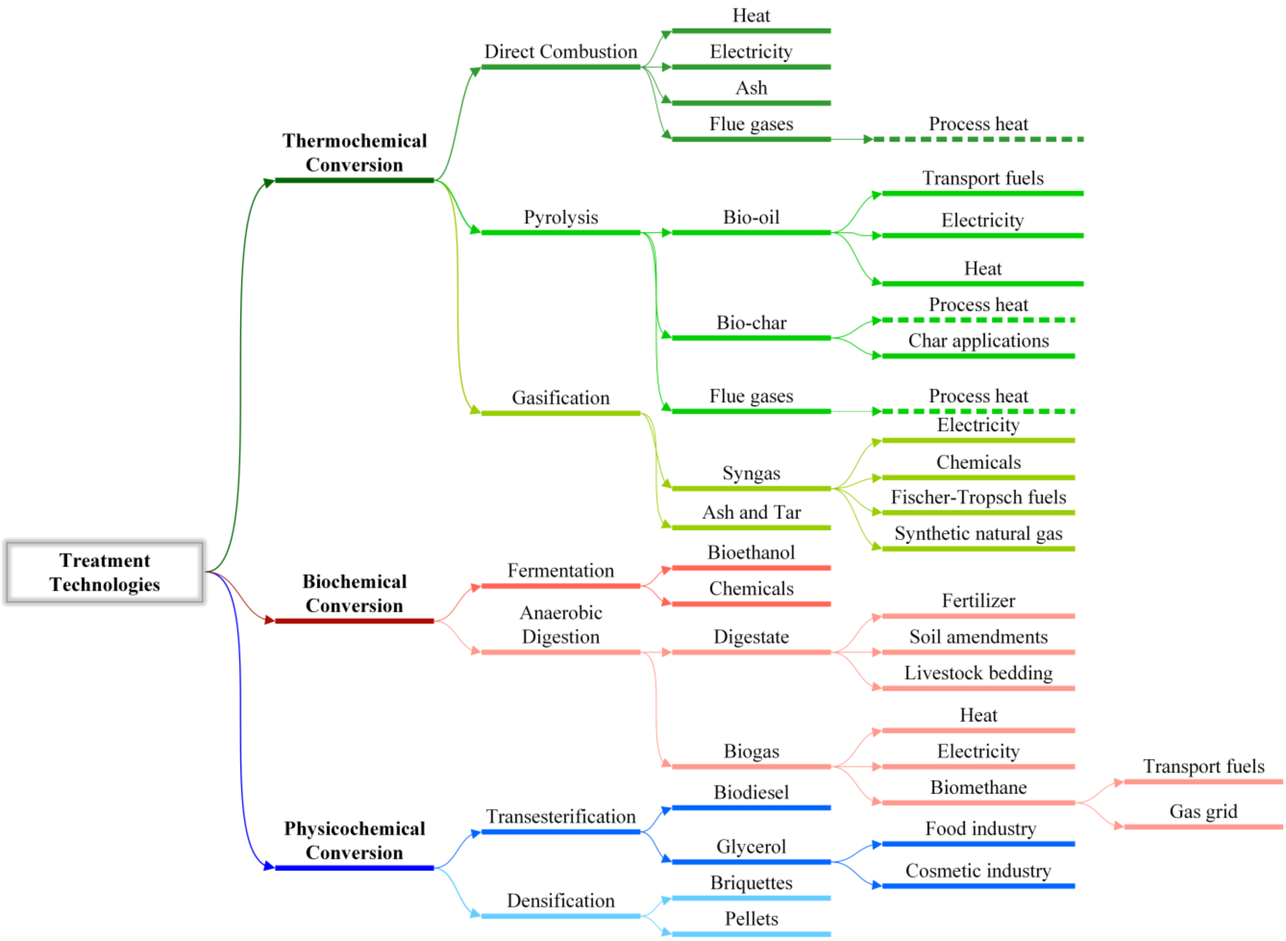

Figure 2. Biomass treatment methods and their resulting products

Thermochemical conversion processes (e.g., incineration, pyrolysis, and gasification) function by applying heat to activate chemical reactions. The oxygen (O_2) level, heating rate, and temperature vary in each of these processes. Commonly, thermochemical conversion processes require high energy intensity but carry out quicker than biochemical methods.[16]

Incineration, known as one of the most reliable and commonly used treatment processes, is the controlled combustion (temperature ranging from 800 to 1200°C) of low moisture feedstock with the recovery of heat to create steam and generate electricity. Fly ash, bottom ash in the combustion chamber, and air-pollution control residues are the solid residues of the incineration process. In combustion, the carbon and hydrogen (H_2) of the feedstock are oxidized into CO_2 and water, which results in releasing energy by breaking down their bonds,[17] followed by a cleaning stage of the produced gases before discharging into the atmosphere. Nakatsuka et al.[18] evaluated the potential of power generation from sewage sludge and MSW in integrated wastewater treatment and incineration plants. Their results indicated that this integration diminishes the total annual costs by 35% and the total annual CO_2 emission by 1%.

The pyrolysis process involves the decomposition of the homogeneous and dry (10-15% moisture content) biomass with relatively low ash and high carbon content by applying an external source of heat with the temperature ranging from 300 to 850°C in an O_2-free environment. Pyrolysis is classified into two types: slow and fast. In the slow pyrolysis process, the main products are organic gas and biochar, whereas the fast pyrolysis mainly yields biochar and organic vapors that are then condensed to bio-oil.[19] In either case, the gas and oil can be vaporized through their combustion in the combined heat and power (CHP) units to generate power or upgraded to several types of transportation fuels (e.g., gasoline and diesel). However, the corrosive properties, high water content, and thermal inconsistency of pyrolysis oil cause its unsuitability for direct use as a transportation fuel or as a fuel additive. Thus, the oil product should be upgraded through hydrotreating, hydrocracking, or chemical extraction to remove its impurities.[20] The production of transportation fuels, including gasoline and diesel, through the pyrolysis of corn stover and subsequent hydrotreating and hydrocracking of the resulting bio-oil, has been studied by NREL.[21] Li et al.[22] analyzed the fast pyrolysis of a mixed feedstock, including wood, straw, grass, organic residue, and husk, and assessed the effect of biomass ash content and oxygen to carbon (O/C) ratio on biochar and biofuel yields. Their experimental results showed that the high ash content in biomass increases biochar yield but reduces biofuel yields, where a higher O/C ratio in biomass diminishes biochar yield and rises biofuel yields with the same ash content level. Patel et al.[23] indicated that the pyrolysis of biomass results in the production of high-grade biofuels, varying from 21.9% to 75% based on the process temperature, type of biomass, and reactor type.

The gasification process gathers energy into chemical bonds in the gas by enhancing H_2 and removing carbon from the feedstock[17] in the presence of limited O_2 with a temperature higher than 650°C (typically 800 to 1200°C). In gasification, the dry biomass with moisture contents of 10 to 20% is converted to syngas (a mixture of carbon monoxide (CO) and H_2, with smaller quantities of CO_2, CH_4, nitrogen (N_2), steam, hydrogen chloride (HCl), hydrogen sulfide (H_2S), light hydrocarbons (e.g., propane and ethane), and heavier hydrocarbons (e.g., tars)).[24,25] The syngas composition varies according to the used gasification reactor (e.g., fixed bed reactors, fluidized bed reactors, entrained flow reactors), the feedstock characteristics, and the operating parameters.[26] Furthermore, the H_2/CO ratio in the syngas can be controlled through the water gas shift reaction. The resulting syngas in the gasification process can then be fed into a gas engine, combined cycle, or fuel cells for electricity generation. Moreover, syngas can be converted to H_2, SNG, methanol, ethanol, dimethyl ether, diesel, gasoline, and jet fuels through various processes, including the separation, catalytic, and Fischer-Tropsch methods.[27] Char, also known as gasification ash, is the solid by-product of the gasification.[26] According to Kirkels and Verbong,[28] wood is the most suitable feedstock for gasification, and black liquor, rice husk, and peat have also been gasified successfully.

The anaerobic digestion occurs in the absence of O_2 and biochemically breaks down the solid and liquid organic waste materials (e.g., livestock waste, food waste, wastewater, crops, the organic components of MSW) through a bacterial process. The biogas, as the main product of anaerobic digestion, mostly contains CH_4 and CO_2, as well as several other gaseous impurities, e.g., ammonia (NH_3), H_2S, N_2, H_2, and O_2.[29] Biogas cleaning for removing harmful impurities and moisture is also included in the biogas generation stage. After the cleaning stage, biogas can be directly combusted in the microturbine unit for electricity production.[30] Another possibility is to remove the CO_2 contained in biogas through a pressure swing adsorption system for producing bio-based CH_4,[31] which can be directly fed to the natural gas grid or liquefied to obtain liquified biomethane.[32] An additional configuration is the use of biomethane gas for electricity production in a turbine, which is similar to the direct combustion of biogas but achieving better efficiencies as a result of the removal of CO_2.

The two drawbacks of biogas utilization include its high storage costs for a lengthy period and its inability to liquefy due to the low dew point of CH_4 (-82.5°C) even with extremely high pressures, that can reach up to 50 bar in function of the liquefaction process.[32,33] The digestate, containing a high concentration of N_2 and phosphorus, is another product of the anaerobic digestion, which can be used in the production of fertilizers and soil amendment.

Fermentation occurs in an anaerobic environment that breaks down organic matter in biomass sources such as starch-based grains (e.g., wheat, corn) and sucrose (e.g., beet, sugarcane), taking from 5 to 7 days at the temperature of 25 to 30°C. Bioethanol, obtained through the distillation process, is the final product of sugar fermentation, and is a leading biofuel globally,[34,35] either used as such or blended with other petroleum-based fuels (e.g., gasoline).[36] Abo et al.[37] stated that bioethanol is currently the only substitute for gasoline that can be consumed directly without requiring considerable changes in the way fuel is disseminated. However, the large-scale use of edible first-generation feedstock to produce bioethanol has been vigorously criticized due to its potential competition with human consumption (food) or animal consumption (feed). As a sustainable substitute, non-food crops (e.g., lignocellulosic feedstock) or waste materials from first-generation feedstock (e.g., waste vegetable oil) are suggested[38] due to their low cost and high availability.

2.3. Biomass treatment in decentralized and centralized supply chain networks

Several studies have developed a monolithic approach for the incorporation of supply chain networks into the production systems of bio-based products such as biogas,[39] bio-oil,[40] bioethanol,[41] biofuel,[42] and bioelectricity.[43] Furthermore, Shabani et al.,[44] Meyer et al.,[45] and Nunes et al.[46] provided a comprehensive review of supply chain management in biomass to energy industries. Although extensive research has been carried out on bio-based waste supply chains, there have been few investigations considering the environmental and socio-economic benefits of the treatment of bio-based waste streams in the integrated multi-scale supply chain networks. Figure 3 illustrates the centralized and decentralized supply chain management of bio-based waste materials.

Centralization refers to locating treatment and production facilities in one central location where end products are dispersed to various demand points. Large-scale plants in the centralized approach require high capital costs but can treat massive quantities of waste materials. This strategy may benefit more from the high capacities of large-scale plants with high production rates and low production costs due to economies of scale and suffer from high transportation costs as biomass supply sites are located at distant locations.[47] According to Yue et al.,[48] the entire biomass supply chain is generally considered a centralized system. It might be true if all supply chain entities, including the collection centers, production facilities, and distributors, are cooperative and united. However, more often, the parties are non-integrated, which results in competition for biomass acquirement, utilization, and price discrimination.

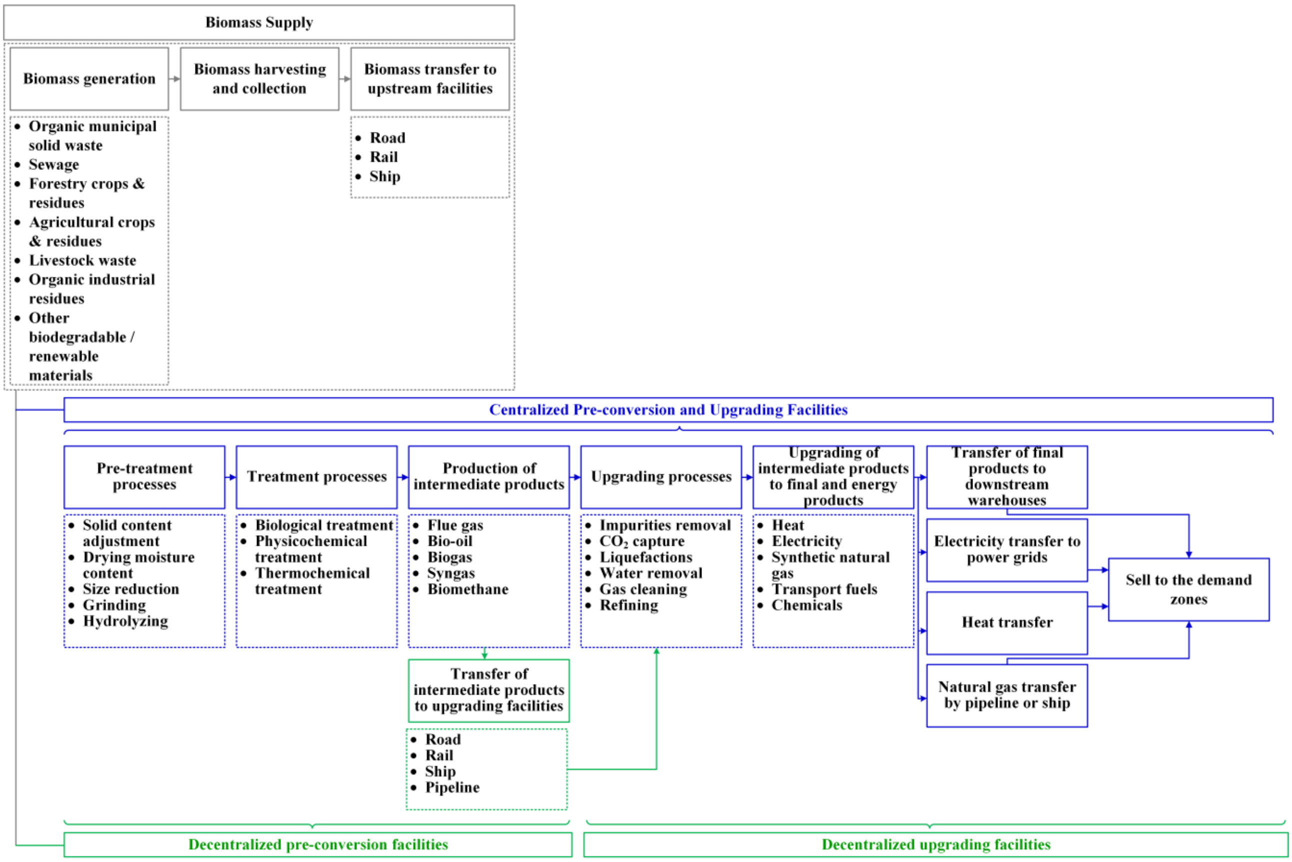

Figure 3. Supply chain network design of bio-based waste management systems

The small-scale decentralized production-distribution system is an alternative to traditional centralized systems where large-scale treatment plants are split into multiple treatment and recovery units and located in several locations, allowing various exchanges of products between different facilities. A shift from large-scale centralized production/treatment facilities towards small regional ones would increase the flexibility and adaptability to local needs.[49] Such a strategy would result in the reduction of storage and transportation costs and an increase in operational expenses. Moreover, the decentralized approach limits collaboration and information sharing among supply chain members.[50] Thiriet et al.[51] developed a mixed-integer linear programming model (MILP) for a decentralized micro-scale anaerobic digestion plant in urban and peri-urban areas aiming at minimizing the payload-distances of biowaste and digestate transportation. They pointed out that the effectiveness of the decentralized method depends on a close integration of the entire treatment chain, from the biowaste generation to the coproduct's valorization, as well as on the close relationship between the various stages of the processing pathway, besides the adaptation of the biowaste management at local and territory levels.

The combined centralized-decentralized strategy refers to the hybrid supply chain where pre-treatment operations are handled by processing facilities situated at several locations, and upgrading operations are carried out at extensive treatment facilities having the capability to perform upgrading operations. You and Wang[52] designed a multi-site distributed centralized supply chain for biomass conversion to liquids, considering economic and environmental aspects through a multi-objective optimization problem. Their results revealed that different environmental performances of the considered supply chain affect the optimal annualized cost, biomass processing, and liquid fuel production network structures.

Sharifzadeh et al.[53] examined centralized, distributed, and mobile biofuel production from lignocellulosic feedstock using an MILP model. They showed that in deterministic settings, the supply chain performs better in conditions where centralized pyrolysis and upgrading centers are combined geographically. However, under uncertain circumstances, it is beneficial to consider mobile pyrolizers to add additional flexibility to the process operations. Their results indicated that in the first case, the production costs are low compared to transportation costs, and the second strategy leads to a lower transportation cost but higher investment and operating costs because the design cannot benefit from economies of scale. Kuznetsova et al.[54] pointed out the pressure on the conventional centralized MSW management systems because of the rapid growth of urban populations, increase in waste generation, and limited disposal capacities. They suggested that to encounter this problem, the conventional centralized waste management system should move toward a more decentralized scheme with smaller treatment capacities. Their computational results indicated that the combined strategy reduces the total operational expenses by about 50% and almost doubles the revenue from electricity recovery in comparison to conventional MSW management. Moreover, compared to the traditional MSW systems, the usage of land and transportation fleet was reduced by 74.8% and 15.3%, respectively.

Together, these studies outline that several factors affect the choice among centralized and decentralized bio-based supply chains, including the feedstock availability, local needs, investments into treatment technologies, collection and transport systems, as well as their economic, social, and environmental implications. In view of all that has been mentioned so far, this research seeks to address how the centralized and decentralized supply chain approaches affect the socio-economic and environmental development of bio-based systems.

3. Problem Formulation

The model is formulated as a multi-product, multi-stage, multi-period supply chain problem. Several types of bio-based waste materials and a set of biomass generation points, potential facility locations, distribution centers, and demand zones are included in the supply chain structure. Section 3.1 presents the constraints related to biomass acquirement, biomass treatment, biofuel and bioenergy production, product distribution, and demand fulfillment, and Section 3.2 represents the proposed multi-objective model with simultaneous consideration of economic, social, and environmental aspects.

3.1 Model constraints

3.1.1 Biomass supply location

Each biomass feedstock supply location can serve multiple pre-conversion and conversion facilities, and each facility can acquire biomass from multiple supply locations. In the decentralized pre-conversion plants, intermediate products are produced, and upgrading and energy generation processes are carried out in other locations. In contrast, in the centralized conversion plants, the production of intermediates and upgrading operations occur at the same location. The centralized production plants can also produce final or energy products directly without any intermediate production. As shown in Eq. (1), the total quantity of biomass distributed to pre-conversion and conversion facilities cannot exceed the maximum collectible biomass in the supply location. For sustainability reasons, some biomass portions should remain on the field to preserve soil structure and maintain the ecosystem. It should be noted that the type of biomass significantly affects the amount of the kept portion. Based on the study conducted by Claassen et al.,[55] at least 30% of residue must be retained on the field to avoid soil erosion.

$$\sum_p \sum_x a^{dec}_{bspxt} + a^{cent}_{bspxt} \le \left(1 - F^{sus}_{bst}\right) \cdot A_{bst} \qquad \forall b \in B, s \in S, t \in T \qquad (1)$$

It is assumed that location p can either possess a decentralized plant or a centralized facility. Therefore, a supply location can transfer the biomass either to a decentralized or a centralized facility, but both facility types cannot be chosen at the same time in location p. For this purpose, generalized disjunctive programming (GDP) is used to formulate the discrete choices among candidate centralized and decentralized facilities. The logical interrelationship between such discrete decisions can be represented using Boolean expression $Y_p^{dec} \underline{\vee} Y_p^{cent}$, and be formulated as linear inequality using their corresponding binary variables, as shown in Eq. (2). It is also possible that a candidate location remains without any production facility. It should be noted that the mixture of centralized and decentralized strategies as a hybrid technique is not considered in this study.

$$y^{dec}_p + y^{cent}_p \le 1 \qquad \forall p \in P \qquad (2)$$

3.1.2 The decentralized model

i. Biomass transfer to decentralized facilities

As enforced by Eq. (3), a maximum transportation distance, D_b^{max}, is considered for biomass transportation to pre-conversion plants. In this study, the haversine formula is applied to calculate the geographic distance between two points on a sphere using their longitudes and latitudes. Each transport mode has a transportation capacity so that the transported amount should not surpass its pre-determined limits. Equation (4) enforces the minimum and maximum bounds of transportation capacity. Equation (5) calculates the number of transfers between biomass locations and decentralized facilities. The moisture content is also considered as the collected biomass has not been dried before transportation. In order to control the number of transfers from a supply location to different production plants, we have set a maximum limit for each possible shipment. It is assumed that the biodiesel or renewable diesel produced by conversion/upgrading facilities can be used alongside fossil-based fuels for transport activities. Equation (6) computes the carbon footprint caused by the transportation of biomass to facilities, considering the number of trips, distance, fossil-based diesel fuel consumption deducting the percentage of biodiesel added to conventional diesel, and the carbon emission factor for diesel fuel. This equation only measures the carbon in the consumed fossil diesel since renewable fuels such as biodiesel are less carbon-intensive, and their GHG impact is neutral (Directive 2009/30/EC)[56].

$$a^{dec}_{bspxt} = 0 \qquad \forall b \in B, s \in S, p \in P, x \in X, t \in T \;\middle|\; D^{max}_b < D_{sp} \qquad (3)$$

$$\sum_x TC^{min}_{sxt} \cdot y^{mode}_{spxt} \le \sum_b \sum_x \left(V_b \cdot a^{dec}_{bspxt} \big/ \left(1 - F^{mois}_b\right)\right) \le \sum_x TC^{max}_{sxt} \cdot y^{mode}_{spxt} \qquad \forall s \in S, p \in P, t \in T \;\middle|\; D_{sp} \le D^{max}_b \qquad (4)$$

$$n_{spxt} - 1 \le \frac{\sum_b \left(V_b \cdot a^{dec}_{bspxt} \big/ \left(1 - F^{mois}_b\right)\right)}{CC_x \cdot F^{util}_x} \le n_{spxt} \qquad \forall s \in S, p \in P, x \in X, t \in T \qquad (5)$$

$$et^{CO_2}_{spxt} = n_{spxt} \cdot D_{sp} \cdot FC^{reg}_x \cdot \left(1 - FC^{bio}_x\right) \cdot FE^{CO_2}_x \qquad \forall s \in S, p \in P, x \in X, t \in T \qquad (6)$$

ii. Type of decentralized facilities

A decentralized facility produces intermediate products, which can be considered as input materials and additives to the upgrading or energy generation processes in other facilities. For instance, a plant can produce pyrolysis oil from MSW that can be transferred to upgrading plants to produce naphtha and diesel, or the produced CH_4 from MSW using anaerobic digestion process can be converted into electricity in energy generation plants. The discrete decisions such as the selection of a facility type and its installed technology are represented using the GDP formulation. If the pre-conversion facility p is operating (Y_p^{dec} is True, which has a one-to-one correspondence with the binary variable $y_p^{dec} = 1$), then a Boolean variable Y_{mrp}^{int} must be True; i.e., $\underset{m,r}{\vee} Y_{mrp}^{int}$ that can be translated into an algebraic equation by the binary variable $\sum_{m,r} y_{mrp}^{int} = 1$, meaning that a facility can be equipped with only one pre-treatment technology type m with a specific capacity level r. The logic relationship of $Y_p^{dec} \Leftrightarrow \underset{m,r}{\vee} Y_{mrp}^{int}$ can be expressed as $(\neg Y_p^{dec} \vee \underset{m,r}{\vee} Y_{mrp}^{int}) \wedge (\neg \underset{m,r}{\vee} Y_{mrp}^{int} \vee Y_p^{dec})$, and according to the De Morgan's theorem and conjunctive normal form[57], can be reformulated as linear equality using their corresponding binary variables, as shown in Eq. (7). Equation (8) limits the total number of decentralized plants in the entire network. Moreover, Eq. (9) imposes the upper limit on the number of intermediate technologies in the entire network.

$$y_p^{dec} = \sum_m \sum_r y_{mrp}^{int} \qquad \forall p \in P \qquad (7)$$

$$\sum_p y_p^{dec} \le NPF \qquad (8)$$

$$\sum_r \sum_p y_{mrp}^{int} \le NIT_m \qquad \forall m \in M \qquad (9)$$

If the Boolean variable Y_p^{dec} becomes True, then the disjunction shown in Eq. (10) will become active, and the constraints within it must be satisfied. The processing capacity of the facility depends on several factors, including the available space, workforces, materials, and technology, and the output capacity depends on the maximum number of products that the facility can produce. Accordingly, the second level of Eq. (10) expresses that the total transported biomass from all supply locations to a facility cannot exceed the maximum input capacity of that facility, and it can only occur when that facility is operating. The next levels of disjunction ensure that the production of intermediate products and by-products does not exceed the production capacity limits. In order to solve the disjunctive model, it can be reformulated into an MILP problem using the Big-M relaxations, as indicated in Eqs. (11) to (13). This approach is used for solving the presented disjunctive inequalities in this study. Among the Big-M and convex hull reformulations used to convert a logic constraint to a set of equations, we selected the Big-M formulation since it requires a lower number of constraints, giving rise to a less intricate problem than the use of convex hull. When Y_p^{dec} is False and the parameter M is significantly large, the associated disjunctions become redundant. In this case, no biomass is transferred to the facility, and no product is produced in that facility.

$$\begin{bmatrix} Y_p^{dec} & \\ \sum_b \sum_s \sum_x a_{bspxt}^{dec} \le IC_{pt} & \forall t \in T \\ PCI_{ipt}^{min} \le \sum_m a_{impt}^{int} \le PCI_{ipt}^{max} & \forall i \in I, t \in T \\ PCB_{opt}^{min} \le \sum_m a_{ompt}^{byp} \le PCB_{opt}^{max} & \forall o \in O, t \in T \end{bmatrix} \vee \begin{bmatrix} \neg Y_p^{dec} \\ a_{bspxt}^{dec} = 0 \\ a_{impt}^{int} = 0 \\ a_{ompt}^{byp} = 0 \end{bmatrix} \qquad \forall p \in P \qquad (10)$$

$$\sum_b \sum_s \sum_x a_{bspxt}^{dec} \le IC_{pt} + M \cdot \left(1 - y_p^{dec}\right) \qquad \forall p \in P, t \in T \qquad (11)$$

$$PCI_{ipt}^{min} \cdot y_p^{dec} \le \sum_m a_{impt}^{int} \le PCI_{ipt}^{max} \cdot y_p^{dec} \qquad \forall i \in I, p \in P, t \in T \quad (12)$$

$$PCB_{opt}^{min} \cdot y_p^{dec} \le \sum_m a_{ompt}^{byp} \le PCB_{opt}^{max} \cdot y_p^{dec} \qquad \forall o \in O, p \in P, t \in T \quad (13)$$

iii. Production of intermediates in decentralized pre-conversion facilities

As shown in Eq. (14), when the Boolean variable Y_{mrp}^{int} is True, then the total amount of biomass utilized by the intermediate technology existing in the pre-conversion facility cannot exceed the received biomass from all supply sources, and the biomass inventory carried over from the previous period taking into account the biomass moisture content and biomass loss during the transportation and unloading process. Moreover, the designed input capacity of the technology is treated as a variable bounded between its lower and upper capacity limits. It should be noted that only one Y_{mrp}^{int} makes the two disjunctions active. On the contrary case, the flow of biomass materials to intermediate technology becomes zero. As given in Eq. (15), the quantity of biomass assigned to an intermediate technology is limited by the input capacity of the technology (e.g., kg/sec) and the total working time during each period. Equation (16) measures the amount of an intermediate product produced by one dry kg of biomass feedstock of type *b* using intermediate technology *m*. This equation considers only the conversion of biomass to an intermediate that is assumed intermediate level 1. Furthermore, intermediate level 1 can be upgraded to other intermediate products at higher levels in the same facility using the same technology. It should be noted that whenever a level adds up, the input to the technology will be the intermediate produced from the previous level. Due to space limitations, we only present intermediate production of level 1. Equation (17) calculates the number of by-products generated during biomass processing. For instance, the digestate produced alongside the production of CH_4 from the sludge feedstock or char produced during the MSW pyrolysis are considered as by-products. Equation (18) refers to the inventory balance of biomass in a pre-conversion plant, which cannot exceed its maximum storage capacity, as given in Eq. (19).

$$\underset{m,r}{\veebar}\begin{bmatrix} Y_{mrp}^{int} \\ a_{bmpt}^{int} \le \left(1-F_{bt}^{deter}\right)\cdot a_{bp,t-1}^{inv} + \sum_s \sum_x \left(1-F_b^{loss}\right)\cdot\left(1-F_b^{mois}\right)\cdot a_{bspxt}^{dec} \quad \forall b \in B, t \in T \\ ITC_{bm,r-1} \le a_{bmrp}^{cap} \le ITC_{bmr} \quad \forall b \in B \end{bmatrix} \vee \begin{bmatrix} \neg Y_{mrp}^{int} \\ a_{bmpt}^{int} = 0 \\ a_{bmrp}^{cap} = 0 \end{bmatrix} \qquad \forall p \in P \quad (14)$$

$$a_{bmpt}^{int} \le WT_{pt} \cdot \sum_r a_{bmrp}^{cap} \qquad \forall b \in B, m \in M, p \in P, t \in T \quad (15)$$

$$a_{impt}^{int} = \sum_b R_{bim}^{conv} \cdot a_{bmpt}^{int} \qquad \forall i \in I, m \in M, p \in P, t \in T \quad (16)$$

$$a_{ompt}^{byp} = \sum_b R_{bom}^{conv} \cdot a_{bmpt}^{int} \qquad \forall o \in O, m \in M, p \in P, t \in T \quad (17)$$

$$a_{bpt}^{inv} = \left(1-F_{bt}^{deter}\right)\cdot a_{bp,t-1}^{inv} + \left(1-F_b^{loss}\right)\cdot\left(1-F_b^{mois}\right)\cdot \sum_s \sum_x a_{bspxt}^{dec} - \sum_i \sum_m R_{bim}^{cons} \cdot a_{impt}^{int} - \sum_o \sum_m R_{bom}^{cons} \cdot a_{ompt}^{byp} \qquad \forall b \in B, p \in P, t \in T \quad (18)$$

$$\sum_b V_b \cdot a_{bpt}^{inv} \le SC_p^{bio} \qquad \forall p \in P, t \in T \quad (19)$$

The total amount of intermediate products transferred from a pre-conversion facility to conversion or energy generation facilities is limited by the production and inventory quantities, as indicated in Eq.

(20). Equation (21) shows the inventory level of intermediates during each period, and Eq. (22) gives the total storage capacity for the intermediate products at a pre-conversion facility.

$$\sum_{c}\sum_{x} a_{ipcxt}^{trans} \le a_{ip,t-1}^{inv} + \sum_{m} a_{impt}^{int} \qquad \forall i \in I, p \in P, t \in T \quad (20)$$

$$a_{ipt}^{inv} = a_{ip,t-1}^{inv} + \sum_{m} a_{impt}^{int} - \sum_{c}\sum_{x} a_{ipcxt}^{trans} \qquad \forall i \in I, p \in P, t \in T \quad (21)$$

$$\sum_{i} V_i \cdot a_{ipt}^{inv} \le SC_p^{int} \qquad \forall p \in P, t \in T \quad (22)$$

iv. Transfer of intermediates from decentralized pre-conversion plants to conversion facilities

Pre-conversion plants are not equipped with upgrading technologies, and thus upgrading operations to final products occur at the conversion facilities. Transfer of intermediates from pre-treatment facilities to upgrading plants cannot exceed the transportation capacity of the selected transport mode, as given in Eq. (23). As enforced by Eq. (24), a maximum transportation distance, D_i^{max}, is considered for intermediates that are not suitable for long-distance transportation. Equation (25) calculates the number of transfers using a specific transport mode, and Eq. (26) is used to calculate the amount of CO_2 emission emitted from transportation activities.

$$\sum_{x} TC_{pxt}^{min} \cdot y_{pcxt}^{mode} \le \sum_{i}\sum_{x} V_i \cdot a_{ipcxt}^{trans} \le \sum_{x} TC_{pxt}^{max} \cdot y_{pcxt}^{mode} \qquad p \in P, c \in C, t \in T \,\big|\, D_{pc} < D_i^{max} \quad (23)$$

$$a_{ipcxt}^{trans} = 0 \qquad \forall i \in I, p \in P, c \in C, x \in X, t \in T \mid D_i^{max} < D_{pc} \quad (24)$$

$$n_{pcxt} - 1 \le \frac{\sum_{i} V_i \cdot a_{ipcxt}^{trans}}{CC_x \cdot F_x^{util}} \le n_{pcxt} \qquad \forall p \in P, c \in C, x \in X, t \in T \quad (25)$$

$$et_{pcxt}^{CO_2} = n_{pcxt} \cdot D_{pc} \cdot FC_x^{reg} \cdot \left(1 - FC_x^{bio}\right) \cdot FE_x^{CO_2} \qquad \forall p \in P, c \in C, x \in X, t \in T \quad (26)$$

v. Selection of the conversion facilities

An intermediate product can be transferred to an upgrading technology in the conversion facility or converted to power in the energy generation plants. For instance, the intermediate product of CH_4 produced from the sludge feedstock in an anaerobic digestion process can be transferred to upgrading plants equipped with biomethane liquefaction technology to produce liquefied CH_4 or converted to electricity in facilities having power generation technologies. The Boolean variables Y_{ujc}^{upgr} and Y_{nkc}^{ener} are used for the selection of a facility type in a conversion facility. It should be noted that if a conversion facility is operating (Y_c^{conv} is True, corresponding to the binary variable $y_c^{conv} = 1$), then either Y_{ujc}^{upgr} or Y_{nkc}^{ener} must be True, but both cannot occur simultaneously (i.e. Y_{ujc}^{upgr} can be True and Y_{nkc}^{ener} False; Y_{ujc}^{upgr} False and Y_{nkc}^{ener} True). Moreover, each candidate treatment facility can be equipped with at most one upgrading technology ($\underset{u,j}{\vee} Y_{ujc}^{upgr}$) or one energy generation technology ($\underset{n,k}{\vee} Y_{nkc}^{ener}$) with a certain capacity level. The logic relationship between these Boolean variables can be expressed as $Y_c^{conv} \Leftrightarrow \underset{u,j}{\vee} Y_{ujc}^{upgr} \vee \underset{n,k}{\vee} Y_{nkc}^{ener}$, and can be reformulated as linear integer inequalities using their corresponding binary variables, as shown in Eq. (27). Equations (28) and (29) enforce the number of conversion facilities to open in location type *c*, showing that each location *c* cannot possess more than one conversion facility. The upper limits of the number of production technologies available in such facilities are given in Eqs. (30) and (31).

$$y_c^{conv} = \sum_u \sum_j y_{ujc}^{upgr} + \sum_n \sum_k y_{nkc}^{ener} \qquad \forall c \in C \quad (27)$$

$$y_c^{conv} \leq 1 \qquad \forall c \in C \quad (28)$$

$$\sum_c y_c^{conv} \leq NCF \quad (29)$$

$$\sum_j \sum_c y_{ujc}^{upgr} \leq NUT_u \qquad \forall u \in U \quad (30)$$

$$\sum_k \sum_c y_{nkc}^{ener} \leq NET_n \qquad \forall n \in N \quad (31)$$

If the Boolean variable Y_c^{conv} is True, then the capacity limit for receiving intermediates should be considered. Furthermore, each conversion facility has capacity limits for producing final products and energy; hence, the amounts of produced products and generated electricity are limited by the minimum and maximum production capacity levels. Equation (32) implies the capacity limits imposed by the conversion facility. Similarly, the Big-M formulation is used to transform the discrete decisions into inequalities. Equation (33) shows the inventory level of intermediates during each period at each conversion facility, and Eq. (34) shows the total storage capacity for the intermediate products. Equation (35) indicates the amount of intermediates that can be used in the production of final and energy products in a conversion facility.

$$\begin{bmatrix} Y_c^{conv} & \\ \sum_i \sum_p \sum_x a_{ipcxt}^{trans} \leq IC_{ct} & \forall t \in T \\ PCF_{fct}^{min} \leq \sum_u a_{fuct}^{fin} \leq PCF_{fct}^{max} & \forall f \in F, t \in T \\ PCE_{ct}^{min} \leq \sum_n a_{nct}^{elec} \leq PCE_{ct}^{max} & \forall t \in T \end{bmatrix} \vee \begin{bmatrix} \neg Y_c^{conv} \\ a_{ipcxt}^{trans} = 0 \\ a_{fuct}^{fin} = 0 \\ a_{nct}^{elec} = 0 \end{bmatrix} \qquad \forall c \in C \quad (32)$$

$$a_{ict}^{inv} = a_{ic,t-1}^{inv} + \sum_p \sum_x a_{ipcxt}^{trans} - \sum_f \sum_u R_{ifu}^{cons} \cdot a_{fuct}^{fin} - \sum_n R_{in}^{econs} \cdot a_{nct}^{elec} \qquad \forall i \in I, c \in C, t \in T \quad (33)$$

$$\sum_i V_i \cdot a_{ict}^{inv} \leq SC_c^{int} \qquad \forall c \in C, t \in T \quad (34)$$

$$\sum_u a_{iuct}^{upgr} + \sum_n a_{inct}^{ener} \leq a_{ic,t-1}^{inv} + \sum_p \sum_x a_{ipcxt}^{trans} \qquad \forall i \in I, c \in C, t \in T \quad (35)$$

vi. Production of final products or electricity in decentralized conversion facilities

When the Boolean variable Y_{ujc}^{upgr} is True, then the total amount of intermediate product utilized by the upgrading technology existing in the treatment facility cannot exceed the on-hand inventory and received intermediates from all pre-conversion plants. Moreover, the amount of intermediates assigned to an upgrading technology is limited by minimum and maximum input capacities of the technology. It should be noted that only one Y_{ujc}^{upgr} makes the two disjunctions active. In the negative case, the flow of intermediates to upgrading technology becomes zero. This decision process is shown in Eq. (36) (on the left side). If the facility c is operating and Boolean variable Y_{nkc}^{ener} is True, then the total intermediate products will be transferred to energy generation technology and the two disjunctions in Eq. (36) (on the right side) must be satisfied. Equations (37) and (38) show the processing capacity of upgrading and energy generation technologies, respectively. Equation (39) measures the amount of produced final product. Equation (40) shows the conversion of intermediate products to electricity.

$$\bigvee_{u,j}\begin{bmatrix} Y^{upgr}_{ujc} \\ a^{upgr}_{iuct} \le a^{inv}_{ic,t-1} + \sum_{p}\sum_{x} a^{trans}_{ipcxt} \;\; \forall i \in I, t \in T \\ UTC_{iu,j-1} \le a^{cap}_{iujc} \le UTC_{iuj} \qquad \forall i \in I \end{bmatrix} \veebar \bigvee_{n,k}\begin{bmatrix} Y^{ener}_{nkc} \\ a^{ener}_{inct} \le a^{inv}_{ic,t-1} + \sum_{p}\sum_{x} a^{trans}_{ipcxt} \;\; \forall i \in I, t \in T \\ ETC_{in,k-1} \le a^{cap}_{inkc} \le ETC_{ink} \qquad \forall i \in I \end{bmatrix} \qquad \forall c \in C \quad (36)$$

$$a^{upgr}_{iuct} \le WT_{ct} \cdot \sum_{j} a^{cap}_{iujc} \qquad \forall i \in I, u \in U, c \in C, t \in T \quad (37)$$

$$a^{ener}_{inct} \le WT_{ct} \cdot \sum_{k} a^{cap}_{inkc} \qquad \forall i \in I, n \in N, c \in C, t \in T \quad (38)$$

$$a^{fin}_{fuct} = \sum_{i} R^{conv}_{ifu} \cdot a^{upgr}_{iuct} \qquad \forall f \in F, u \in U, c \in C, t \in T \quad (39)$$

$$a^{elec}_{nct} = \sum_{i} R^{econv}_{in} \cdot a^{ener}_{inct} \qquad \forall n \in N, c \in C, t \in T \quad (40)$$

3.1.3 The centralized model

Centralized facilities are more suitable for the intermediates that cannot be relocated. For instance, syngas is an intermediate product of the gasification that is not suitable for transfer over long distances due to the need for special equipment for the transportation of H_2, since it can leak through the walls of standard pipes and tanks. Thus, H_2 has to be used on site. For this purpose, the produced syngas will be distributed to an upgrading technology existing in the same facility. For the transfer of biomass to centralized facilities, the same Eqs. (3) to (6) used for the biomass transfer to decentralized pre-conversion facilities will be applied. The only difference is that a^{cent}_{bspxt} will replace a^{dec}_{bspxt}.

i. Type of centralized conversion facilities

It is assumed that a centralized conversion facility can produce either final products or electricity from the produced intermediate products. Moreover, the facility can directly generate final products or electricity from biomass and omit the production of intermediate products. If centralized conversion facility p is operating (Y^{cent}_{p} is True), then either a Boolean variable $\bigvee_{m,r} Y^{pre}_{mrp}$ (for the production of intermediates used in final production or power generation processes), or a Boolean variable $\bigvee_{u,j} Y^{fin}_{ujp}$ (for the direct production of final products from biomass), or a Boolean variable $\bigvee_{n,k} Y^{elec}_{nkp}$ (for the direct generation of electricity from biomass) must be True, but all of these three Boolean variables cannot be False together nor can happen simultaneously. The logic relationship of $Y^{cent}_{p} \Leftrightarrow (\bigvee_{m,r} Y^{pre}_{mrp} \veebar \bigvee_{u,j} Y^{fin}_{ujp} \veebar \bigvee_{n,k} Y^{elec}_{nkp})$ can be reformulated as Eq. (41).

$$y^{cent}_{p} = \sum_{m}\sum_{r} y^{pre}_{mrp} + \sum_{u}\sum_{j} y^{fin}_{ujp} + \sum_{n}\sum_{k} y^{elec}_{nkp} \qquad \forall p \in P \quad (41)$$

In addition, the intermediate production process is restricted to the existence of final production or power generation technologies. The logic proposition between these variables is $\bigvee_{m,r} Y^{pre}_{mrp} \Leftrightarrow (\bigvee_{u,j} Y^{prod}_{ujp} \veebar \bigvee_{n,k} Y^{pwr}_{nkp})$, and can be reformulated as linear equality, as shown in Eq. (42).

$$\sum_{m}\sum_{r} y^{pre}_{mrp} = \sum_{u}\sum_{j} y^{prod}_{ujp} + \sum_{n}\sum_{k} y^{pwr}_{nkp} \qquad \forall p \in P \quad (42)$$

The upper bound of total y_p^{cent} in the entire network is previously given in Eq. (8), y_{mrp}^{pre} in Eq. (9), y_{ujp}^{fin} and y_{ujp}^{prod} in Eq. (30), and y_{nkp}^{elec} and y_{nkp}^{pwr} in Eq. (31). It is obvious that if e.g. a Boolean variable Y_p^{cent} in location p becomes True, then Y_p^{dec} in the same location p become False, and all Eqs. (7) to (40) related to the decentralized case will become deactivated, and one of the three options shown in Eq. (41) will occur. Equation (43) shows the disjunction for the centralized processing facilities. It indicates the capacity limits for receiving biomass, production of intermediates and its by-products, production of final products, and power generation.

$$\begin{bmatrix} Y_p^{cent} & \\ \sum_b \sum_s \sum_x a_{bspxt}^{cent} \le IC_{pt} & \forall t \in T \\ PCI_{ipt}^{min} \le \sum_m a_{impt}^{int} \le PCI_{ipt}^{max} & \forall i \in I, t \in T \\ PCB_{opt}^{min} \le \sum_m a_{ompt}^{byp} \le PCB_{opt}^{max} & \forall o \in O, t \in T \\ PCF_{fpt}^{min} \le \sum_u a_{fupt}^{fin} \le PCF_{fpt}^{max} & \forall f \in F, t \in T \\ PCE_{pt}^{min} \le \sum_n a_{npt}^{elec} \le PCE_{pt}^{max} & \forall t \in T \end{bmatrix} \vee \begin{bmatrix} \neg Y_p^{cent} \\ a_{bspxt}^{cent} = 0 \\ a_{impt}^{int} = 0 \\ a_{ompt}^{byp} = 0 \\ a_{fupt}^{fin} = 0 \\ a_{npt}^{elec} = 0 \end{bmatrix} \qquad \forall p \in P \quad (43)$$

To produce and store the intermediates in centralized conversion facilities, the same Eqs. (14) to (19) are used, and to produce final products and electricity the same Eqs. (36) to (40) are applied. The only difference is that intermediates are upgraded in the same facility, and no transportation of intermediate products occurs. Therefore, Eqs. (23) to (26) will not be considered in the centralized case. To prevent repeating some commonly used formulations indicated in the previous sections, in Section A of the Supporting Information 1, we present the reformulation for the case of the production of intermediates, final products, and electricity at centralized conversion facilities. Moreover, in Section B of the Supporting Information 1, we present the direct conversion of biomass to final products and power (similar to Eqs. (37) to (40)). In this case, the only difference is that instead of intermediates, the inlet biomass is converted to final goods or power without any intermediate production.

3.1.4 Transfer and selling final products, by-products, and electricity to consumers

It is assumed that decentralized conversion facilities (type *c*) and centralized upgrading plants (type *p*) do not store the final products, and the produced final products, excluding the biodiesel fuel used for transportation activities in the entire network, will be entirely transferred to warehouses for storage and sell, as shown in Eq. (44). The produced biodiesel can substitute or partial substitute for diesel to reduce the usage of fossil-based fuels. Equation (45) indicates the total amount of biodiesel that can be transferred to warehouses for retail sales, in addition to using it for transportation. To simplify the model, selling and transportation costs of biodiesel to supply locations and facilities are excluded from the analysis. Equation (46) shows the total amount of biodiesel that can be used in transportation activities. It is assumed that the biodiesel in transportation fuels can be used from the second period. Equation (47) shows the transport capacity limits imposed by transport modes.

$$\sum_u a_{fuqt}^{fin} = \sum_w \sum_x a_{fqwxt}^{trans} \qquad \forall f \in F \setminus \{f = biodiesel\}, q \in \{P \cup C\}, t \in T \quad (44)$$

$$\sum_w \sum_x a_{fqwxt}^{trans} + \sum_x a_{fxt}^{use} = \sum_u a_{fuqt}^{fin} \qquad \forall f = biodiesel, q \in \{P \cup C\}, t \in T \quad (45)$$

$$a_{fxt}^{use} \le \left(\sum_s \sum_p n_{spxt} \cdot D_{sp} + \sum_p \sum_c n_{pcxt} \cdot D_{pc} + \sum_{q \in \{P \cup C\}} \sum_w n_{qwxt} \cdot D_{qw} \right) \cdot FC_x^{reg} \cdot FC_x^{bio} \qquad \forall f = biodiesel, x \in X, t \in \mathrm{T} \text{ and } t \ge 2 \quad (46)$$

$$\sum_x TC_{qxt}^{min} \cdot y_{qwxt}^{mode} \le \sum_f \sum_x V_f \cdot a_{fqwxt}^{trans} \le \sum_x TC_{qxt}^{max} \cdot y_{qwxt}^{mode} \qquad \forall q \in \{P \cup C\}, w \in W, t \in T \quad (47)$$

Equation (48) calculates the number of transfers carried out in conversion plants and Eq. (49) is used to calculate the amount of released CO_2 emission from this transfer. Biofuels are perceived as carbon neutral and can decrease the consumption of fossil fuels. Biodiesel emits less CO, sulfur dioxide (SO_2), and particulate matters. It has the advantage of not contributing to overall GHG emissions compared to gasoline and diesel fuel, as it is made up of renewable sources such as agricultural residues, vegetable oil, or animal fat. Therefore, the consumed biodiesel as a transport fuel is deducted from the petroleum-based diesel fuel to include only the impact of regular fuel on the emissions emitted from transport activities.

$$n_{qwxt} - 1 \le \frac{\sum_f V_f \cdot a_{fqwxt}^{trans}}{CC_x \cdot F_x^{util}} \le n_{qwxt} \qquad \forall q \in \{P \cup C\}, w \in W, x \in X, t \in T \quad (48)$$

$$et_{qwxt}^{CO_2} = n_{qwxt} \cdot D_{qw} \cdot FC_x^{reg} \cdot \left(1 - FC_x^{bio}\right) \cdot FE_x^{CO_2} \qquad \forall q \in \{P \cup C\}, w \in W, x \in X, t \in T \quad (49)$$

Equation (50) presents the inventory level of the final products in a warehouse. The backorder of products is not allowed, and the unmet demand is considered as a lost sale. Each warehouse has a limited capacity to store the products received by all production facilities, as given in Eq. (51). The warehouse capacity is assumed to be constant over the planning horizon. Equation (52) ensures that products requested from the demand zones are met by the total units of products available at a warehouse, which cannot exceed demand, as given in Eq. (53). Equation (54) calculates the lost demand for final products.

$$a_{fwt}^{inv} = a_{fw,t-1}^{inv} + \sum_{q \in \{P \cup C\}} \sum_x a_{fqwxt}^{trans} - \sum_z a_{fwzt}^{sold} \qquad \forall f \in F, w \in W, t \in T \quad (50)$$

$$\sum_f V_f \cdot a_{fwt}^{inv} \le WC_w \qquad \forall w \in W, t \in T \quad (51)$$

$$\sum_z a_{fwzt}^{sold} \le a_{fw,t-1}^{inv} + \sum_{q \in \{P \cup C\}} \sum_x a_{fqwxt}^{trans} \qquad \forall f \in F, w \in W, t \in T \quad (52)$$

$$\sum_w a_{fwzt}^{sold} \le DF_{fzt} \qquad \forall f \in F, z \in Z, t \in T \quad (53)$$

$$a_{fzt}^{lost} = DF_{fzt} - \sum_w a_{fwzt}^{sold} \qquad \forall f \in F, z \in Z, t \in T \quad (54)$$

Equation (55) shows the total electricity transferred from an energy generation plant to demand zones, considering the electricity losses at distribution grids and the consumed energy by the facility. Equation (56) shows that the total electricity transfer should be equal to or less than its demand.

$$\sum_z a_{qzt}^{esold} \le \left(1 - F_{qt}^{econs}\right) \cdot \left(1 - F_{qt}^{eloss}\right) \cdot \sum_n a_{nqt}^{elec} \qquad \forall q \in \{C \cup P\}, t \in T \quad (55)$$

$$\sum_{q \in \{P \cup C\}} a_{qzt}^{esold} \le DE_{zt} \qquad \forall z \in Z, t \in T \quad (56)$$

Moreover, the by-products produced during the conversion of biomass to intermediates in decentralized pre-conversion and centralized plants *p* can be sold on-site, as given in Eqs. (57) and (58), and their transportation to warehouses and lost sale cost are not considered. The by-products include e.g., char that can be sold as charcoal briquettes or refined to activated carbon, and digestate that can be sold as fertilizer.

$$\sum_{z} a_{opzt}^{sold} \leq \sum_{m} a_{ompt}^{byp} \qquad \forall o \in O, p \in P, t \in T \quad (57)$$

$$\sum_{p} a_{opzt}^{sold} \leq DB_{ozt} \qquad \forall o \in O, z \in Z, t \in T \quad (58)$$

3.1.5 Emissions by industrial operations

Waste treatment processes release GHGs (e.g., CO_2, nitrous oxide (N_2O), CH_4) and air pollutants (e.g., CO, SO_2, nitrogen oxides (NO_x), NH_3, non-methane volatile organic compounds (NMVOCs)). The amount and type of emission emitted from waste treatment processes depend on the type of feedstock (biogenic and non-biogenic fractions of waste), the carbon content of biogenic materials, processing technologies, and the input fuel used in the energy generation as a start-up (e.g., coal, natural gas, or petroleum used to start the fire in the incinerator). CO_2 is considered the major contributor to the greenhouse effect. In pyrolysis and gasification processes, the formation of dioxins-like chemicals, air pollutants, as well as the release of GHG gases are substantially lower compared to incineration, as energy from waste in these technologies is produced through an O_2-controlled process.[58,59] Moreover, the resulting syngas is cleaned of contaminants before combustion, which reduces the amount of GHG emissions tremendously. In this study, the measurement of the environmental factor is reported based on CO_2 emission, as shown in Eq. (59). Accordingly, each plant is subject to penalties for violations of the CO_2 emission limit. The first line in Eq. (59) shows the emission released by the processes of biomass conversion to intermediates and by-products either in decentralized pre-conversion or centralized conversion plants *p*, followed by the emission discharged due to conversion of biomass to final products or power in centralized conversion plants *p*, and emission released during upgrading intermediates to final goods or power in decentralized conversion plants *c* or centralized conversion plants *p*.

$$\begin{aligned} ep_{qt}^{CO_2} = & \sum_{b}\sum_{i}\sum_{m} R_{bim}^{cons} \cdot a_{imqt}^{int} \cdot E_{bim}^{CO_2} + \sum_{b}\sum_{o}\sum_{m} R_{bom}^{cons} \cdot a_{omqt}^{byp} \cdot E_{bom}^{CO_2} \\ & + \sum_{b}\sum_{f}\sum_{u} R_{bfu}^{cons} \cdot a_{fuqt}^{fin} \cdot E_{bfu}^{CO_2} + \sum_{b}\sum_{n} R_{bn}^{econs} \cdot a_{nqt}^{elec} \cdot E_{bn}^{CO_2} \\ & + \sum_{i}\sum_{f}\sum_{u} R_{ifu}^{cons} \cdot a_{fuqt}^{fin} \cdot E_{ifu}^{CO_2} + \sum_{i}\sum_{n} R_{in}^{econs} \cdot a_{nqt}^{elec} \cdot E_{in}^{CO_2} \end{aligned} \qquad \forall q \in \{C \cup P\}, t \in T \quad (59)$$

3.1.6 Workforce requirements in production facilities

The workers in each facility are required to e.g. carry the raw materials and work-in-processes to the workstations, locate and remove them from the equipment, and screen the equipment operations. Equation (60) calculates the required number of workforces at pre-conversion and conversion facilities. Equation (61) enforces the minimum and maximum numbers of workforces in a facility. In this study, only permanent workers are included, and it is assumed that permanent workers cannot be laid off.

$$\begin{aligned} WH_{vq} \cdot wf_{vq} \leq & \sum_{i}\sum_{m}\sum_{t} WR_{viq}^{int} \cdot a_{imqt}^{int} + \sum_{o}\sum_{m}\sum_{t} WR_{voq}^{byp} \cdot a_{omqt}^{byp} + \sum_{f}\sum_{u}\sum_{t} WR_{vfq}^{fin} \cdot a_{fuqt}^{fin} \\ & + \sum_{n}\sum_{t} WR_{vq}^{elec} \cdot a_{nqt}^{elec} \leq WH_{vq} \cdot \left(wf_{vq} + 1\right) \end{aligned} \qquad \forall v \in V, q \in \{C \cup P\} \quad (60)$$

$$WF_{vq}^{min} \leq wf_{vq} \leq WF_{vq}^{max} \qquad \forall v \in V, q \in \{C \cup P\} \quad (61)$$

3.2 Objective function

The first part of the objective function presented in Eq. (62a) determines the social benefits of the considered system, aiming to contribute to local development through job and income creation considering the human development index (HDI) of each region.[60] The employment indicator is displayed by the number of jobs created by an open facility multiplied by the unemployment rate. This lets the selection of regions with higher unemployment rates that demand more jobs. The local development indicator is defined by the total income earned through employment in each area multiplied by the local development rate, which secures the stabilized development between regions.

$$Max\ Z^{social} = \sum_{v} \sum_{q \in \{C \cup P\}} RU_q \cdot wf_{vp} + \sum_{v} \sum_{q \in \{C \cup P\}} \left(1 - RD_q\right) \cdot wf_{vq} \cdot WH_{vq} \cdot W_{vq} \tag{62a}$$

The second part of the objective function presented in Eq. (62b) determines the economic benefits of the considered biomass management system, considering the revenue from the sales of produced products and the total cost involved in the entire process. This term also includes the environmental objective, denoted as CET, which is measured through the CO_2 emissions associated with the treatment of organic residues. The CO_2 emissions have been monetized using a taxation scheme based on the European Emission Trading Systems (ETS),[61] as described in Section 5.5.

$$Max\ Z^{economic} = R - \left(CIF + CIT + CBP + CIH + CPR + CDE + CLS + CET + CEP + CTR\right) \tag{62b}$$

The first term in Eq. (62b) (shown by R) represents the revenue earned from selling the final products, by-products, and electricity throughout the planning horizon.

$$R = \sum_{f} \sum_{w} \sum_{z} \sum_{t} S_{fwt}^{fin} \cdot a_{fwzt}^{sold} + \sum_{o} \sum_{p} \sum_{z} \sum_{t} S_{opt}^{byp} \cdot a_{opzt}^{sold} + \sum_{c} \sum_{z} \sum_{t} S_{ct}^{elec} \cdot a_{czt}^{esold} + \sum_{p} \sum_{z} \sum_{t} S_{pt}^{elec} \cdot a_{pzt}^{esold}$$

The second term (shown by CIF) calculates the annualized investment costs associated with establishing pre-conversion and conversion facilities, considering the capital recovery factors. The capital recovery ratios, used to obtain the present value of an annuity, are calculated by $DR \cdot (1 + DR)^{LT} / [(1 + DR)^{LT} - 1]$ where DR is the annual discount rate and LT is the lifetime of facilities and technologies launched for the production of intermediates, final products, and energy.

$$CIF = \sum_{p} CR_{p}^{fac} \cdot CIF_p \cdot y_p^{dec} + \sum_{c} CR_{c}^{fac} \cdot CIF_c \cdot y_c^{conv} + \sum_{p} CR_{p}^{fac} \cdot CIF_p \cdot y_p^{cent}$$

The third term (shown by CIT) computes the cost of investing in processing technologies. The capital investment of technologies is a function of the installed capacity of each technology. Since different capacity levels for a treatment technology are considered, investment costs are calculated using the piecewise linearization approach. It should be noted that the investment cost of the technology itself is obtained from a fixed cost plus a variable cost for each specific capacity level.

$$\begin{aligned}
CIT = & \sum_{b} \sum_{m} \sum_{r} \sum_{p} CR_{mp}^{tech} \cdot \left(CIT_{bm,r-1}^{int} \cdot y_{mrp}^{int} + \left(a_{bmrp}^{cap} - ITC_{bm,r-1} \cdot y_{mrp}^{int} \right) \cdot \frac{CIT_{bmr}^{int} - CIT_{bm,r-1}^{int}}{ITC_{bmr} - ITC_{bm,r-1}} \right) \\
& + \sum_{i} \sum_{u} \sum_{j} \sum_{c} CR_{uc}^{tech} \cdot \left(CIT_{iu,j-1}^{upgr} \cdot y_{ujc}^{upgr} + \left(a_{iujc}^{cap} - UTC_{iu,j-1} \cdot y_{ujc}^{upgr} \right) \cdot \frac{CIT_{iuj}^{upgr} - CIT_{iu,j-1}^{upgr}}{UTC_{iuj} - UTC_{iu,j-1}} \right) \\
& + \sum_{i} \sum_{n} \sum_{k} \sum_{c} CR_{nc}^{tech} \cdot \left(CIT_{in,k-1}^{ener} \cdot y_{nkc}^{ener} + \left(a_{inkc}^{cap} - ETC_{in,k-1} \cdot y_{nkc}^{ener} \right) \cdot \frac{CIT_{ink}^{ener} - CIT_{in,k-1}^{ener}}{ETC_{ink} - ETC_{in,k-1}} \right) \\
& + \sum_{b} \sum_{m} \sum_{r} \sum_{p} CR_{mp}^{tech} \cdot \left(CIT_{bm,r-1}^{int} \cdot y_{mrp}^{pre} + \left(a_{bmrp}^{cap} - ITC_{bm,r-1} \cdot y_{mrp}^{pre} \right) \cdot \frac{CIT_{bmr}^{int} - CIT_{bm,r-1}^{int}}{ITC_{bmr} - ITC_{bm,r-1}} \right) \\
& + \sum_{i} \sum_{u} \sum_{j} \sum_{p} CR_{up}^{tech} \cdot \left(CIT_{iu,j-1}^{upgr} \cdot y_{ujp}^{prod} + \left(a_{iujp}^{cap} - UTC_{iu,j-1} \cdot y_{ujp}^{prod} \right) \cdot \frac{CIT_{iuj}^{upgr} - CIT_{iu,j-1}^{upgr}}{UTC_{iuj} - UTC_{iu,j-1}} \right) \\
& + \sum_{i} \sum_{n} \sum_{k} \sum_{p} CR_{np}^{tech} \cdot \left(CIT_{in,k-1}^{ener} \cdot y_{nkp}^{pwr} + \left(a_{inkp}^{cap} - ETC_{in,k-1} \cdot y_{nkp}^{pwr} \right) \cdot \frac{CIT_{ink}^{ener} - CIT_{in,k-1}^{ener}}{ETC_{ink} - ETC_{in,k-1}} \right) \\
& + \sum_{b} \sum_{u} \sum_{j} \sum_{p} CR_{up}^{tech} \cdot \left(CIT_{bu,j-1}^{upgr} \cdot y_{ujp}^{fin} + \left(a_{bujp}^{cap} - UTC_{bu,j-1} \cdot y_{ujp}^{fin} \right) \cdot \frac{CIT_{buj}^{upgr} - CIT_{bu,j-1}^{upgr}}{UTC_{buj} - UTC_{bu,j-1}} \right) \\
& + \sum_{b} \sum_{n} \sum_{k} \sum_{p} CR_{np}^{tech} \cdot \left(CIT_{bn,k-1}^{ener} \cdot y_{nkp}^{elec} + \left(a_{bnkp}^{cap} - ETC_{bn,k-1} \cdot y_{nkp}^{elec} \right) \cdot \frac{CIT_{bnk}^{ener} - CIT_{bn,k-1}^{ener}}{ETC_{bnk} - ETC_{bn,k-1}} \right)
\end{aligned}$$

The fourth term (shown by *CBP*) is the cost of biomass purchasing.

$$CBP = \sum_b \sum_s \sum_p \sum_x \sum_t CP_{bst} \cdot a_{bspxt}^{dec} + \sum_b \sum_s \sum_p \sum_x \sum_t CP_{bst} \cdot a_{bspxt}^{cent}$$

The fifth term (shown by *CIH*) computes the inventory holding cost of biomass, intermediates, and final products.

$$CIH = \sum_b \sum_p \sum_t CH_{bpt} \cdot a_{bpt}^{inv} + \sum_i \sum_p \sum_t CH_{ipt} \cdot a_{ipt}^{inv} + \sum_i \sum_c \sum_t CH_{ict} \cdot a_{ict}^{inv} + \sum_f \sum_w \sum_t CH_{fwt} \cdot a_{fwt}^{inv}$$

The sixth term (shown by *CPR*) measures the processing cost of biomass and intermediates used in producing final products and electricity. The first part of this equation indicates the processing cost of biomass either in decentralized pre-conversion plants or centralized conversion plants, followed by the cost incurred by processing intermediates in decentralized conversion plants using upgrading or energy generation technologies, conversion of intermediates in centralized conversion plants, and processing biomass materials to produce final or energy products directly in centralized conversion plants.

$$CPR = \sum_b \sum_m \sum_p \sum_t CPB_{bmpt} \cdot a_{bmpt}^{int} + \sum_i \sum_u \sum_c \sum_t CPI_{iuct} \cdot a_{iuct}^{upgr} + \sum_i \sum_n \sum_c \sum_t CPI_{inct} \cdot a_{inct}^{ener}$$
$$+ \sum_i \sum_u \sum_p \sum_t CPI_{iupt} \cdot a_{iupt}^{upgr} + \sum_i \sum_n \sum_p \sum_t CPI_{inpt} \cdot a_{inpt}^{ener} + \sum_b \sum_u \sum_p \sum_t CPB_{bupt} \cdot a_{bupt}^{upgr} + \sum_b \sum_n \sum_p \sum_t CPB_{bnpt} \cdot a_{bnpt}^{ener}$$

We considered the processing cost as a multiple breakpoint piecewise linear function. For instance, Eq. (63) indicates the processing cost of biomass materials using intermediate technologies that varies for each pre-defined processing level. The processing cost itself is composed of fixed (CFP_{bmp}) and variable (CVP_{bmp}) costs. The binary variable y_{bmpt}^{proc} takes the value of one if biomass processing occurs during a period.

$$CPB_{bmpt}\left(a_{bmpt}^{int}\right) = \begin{cases} CFP_{bmp}^{2} \cdot y_{bmpt}^{proc} + CVP_{bmp}^{2} \cdot a_{bmpt}^{int} \;\; if \;\; A_{bmpt}^{1} \le a_{bmpt}^{int} \le A_{bmpt}^{2} \\ CFP_{bmp}^{3} \cdot y_{bmpt}^{proc} + CVP_{bmp}^{3} \cdot a_{bmpt}^{int} \;\; if \;\; A_{bmpt}^{2} < a_{bmpt}^{int} \le A_{bmpt}^{3} \\ \vdots \\ CFP_{bmp}^{e} \cdot y_{bmpt}^{proc} + CVP_{bmp}^{e} \cdot a_{bmpt}^{int} \;\; if \;\; A_{bmpt}^{e-1} < a_{bmpt}^{int} \le A_{bmpt}^{e} \end{cases} \tag{63}$$

Suppose that the piecewise linear function has breakpoints $A_{bmpt}^{1}, A_{bmpt}^{2}, \ldots, A_{bmpt}^{e}$. For some breakpoints *n* ($n = 1, 2, \ldots, e-1$), we have $A_{bmpt}^{n} \le a_{bmpt}^{int} \le A_{bmpt}^{n+1}$, which can be written as $a_{bmpt}^{int} = z_n \cdot A_{bmpt}^{n} + (1 - z_n) \cdot A_{bmpt}^{n+1}$ using a real number 0 ≤ z_n ≤ 1. Since $CPB_{bmpt}\left(a_{bmpt}^{int}\right)$ is linear for $A_{bmpt}^{n} \le a_{bmpt}^{int} \le A_{bmpt}^{n+1}$, we can write $CPB_{bmpt}\left(a_{bmpt}^{int}\right) = z_n \cdot CPB_{bmpt}\left(A_{bmpt}^{n}\right) + (1 - z_n) \cdot CPB_{bmpt}\left(A_{bmpt}^{n+1}\right)$. Accordingly, using binary variables, piecewise linear functions can be converted to a general linear form as indicated in Eq. (64).

$$CPB_{bmpt}\left(a_{bmpt}^{int}\right) = z_1 \cdot CPB_{bmpt}\left(A_{bmpt}^{1}\right) + z_2 \cdot CPB_{bmpt}\left(A_{bmpt}^{2}\right) + \cdots + z_e \cdot CPB_{bmpt}\left(A_{bmpt}^{e}\right) CPB_{bmpt}\left(a_{bmpt}^{int}\right) \tag{64}$$
$$a_{bmpt}^{int} = z_1 \cdot A_{bmpt}^{1} + z_2 \cdot A_{bmpt}^{2} + \cdots + z_e \cdot A_{bmpt}^{e}$$
$$z_1 \le y_1,\; z_2 \le y_1 + y_2, \ldots,\; z_{e-1} \le y_{e-2} + y_{e-1}, z_e \le y_{e-1}$$
$$\sum_{n=1}^{n=e-1} y_n = 1$$
$$\sum_{n=1}^{n=e} z_n = 1$$
$$y_n = \{0,1\}$$
$$z_n \ge 0$$

The processing costs for the rest of variables, including $a_{iuct}^{upgr}, a_{inct}^{ener}, a_{iupt}^{upgr}, a_{inpt}^{ener}, a_{bupt}^{upgr}, a_{bnpt}^{ener}$, are calculated in an equivalent way.
The seventh term in Eq. (62b) (shown by *CDE*) gives the cost of transferring electricity and other fees related to network services from power generation plants to end-users.

$$CDE = \sum_p \sum_z \sum_t CD_{pzt} \cdot a_{pzt}^{esold} + \sum_c \sum_z \sum_t CD_{czt} \cdot a_{czt}^{esold}$$

The eighth term (shown by *CLS*) calculates the lost sale cost of final products.

$$CLS = \sum_f \sum_z \sum_t CL_{fzt} \cdot a_{fzt}^{lost}$$

The ninth term (shown by *CET*) denotes the penalty cost for the CO_2 emission exceeding the permissible emission limits for transportation. In order to control the amount of CO_2 emission from transportation, a threshold level for the distance is considered, so that distances exceeding the predetermined limit will impose a penalty cost. The penalty cost for distances below the limit is considered zero. Considering emission limits and the penalty cost for emissions exceeding their limits will result in the reduction of air pollutants.

$$CET = \sum_s \sum_p \sum_x \sum_t n_{spxt} \cdot \left(D_{sp} - D_{sp}^{limit}\right) \cdot CE^{tem} + \sum_p \sum_c \sum_x \sum_t n_{pcxt} \cdot \left(D_{pc} - D_{pc}^{limit}\right) \cdot CE^{tem}$$
$$+ \sum_c \sum_w \sum_x \sum_t n_{cwxt} \cdot \left(D_{cw} - D_{cw}^{limit}\right) \cdot CE^{tem} + \sum_p \sum_w \sum_x \sum_t n_{pwxt} \cdot \left(D_{pw} - D_{pw}^{limit}\right) \cdot CE^{tem}$$

The tenth term (shown by *CEP*) represents the penalty cost for the CO_2 emission emitted during the industrial processes.

$$CEP = \sum_p \sum_t ep_{pt}^{CO_2} \cdot CE^{pem} + \sum_c \sum_t ep_{ct}^{CO_2} \cdot CE^{pem}$$

The last term in Eq. (62b) (shown by *CTR*) presents the fixed and variable costs of transferring biomass from supply location to processing facilities, intermediates from pre-conversion to conversion plants, and final products from conversion plants to warehouses.

$$CTR = \sum_s \sum_p \sum_x \sum_t \left(CT_{spxt}^{fix} \cdot y_{spxt}^{ship} + CT_{spxt}^{var} \cdot D_{sp} \cdot n_{spxt}\right) + \sum_p \sum_c \sum_x \sum_t \left(CT_{pcxt}^{fix} \cdot y_{pcxt}^{ship} + CT_{pcxt}^{var} \cdot D_{pc} \cdot n_{pcxt}\right)$$
$$+ \sum_c \sum_w \sum_x \sum_t \left(CT_{cwxt}^{fix} \cdot y_{cwxt}^{ship} + CT_{cwxt}^{var} \cdot D_{cw} \cdot n_{cwxt}\right) + \sum_p \sum_w \sum_x \sum_t \left(CT_{pwxt}^{fix} \cdot y_{pwxt}^{ship} + CT_{pwxt}^{var} \cdot D_{pw} \cdot n_{pwxt}\right)$$

The binary variables y_{spxt}^{ship}, y_{pcxt}^{ship}, y_{cwxt}^{ship}, and y_{pwxt}^{ship} take the value of one if there is a transfer between the corresponding entity nodes; i.e. $\sum_b a_{bspxt}^{dec}$, $\sum_b a_{bspxt}^{cent}$, $\sum_i a_{ipcxt}^{trans}$, $\sum_f a_{fcwxt}^{trans}$, and $\sum_f a_{pcwxt}^{trans}$ are greater than zero.

4. Data Gathering

4.1. Spatial area

The case study considered for the application of the supply chain formulation presented in this work is the Spanish region of Castilla y León. Castilla y León is the largest region of Spain and the third largest region in the European Union, with an area of 94226 km^2 and a population of 2418694 inhabitants. It is divided into nine provinces, including Ávila, Burgos, Salamanca, Segovia, Soria, Palencia, León, Valladolid, and Zamora. This region has nine main urban areas corresponding to each province's capital, and a large rural population distributed in 2248 boroughs dispersed across the territory. Besides, the region has a vast agricultural infrastructure where the cropland area represents around half of the county's total area. Regarding the farming sector, this region accounts for 2.8 million swine livestock and 1.2 million cattle. The agricultural segment of Castilla y León comprises 7.6% of the Spanish agriculture gross domestic product (GDP). The duality between some urban centers with a relatively high population density and small population centers sparse across the vast majority of the territory makes the region of Castilla y León a challenging area for the design of an optimal supply chain for the management of organic waste, as well as assessing the proposed model formulations. In addition to these nine considered supply sites as biomass sources, the multi-echelon supply chain problem consists of eighteen suggested locations for simultaneous pre-treatment and upgrading operations for the case of centralized network, eighteen plants for pre-treatment processes and twelve facilities for upgrading operations for the decentralized approach, nine warehouses, and nine demand zones. The information related to the geographic distances between supply locations, potential pre-treatment and upgrading plants, and warehouses along with their longitudes and latitudes can be found in Supporting Information 2 (see sheet location coordinates).

4.2. Organic waste generation

Four sources of organic waste are considered in this study, i.e., crop waste, animal manure, MSW, and sludge from wastewater treatment plants. The organic waste produced by livestock is estimated from a couple of animals in the region, including swine and cattle. The inventory of livestock facilities is retrieved from the Castilla y León government statistics website to obtain the number and type of the animals of the farms located in the region, as well as their physical address.[62,63] The data is aggregated at the province level, and the organic waste generated is estimated from the animal units of each species, defined as an animal equivalent of 1000 pounds live weight cow.[64] The values assumed for cattle are an animal unit equivalency of 0.87 animals per animal unit (average value between animal unit equivalence for dairy and beef cattle) and an average waste generation rate of 33.23 kg/(day·animal unit). For swine, animal per animal unit rates of 9.09 and 2.67 and waste generation rates of 36.52 and 15.18 kg/(day·animal unit) are considered for piglets and hogs, respectively.[65] The estimated organic residues from crops, the yearly amount of wheat, barley, oat, rye, triticale, and corn produced in each shire are taken from the official regional.[66] The amounts of residues produced per mass of product obtained are calculated through the Residue-to-Product-Ratio (RPR) reported by Koopmans and Koppejan[67] and can be found in Supporting Information 2 (see sheet residue-to-product-ratio).

The wastewater sludge generated by each province is retrieved from the regional government's official statistics page.[68] Finally, the generation of MSW is considered for the whole region, since the disaggregated data for each shire was not available. Therefore, the MSW production was aggregated at the province and agricultural regions level, weighing the regional MSW generation by the share of each region's population. Datasets for each type of waste generated in the shires of Castilla y León, as well the composition of the evaluated organic waste components are available in Supporting Information 2 (see sheets waste data and waste composition). Overall, the four considered biomass types include wet manure of 16597 million kilograms (Mkg) during a year, followed by 13276.96 Mkg dry crops, 1076.20 Mkg wet MSW, and 146.75 Mkg wet Sludge. The data for the annual generation of waste was adapted to fit the weekly planning considered in this paper. The purchasing price of the crop waste is assumed 32 to 55 euros/ton, and for the rest of the waste feedstocks, the procurement price is considered zero.

4.3. Applied processing methods

Since each of the considered waste types has distinctive characteristics regarding composition, moisture content, and density, only specific treatment processes are suitable for each waste type. In general, the problem involves five different types of intermediate products (assumed as intermediate level 1), including biomethane, biogas, bio-oil, flue gas, and syngas; three types of intermediate level 2 (H_2, biomethanol, and clean biogas); and two kinds of intermediate level 3 (biomethanol and biomethane). These intermediates can then be converted to electricity and various final products such as liquid biomethane, naphtha, biodiesel, Fischer-Tropsch gasoline and diesel, bioethanol, and H_2. By-products such as digestate and char are also produced during the conversion of biomass to intermediate products. Furthermore, three types of intermediate technologies (anaerobic digestion, pyrolysis, and gasification) and four types of energy generation technologies (anaerobic digestion with electricity generator, pyrolysis with CHP, incineration with gas cleaning and Brayton cycle) are taken into account. The considered upgrading technologies involve biomethane liquefaction, transport fuel production with and without H_2 production, biodiesel production, Fischer-Tropsch fuels production, ethanol production, and fermentation for ethanol production. The details of all used conversion techniques for each type of waste along with their capacity levels, conversion rates and yielded products, investment and processing costs, and the amount of CO_2 emission emitted during the biomass treatment and intermediates upgrading can be found in Supporting Information 2 (see sheet applied processes). Moreover, to better show the implemented treatment processes, the utilized approaches for each type of waste are illustrated in Supporting Information 3.

4.4. Additional data

The modes of transportation for biomass and solid product transfer involve small, medium, and large trucks with capacities of 5 tons (15 m^3), 25 tons (35 m^3), and 40 tons (100 m^3), as well as rail transportation with the capacity of 1000 tons (2500 m^3). Moreover, liquid tank truck (35 tons, 30 m^3) and liquid tank trailer (70 tons, 60 m^3) are utilized to transfer liquid products. The planning horizon is one year, and the length of the time period used in the computational experiments is one week to satisfy weekly fluctuating demands imposed by the demand zones.

Data regarding the consumption of electricity, natural gas, and transportation fuels for the shires of Castilla y León was retrieved from the government statistics to estimate the demand for products. The electricity consumption for each province is retrieved from the annual energy statistics report of the region.[69] We have used the time-series forecasting method of trend and seasonality corrected exponential smoothing (known as Winter's model) to forecast the weekly electricity demand for the year 2020. This approach is suitable when the systematic components of historical demand data have trend and seasonality. Using this approach resulted in a relatively low mean absolute percentage error (MAPE) of 2.4%. The obtained tracking signal, which is a way of monitoring the accuracy of estimation ranging from -6 to +6, varied from -1.62 to 2.95, which means the forecast using this technique did not indicate any significant bias. Furtherer, the consumption of natural gas and transportation fuels of the shire, mainly gasoline, diesel, and bioethanol, is collected from the annual report published by the market regulatory agency of Spain.[70,71] Datasets containing products demand for the considered shires of Castilla y León are available in Supporting Information 2 (see sheets demand for electricity, demand for natural gas, demand for gasoline, demand for ethanol, and demand for diesel).

Finally, the human development index (HDI) is the metric selected to assess the development of the different regions and required for the calculation of the social aspect of the proposed model. It is an index proposed by the United Nations Development Programme (UNDP) to measure the regional development level considering three dimensions: health, education, and economy.[60] The UNDP calculates this index at the country level. However, using the same methodology, the HDI of each province along with the unemployment rates is calculated and shown in Supporting Information 2 (see sheets human development index and unemployment rate). In Section C of Supporting Information 1, we present further information regarding the HDI.

5. Results and Discussions

5.1. Results of the MILP optimization model

The model is formulated and solved using GAMS/CPLEX (v.24.9.1) on a computer with Intel Core i5 (2.40 GHz) and 8 GB RAM. Table 1 presents the computational performances of the proposed MILP models. In this study, we applied the epsilon-constraint method to solve the proposed multi-objective model, which aims to maximize economic and social objectives simultaneously. It should be noted that the environmental objective is measured through the monetization of the CO_2 emissions, and therefore it is implicitly expressed in the economic objective function. The epsilon-constraint procedure optimizes one of the objective functions and converts the other one into the constraint. For a multi-objective optimization problem, no single solution exists that at the same time optimizes each objective. The resulting Pareto curve connecting all non-dominated solutions is shown in Supporting Information 2 (see sheet Pareto results). All Pareto optimal solutions are considered acceptable. We have selected the knee point of the curve as it almost reaches the optimal value for each of the defined objectives. This point leads to the production of a balanced solution, which also satisfies the subjective preferences of the decision-maker regarding economic and social aspects.

Table 1. Comparison of the computational performance of the proposed centralized and decentralized models

Model	Cost (M€)	Revenue (M€)	Profit (M€)	Relative gap	CPU (sec)	Iterations	Nodes	No. of constraints	No. of continuous variables	No. of discrete (binary and integer) variables
Centralized	800.4	668.5	-131.9	0.003	3529.14	801167	81	1551416	1654874	504180
Decentralized	240.6	44.0	-196.6	0.010	734.64	487295	70	1072854	1784398	184716

5.2. Impacts of centralized and decentralized supply chain strategies on the production of value-added products

Decision-making in the considered supply chain networks is performed under centralized and decentralized strategies. Figure 4a displays the location of the selected plants along with their technologies, and Fig. 4b illustrates an optimum supply chain configuration for the centralized approach. The network has treated 1680.61 Mkg of biomass during a year, comprising 52.01% of MSW, 41.88% of sludge, 3.92% of crops, and 2.19% of manure. It can be observed that among 18 suggested plants, 14 facilities are selected as conversion facilities that transform biomass into intermediates, which then are upgraded to final products. Up to six of the facilities got equipped with anaerobic digestion technology (with capacities ranging from 0.70 to 10.98 kg/s), followed by five pyrolysis technologies (all with capacities of 4.5 kg/s), and three gasification technologies (with capacities from 3.08 to 18.75 kg/s). Collectively, 99.21% of the total produced biomethane, 27.63% of bio-oil, and 100% of syngas are further processed by other upgrading technologies existing in the corresponding facilities. Accordingly, the bio-based methane is further processed to obtain liquified

biomethane. The produced bio-oil is upgraded to diesel and naphtha using hydrotreating and hydrocracking techniques. The flue gases produced in pyrolysis plants are used as process heat, and thus, its transportation/further processing is not considered. The resulting syngas is used for the production of synthetic fuels (gasoline and diesel) following the Fischer-Tropsch process. Three plants producing low portions of biogas and biomethane did not select any upgrading technology due to the high investment costs in technologies compared to the production quantity of intermediates. However, these three facilities relatively produced a high proportion of digestate comparing to their intermediate products, which then are sold to the markets. The results also indicated that three plants are selected to produce power from MSW without intermediate production. The MSW has a relatively high yield of electricity with the conversion rate of 0.14 kWh/kg MSW using anaerobic digestion with electricity generator, 0.56 kWh/kg MSW via incineration technology, and 0.88 kWh/kg MSW by pyrolysis technology equipped with the CHP system. Furthermore, one fermentation facility with a capacity of 1.08 kg/s is selected that directly produces bioethanol from sludge.
communities.

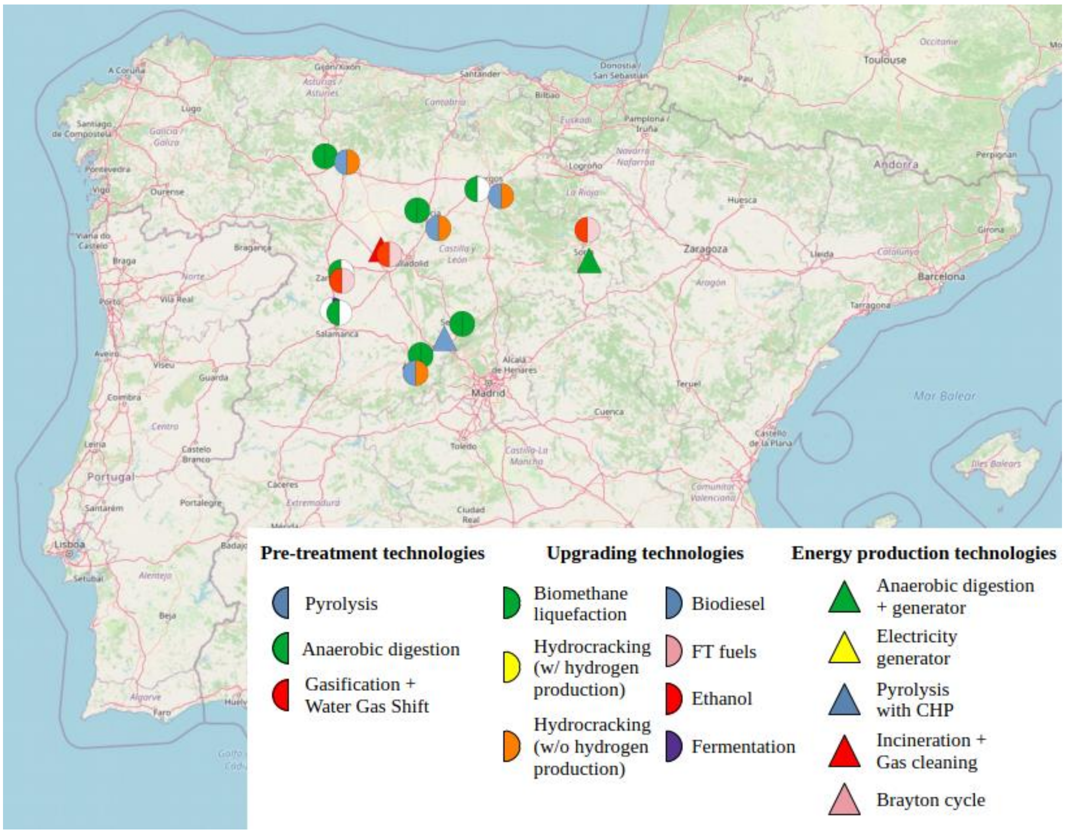

Figure 4a. Selected pre-treatment and upgrading plants in the centralized network[72]

Intermediate Production, Upgrading, and Energy Generation Plants – Centralized Case

Transferred Biomass	Processed Biomass	Selected Plant	Selected Technology	Technology Capacity	Produced Intermediate Product		Upgrading / Energy Technology	Technology Capacity	Final Product	Produced By-product
MSW	69.59 Mkg	Plant 1	Pyrolysis	4.5 kg/s	Flue gas 10.18 Mkg	Bio oil 6.83 Mkg	Fuel production	0.44 kg/s	Naphtha 0.28 Mkg Biodiesel 0.28 Mkg	Char 22.88 Mkg
MSW	69.62 Mkg	Plant 3	Pyrolysis	4.5 kg/s	Flue gas 10.19 Mkg	Bio oil 6.84 Mkg	Fuel production	0.44 kg/s	Naphtha 0.67 Mkg Biodiesel 0.67 Mkg	Char 22.89 Mkg
MSW	66.27 Mkg	Plant 4	Pyrolysis	4.5 kg/s	Flue gas 9.70 Mkg	Bio oil 6.51 Mkg	Fuel production	0.44 kg/s	Naphtha 0.31 Mkg Biodiesel 0.31 Mkg	Char 21.79 Mkg
MSW	64.06 Mkg	Plant 10	Pyrolysis	4.5 kg/s	Flue gas 9.38 Mkg	Bio oil 6.29 Mkg	Fuel production	0.44 kg/s	Naphtha 0.22 Mkg Biodiesel 0.22 Mkg	Char 21.06 Mkg
MSW	65.32 Mkg	Plant 11	Pyrolysis	4.5 kg/s	Flue gas 9.56 Mkg	Bio oil 6.42 Mkg	Fuel production	0.44 kg/s	Naphtha 0.43 Mkg Biodiesel 0.43 Mkg	Char 21.47 Mkg
MSW	322.25 Mkg	Plant 16	Gasification	18.75 kg/s	Syngas 383.47 Mkg		Fischer-Tropes	55.65 kg/s	Gasoline 36.18 Mkg Diesel 108.87 Mkg	
MSW	55.27 Mkg	Plant 6	Pyrolysis with CHP	4.5 kg/s					Electricity 49073.16 MWh	
MSW	9.59 Mkg	Plant 7	Anaerobic digestion	3.17 kg/s					Electricity 1378.44 MWh	
MSW	152.19 Mkg	Plant 8	Incineration	13.32 kg/s					Electricity 85762.45 MWh	
Manure	36.80 Mkg	Plant 13	Anaerobic digestion	1.17 kg/s	Biomethane 0.30 Mkg		Biomethane liquefaction	0.009 kg/s	Liquid Biomethane 0.30 Mkg	Digestate 36.11 Mkg
Crop waste	24.94 Mkg	Plant 17	Gasification	3.10 kg/s	Syngas 17.99 Mkg		Fischer-Tropes	2.24 kg/s	Gasoline 1.70 Mkg Diesel 5.11 Mkg	
Crop waste	28.50 Mkg	Plant 18	Gasification	3.08 kg/s	Syngas 20.56 Mkg		Fischer-Tropes	2.22 kg/s	Gasoline 1.94 Mkg Diesel 5.84 Mkg	
Crop waste	12.45 Mkg	Plant 14	Fermentation	1.08 kg/s					Bioethanol 3.43 Mkg	
Sludge	7.37 Mkg	Plant 2	Anaerobic digestion	2.08 kg/s	Biogas 0.14 Mkg					Digestate 7.20 Mkg
Sludge	3.78 Mkg	Plant 5	Anaerobic digestion	1.78 kg/s	Biomethane 0.04 Mkg					Digestate 3.71 Mkg
Sludge	2.01 Mkg	Plant 9	Anaerobic digestion	0.70 kg/s	Biomethane 0.02 Mkg					Digestate 1.98 Mkg
Sludge	345.30 Mkg	Plant 12	Anaerobic digestion	10.97 kg/s	Biomethane 3.21 Mkg		Biomethane liquefaction	0.102 kg/s	Liquid Biomethane 3.21 Mkg	Digestate 338.89 Mkg
Sludge	345.30 Mkg	Plant 15	Anaerobic digestion	10.98 kg/s	Biomethane 3.21 Mkg		Biomethane liquefaction	0.102 kg/s	Liquid Biomethane 3.21 Mkg	Digestate 338.89 Mkg

Figure 4b. Biomass treatment and conversion to value-added bio-products in the centralized network

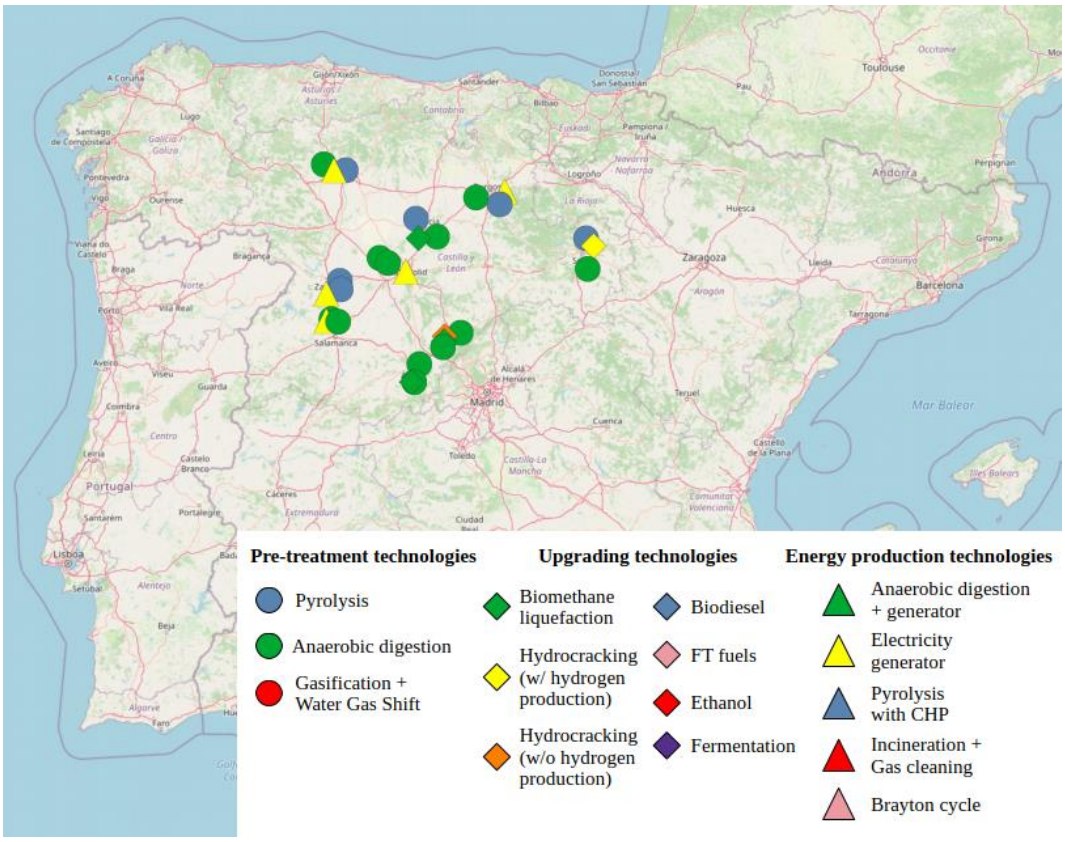

Figure 5a. Selected pre-treatment and upgrading plants in the decentralized network[72]

Intermediate Production Plants – Decentralized Case

Transferred Biomass	Processed Biomass	Selected Plant	Selected Technology	Technology Capacity	Produced Intermediate Product		Produced By-product
MSW	70.19 Mkg	Plant 3	Pyrolysis	4.5 kg/s	Flue gas 10.28 Mkg	Bio oil 6.90 Mkg	Char 23.08 Mkg
MSW	177.51 Mkg	Plant 4	Anaerobic digestion	12.0 kg/s	Biomethane 4.26 Mkg		
MSW	30.20 Mkg	Plant 9	Pyrolysis	4.5 kg/s	Flue gas 4.42 Mkg	Bio oil 2.97 Mkg	Char 9.93 Mkg
MSW	17.04 Mkg	Plant 11	Pyrolysis	4.5 kg/s	Flue gas 2.49 Mkg	Bio oil 1.67 Mkg	Char 5.60 Mkg
MSW	24.84 Mkg	Plant 13	Pyrolysis	4.5 kg/s	Flue gas 3.64 Mkg	Bio oil 2.44 Mkg	Char 8.17 Mkg
MSW	180.99 Mkg	Plant 15	Anaerobic digestion	12.0 kg/s	Biomethane 4.34 Mkg		
MSW	4.83 Mkg	Plant 16	Pyrolysis	4.5 kg/s	Flue gas 0.71 Mkg	Bio oil 0.47 Mkg	Char 1.59 Mkg
MSW	0.87 Mkg	Plant 18	Pyrolysis	1.2 kg/s	Flue gas 0.13 Mkg	Bio oil 0.09 Mkg	Char 0.29 Mkg
Manure	24.06 Mkg	Plant 6	Anaerobic digestion	1.17 kg/s	Biomethane 0.20 Mkg		Digestate 23.61 Mkg
Manure	17.58 Mkg	Plant 7	Anaerobic digestion	1.17 kg/s	Biomethane 0.15 Mkg		Digestate 17.26 Mkg
Manure	24.76 Mkg	Plant 10	Anaerobic digestion	1.17 kg/s	Biomethane 0.20 Mkg		Digestate 24.30 Mkg
Manure	17.36 Mkg	Plant 17	Anaerobic digestion	1.17 kg/s	Biomethane 0.14 Mkg		Digestate 17.03 Mkg
Sludge	688.51 Mkg	Plant 1	Anaerobic digestion	25.44 kg/s	Biomethane 6.40 Mkg		Digestate 675.73 Mkg
Sludge	457.48 Mkg	Plant 2	Anaerobic digestion	25.44 kg/s	Biomethane 4.25 Mkg		Digestate 448.98 Mkg
Sludge	504.87 Mkg	Plant 5	Anaerobic digestion	25.44 kg/s	Biomethane 4.69 Mkg		Digestate 495.49 Mkg
Sludge	558.66 Mkg	Plant 8	Anaerobic digestion	25.44 kg/s	Biomethane 5.19 Mkg		Digestate 548.28 Mkg
Sludge	541.09 Mkg	Plant 12	Anaerobic digestion	25.44 kg/s	Biomethane 5.03 Mkg		Digestate 531.04 Mkg
Sludge	557.09 Mkg	Plant 14	Anaerobic digestion	25.44 kg/s	Biomethane 5.18 Mkg		Digestate 546.75 Mkg

Upgrading and Energy Generation Facilities – Decentralized Case

Transferred Intermediate	Processed Intermediate	Selected Facility	Upgrading / Energy Technology	Technology Capacity	Final Product
Biomethane	0.72 Mkg	Facility 1	Biomethane liquefaction	0.102 kg/s	Liquid Biomethane 0.72 Mkg
Biomethane	0.73 Mkg	Facility 4	Biomethane liquefaction	0.102 kg/s	Liquid Biomethane 0.73 Mkg
Biomethane	0.67 Mkg	Facility 12	Biomethane liquefaction	0.102 kg/s	Liquid Biomethane 0.67 Mkg
Bio-oil	2.64 Mkg	Facility 6	Fuel production	0.530 kg/s	Naphtha 0.55 Mkg Biodiesel 0.55 Mkg
Bio-oil	11.81 Mkg	Facility 7	Fuel production	0.603 kg/s	Naphtha 2.48 Mkg Biodiesel 2.48 Mkg
Biomethane	4.47 Mkg	Facility 2	Electricity generator	0.240 kg/s	Electricity 42278.64 MWh
Biomethane	5.61 Mkg	Facility 3	Electricity generator	0.240 kg/s	Electricity 53139.04 MWh
Biomethane	5.92 Mkg	Facility 5	Electricity generator	0.240 kg/s	Electricity 56040.30 MWh
Biomethane	5.01 Mkg	Facility 8	Electricity generator	0.240 kg/s	Electricity 47429.39 MWh
Biomethane	5.75 Mkg	Facility 9	Electricity generator	0.240 kg/s	Electricity 54420.43 MWh
Biomethane	5.63 Mkg	Facility 10	Electricity generator	0.240 kg/s	Electricity 53350.78 MWh
Biomethane	5.50 Mkg	Facility 11	Electricity generator	0.240 kg/s	Electricity 52115.43 MWh

Figure 5b. Biomass pre-treatment and upgrading to bio-based products in the decentralized network

Figures 5a and 5b indicate the location of the selected plants and the optimal treatment network of the decentralized approach. In the decentralized case, pre-treatment and upgrading operations are carried out in separate locations. As it can be seen, the network of the decentralized case involves 18 plants treating 3897.93 Mkg of biomass, including 84.86% of sludge, 12.99% of MSW, and 2.15% of manure. In the decentralized option, the optimization model has not selected the crop waste as a feedstock since the primary treatment for its valorization is the production of syngas as an intermediate product that consists of a high percentage of H_2, leading to the explosive potentials that restrict its transportation to the usage of specific equipment. Another limitation lies in the fact that in the decentralized facilities, biogas is also not produced as its transfer was not allowed. Therefore, the decentralized model was limited to the production of biomethane using anaerobic digestion (12 plants) and bio-oil using pyrolysis technology (6 plants) as intermediates. Accordingly, considering the maximum distance threshold of zero km for biogas and syngas justifies the low production rates of final products. After pre-treatment operations, the entire produced intermediates (40.02 Mkg of biomethane and 14.45 Mkg of bio-oil) are transferred to upstream upgrading and power generation facilities, as shown in Fig. 5b. The results reported that three conversion facilities equipped with biomethane liquefaction are selected for further processing the biomethane. Moreover, two facilities with technologies of transportation fuel production (with and without H_2 generation) are chosen to convert bio-oil to naphtha and biodiesel. Interestingly, the decentralized optimization model has mostly selected the conversion of biomethane to electricity (7 facilities), thus contributing to the higher profit obtained from selling energy and increasing electricity access in decentralized

Figure 6 provides a summary of the demand and the total annual amount of produced final products (in Mkg) and electricity (in GWh) in centralized (shown by C) and decentralized (shown by D) systems. A comparison of the two strategies reveals that biomass treatment in the centralized case contributed to almost 1.11% of the annual electricity demand of 12313.56 GWh, where decentralized facilities were able to meet about 2.91% of the total electricity demand. Moreover, in the decentralized case, upgrading plants were able to satisfy the total demand for naphtha, digestate, and char. They also met 60.42% and 85.84% of the demand for liquid biomethane and biodiesel, respectively. In the centralized case, production facilities could satisfy 100% of the demand for digestate, followed by 90.77% of the demand for Fischer-Tropsch gasoline, 72.52% of naphtha, 67.98% of Fischer-Tropsch diesel, 54.14% of biodiesel, 48.67% of char, 39.09% of bioethanol, and 12.71% of liquid biomethane. The difference between the production and sold quantities could be due to restrictions on the number of transfers to the demand zones and controlling the CO_2 emissions from transportation. If the entire products had been sold, specifically by-products of char and digestate, the profit would have increased remarkably.

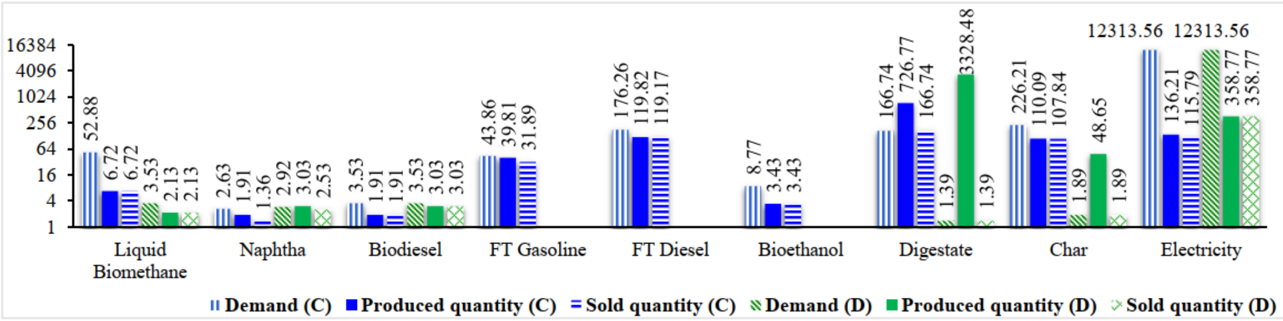

Figure 6. Fuel production (Mkg) and electricity (GWh) vs. sold quantity in the considered centralized and decentralized supply chain networks

Thus far, the results support the idea that the centralized approach enhances information sharing and collaboration among the supply chain parties. Such a strategy, focusing on integrating the organization's internal and external processes across the chain, improves the performance of each member of the network. Large-scale plants in the centralized approach require high capital costs but enhance the usage of biomass resources and treat more waste on account of their higher capacities. Accordingly, this strategy reduces inventory and back-ordering costs. Adversely, moving from large-scale centralized production towards small-scale facilities increases the supply chain's responsiveness to local needs. The high availability of such sources on the local territory also increases the access to lower-priced feedstocks and decreases the shipping cost of biomass. However, the generalizability of these results is conditional on certain limitations. The results proved that selection among centralized and decentralized approaches is driven by the demand generated at the markets, as well as the capacity and production levels in the facilities. The results collectively outline the critical effects of waste availability, processing technologies, transportation modes, and demand for bio-based products on the choice among centralized and decentralized alternatives.

5.3. Societal effects of centralized and decentralized supply chain strategies

There are various indicators to evaluate the social aspect. In this study, we have considered the unemployment rate (UR) and local development rate (DR) to measure social performance. The integration of these two indicators is necessary to reach a balance between their conflicting impacts. A higher local UR means the region needs more jobs. A higher DR indicates a higher development of the region, and thus, less developed areas with lower DR require the balancing of their economic advancement. In the decentralized scenario, 10927 jobs were created, where the majority of job opportunities belong to the biopower sector, comprising 51.71% of the total employment, followed by 38.50% in the biofuel industries, and 9.79% in the pre-treatment facilities. The centralized case contributed to the generation of 11352 jobs, where 84.62% of it belongs to the biofuel industries, and the rest were employed in the bioelectricity sector. Among the ten considered jobs, the proportion of the employees with skill level 1 (production laborer) accounted for 69.80% and 69.83% of the total hired workers in the decentralized and centralized networks, respectively. Figures 7 and 8 present the number of workers employed in facilities operating under centralized and decentralized strategies. The results indicated that plants located in regions with higher unemployment rates (shown by UR) tend to hire more employees while considering the local development rate (shown by DR) to balance the development among regions.

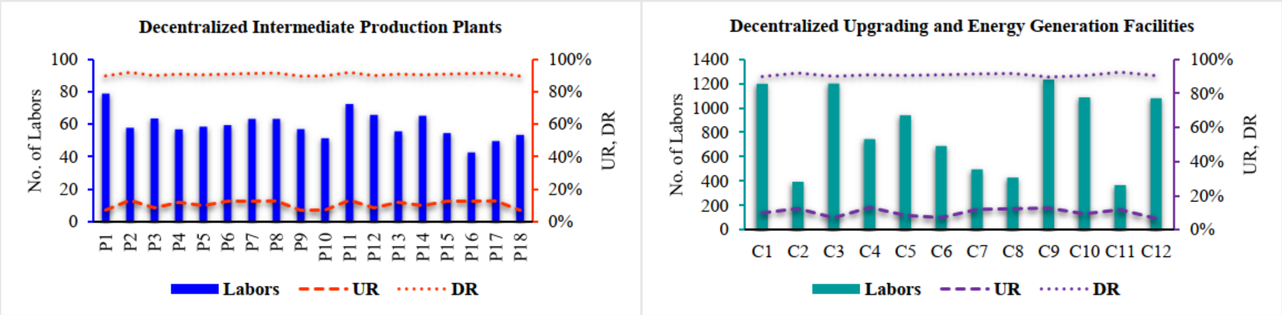

Figure 7. Impact of decentralization on employment opportunities

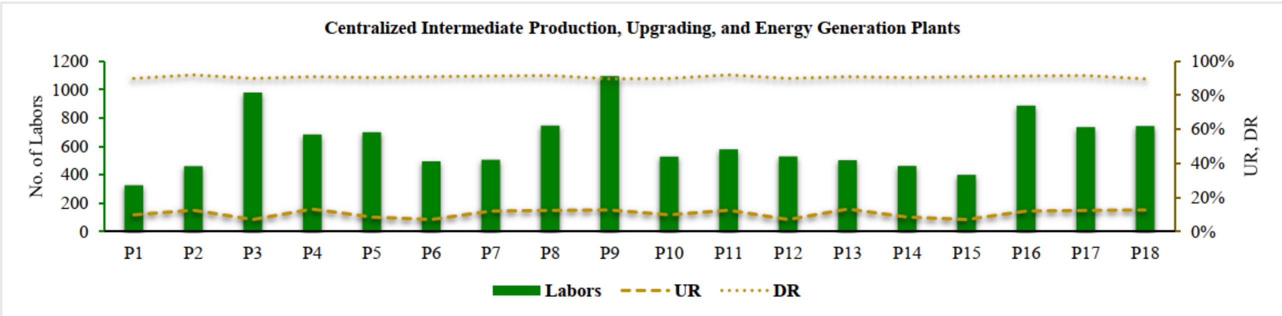

Figure 8. Impact of centralization on employment opportunities

The model, as shown in Eq. (62a), ensures an evenhanded development among regions by balancing the UR and DR. For instance, in the decentralized case, pre-treatment plant 16 with UR of 12.43% and DR of 91.36% hired 43 workers where plant 1 with UR of 7.05% and DR of 89.86% hired 79 employees. Therefore, Plant 1 having 5.38% lower UR (positive aspect) and 1.5% lower DR (negative aspect), compared to plant 16, employed more workforces. In the centralized network, plant 9 with UR of 12.65% and DR of 89.63% provided the highest number of jobs among the other plants, implying that the number of workforces is positively related to the unemployment and development rates. The income created by job opportunities in the small-scale decentralized plants was 17.26 million euros (M€), where large-scale centralized facilities contributed to 17.93 M€. This research supports the conclusion that opening more facilities in the decentralized areas will lead to protecting rural employment and creating additional income and jobs, as the more facilities open in the local regions, the more jobs will be available. From the social point of view, providing new jobs will result in learning, training, and educational opportunities, and lead to superior coordination between local workers, property-owners, and biofuel and biopower industries, in addition to providing greater energy security.

5.4. Economic benefits derived from centralized and decentralized supply chain strategies

The characteristics and limitations of the centralized and decentralized strategies for the deployment of facilities to process the organic waste generated in a region define the system's economic performance. It is worth noting that the model decides the proportion of the demand to satisfy, and accordingly, selects the type and number of technologies, considering maximizing the economic performance of the system, as well as the environmental and social benefits as defined in the objective function of the formulated problem. As stated previously, the intermediate products in which their shipments between the decentralized facilities are feasible were limited to biomethane and bio-oil. Therefore, in the decentralized scheme, more waste is devoted to electricity production, covering a higher portion of electricity demand, and a part of the market demand for liquefied biomethane and transportation fuels (assumed as scenario 1). Adversely, the centralized strategy would cover a portion of the electricity demand and the entire portfolio of the considered chemical products. In addition, to analyze the impact of changes in electricity demand on the allocation of waste to the production of chemicals, a sensitivity analysis was carried out by reducing the electricity demand until attaining the highest amount of produced chemicals. The results indicated that reducing the electricity demand by one-third of the primary scenario will result in reaching the highest portion of the chemical production (assumed as scenario 2). Further reductions in electricity demand do not show significant increments in the production of chemicals.

The optimal installation of centralized facilities for the treatment of organic waste in the region of Castilla y León resulted in the installation of a myriad of technologies to cover the demand for different products, including transport fuels (gasoline and diesel), ethanol, liquefied biomethane, and electricity (see Fig. 4b). On the other hand, due to the transportation limitations, the optimal solution for the deployment of the organic waste considering a decentralized approach retrieves a limited number of technologies, as indicated in Fig. 5b. Considering scenario 1, the number of power plants is about three times bigger than the low electricity demand scenario 2. The latter case selects a higher number of facilities (triple than the first case) to produce higher amounts of liquified biomethane and transportation fuels. It is assumed that the capital financed for the infrastructures and technologies would have annual interest rates ranging from 7% to 13% over a 25-year project.[73] It should be noted that the capital expenditure is a one-time cost and is not incurred in one year, while the operating expenses are annual. Therefore, for comparison purposes, the capital cost is annualized. Table 2 reports the total investment cost in the entire planning horizon, annual operating cost (the sum of all costs incurred by the supply chain, including the annualized investment cost), annual generated revenue, and the annual net profit across the supply chain (total revenue minus total cost) of the considered scenarios.

Table 2. Economic performance of the centralized and decentralized waste processing strategies

Economic components	**Centralized case**	**Decentralized case**	
		High electricity demand scenario	**High chemical products demand scenario**
Investment cost (M€)	1453.0	946.2	632.0
Operating cost (M€/year)	800.3	240.6	271.5
Revenue (M€/year)	668.5	44.0	51.6
Net profit (M€/year)	-131.9	-196.6	-219.9

In the centralized approach, to satisfy the demand of all chemical products, the established facilities contain technologies that have high investment costs, such as gasification, Fischer-Tropsch fuels production, and the reforming and hydrocracking of the pyrolysis oil for the production of gasoline and diesel fuels, among others. Accordingly, it led to high investment costs of 1453.0 M€ for deploying these technologies in the region of Castilla y León throughout the entire project lifetime and producing annual revenue of 668.5 M€ and net profit of -131.9 M€. For the decentralized strategy, where the installation of electricity generation systems is superior, the investment cost is equivalent to 65.12% of the centralized scenario, resulting in 946.2 M€. Although the investment cost is significantly lower than the centralized approach, the annual net profit is remarkably lower (-196.6 M€), leading to higher economic losses. Compared to scenario 1, the second decentralized scenario generated a lower investment cost (a decrease of 33.21%) and higher revenue (an increase of 17.27%). However, the net profit, in this case, is lower by 11.79%. It should be noted that, although none of these scenarios reached a positive net economic benefit, a portion of the generated products are stored in warehouses to mitigate the CO_2 emissions emitted from transportation. Improvements in the profit margins could be achieved by selling the entire produced products, which will result in a positive net profit, especially for the centralized case (see Fig. 6).

The distribution of the investment needed for each approach can be analyzed through the different stages of the organic waste treatment and valorization processes, i.e., the processing of the biomass for the production of intermediate products (which in some cases are marketable without further processing), upgrading processes for the production of chemical products, and upgrading processes for the generation of electricity. The results indicated that, for both strategies, the largest share of investment costs belongs to organic waste processing, accounting for 78% (centralized case) and 95% (decentralized case) of the total investment cost, as shown in Table 3. In the centralized scenario, the investment cost for upgrading technologies used for chemicals production is about 12 times higher than the decentralized case, while the investment cost for energy generation technologies is only 2.5 times bigger. In the centralized approach, investment costs for chemical upgrading and power generation technologies comprise 11.7% and 9.8% of the total investment cost, respectively. However, for the decentralized strategy, the cost for chemical production technologies is around 1.5% of the total investment cost in both scenarios. In contrast, the investment costs for electricity generation technologies are 6.0% and 2.6% of the total investment cost for scenarios 1 and 2, respectively. Table 3 shows the results obtained from the analysis of the total cost incurred in decentralized and centralized networks. In this study, we only considered the purchasing cost for the crop waste, and as in the decentralized approach crop waste was not processed, the biomass purchasing cost, in this case, is zero.

Table 3. Breakdown of the investment and operating costs for centralized and decentralized waste processing strategies

Cost components	**Centralized case**	**Decentralized case**	
		High electricity demand scenario	**Low electricity demand scenario**
Investment costs			
Organic waste treatment facilities (M€)	1139.51	875.24	606.51
Upgrading processes for chemical products (M€)	170.57	13.97	9.18
Upgrading processes for electricity generation (M€)	142.89	57.01	16.29
Operating costs			
Biomass purchasing cost (M€/year)	3.62	0	0
Amortization of investment (M€/year)	167.31	106.88	73.14
Biomass processing cost (M€/year)	69.77	68.83	133.17
Chemical production cost (M€/year)	523.79	1.53	13.24
Electricity production cost (M€/year)	4.82	3.58	1.21

Electricity distribution cost (M€/year)	3.60	11.16	3.75
Transportation cost (M€/year)	22.02	38.42	37.70
Emission cost from transportation (M€/year)	2.08	6.56	4.52
Emission cost by processes (M€/year)	3.37	3.67	4.78

Regarding the production costs, there are significant differences between the strategies studied for the deployment of organic waste treatment and upgrading facilities, as indicated in Fig. 9. For the centralized model, the largest share of costs occurs due to the operating costs of facilities for upgrading the intermediate products to chemicals, comprising 65% of the production costs. This result could be explained by the fact that the production of a variety of products is higher to cover the regional demand for chemicals. On the other hand, for the two scenarios considered in the decentralized model, the largest share of production costs belongs to organic waste treatment to produce intermediate products. It is primarily due to the established restrictions in the production of intermediates that limited the usage of upgrading processes with high operating costs (mainly those related to processing syngas). Consequently, a substantial portion of the waste was destined for the generation of electricity, resulting in lower operating costs compared to the upgrading processes used in the production of chemical products. Besides, in the decentralized approach, the transportation expenses are higher due to the more massive exchange of products between different facilities, as well as the cost for the distribution of electricity in the high electricity demand scenario.

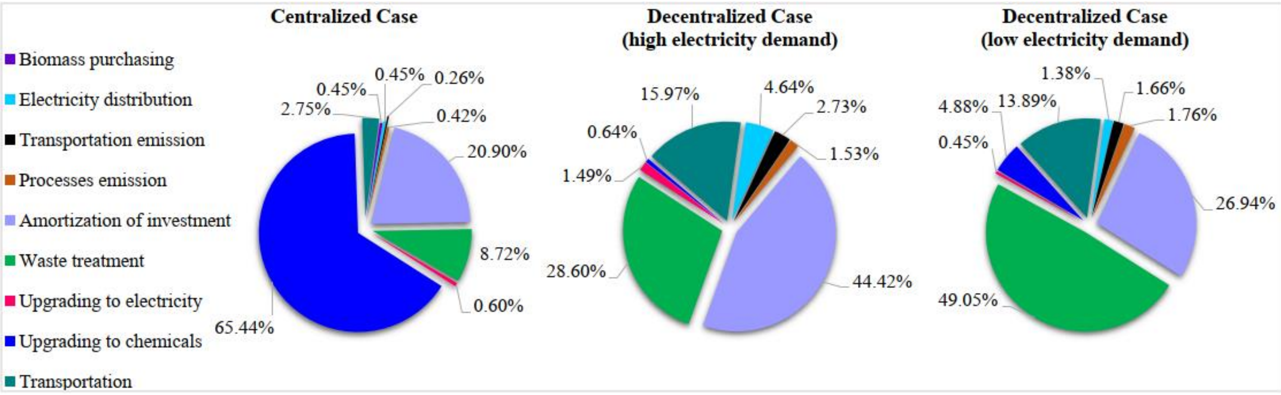

Figure 9. Distribution of operating cost in centralized and decentralized systems

The results indicated that the production of a broad portfolio of chemical products and electricity by the centralized approach leads to higher economic performances than the decentralized strategy, although higher investments are required. It is remarkable to note that, although the centralized approach has a lower electricity production capacity than the decentralized model, it needs a more substantial investment in technologies for electricity generation. The lower investment cost in the decentralized network could be due to the electricity generation using microturbines operated with biogas from anaerobic digestion units. However, in the centralized approach, the electricity is produced through more expensive processes, including waste pyrolysis coupled with CHP units and waste incineration with further cleaning of the flue gases. Therefore, the centralized strategy is less efficient in producing electricity than the decentralized case. On the other hand, the decentralized scheme shows a worse global economic performance in form of net profit, suggesting that the production of chemicals is the main driver for the profitability of the network treating the organic waste. Nevertheless, since the difference in the net profit is relatively small between both approaches, and the implementation of a decentralized scheme for the bio-based waste treatment facilities involves a weaker economic barrier in the form of investment costs, this scheme should not be discarded without a detailed financial analysis if the production of electricity is the main priority.

5.5. Environmental impacts of the analyzed strategies

Two leading environmental aspects have been studied in the development of centralized and decentralized supply chain models, including GHG emissions from treatment and upgrading operations, and emissions from transportation. Monetary penalization for the CO_2 emitted from the industrial processes is considered that enforces the acquisition of emission allowances. The price for the emission allowances is taken from the European Emission Trading Systems (ETS) at 25.15 € per ton of CO_2.[74] Following the scheme proposed by the ETS, the facilities generating power must buy enough allowances to cover all their emissions.[75] Furthermore, the facilities producing chemicals are exempted from purchasing allowances for 51.2% of their CO_2 emissions, which enforces to cover only 48.8% of the emissions through emission allowances (based on the data from the European Environment Agency[61]). It should be highlighted that following the current regulation, the facilities considered in this work would be exempted from buying allowances for CO_2 emissions, as the Annex I of the Council Directive 2009/29/EC[76] regulating the operation of the ETS excludes the facilities that exclusively process biomass materials. However, to promote the installation of technologies with low CO_2 emissions, this scheme is extended to the biomass-based processes assessed in this research. Regarding the emissions from transportation, no monetary penalty for the first 100 km was considered. For the long distances above 100 km, penalization occurs for 0.15 €/km that disincentives shipments over long distances, and consequently, reduces GHGs emissions.[77]

The results showed that, although the infrastructure of the centralized and decentralized networks is quite different in a way that centralization possesses a higher number of upgrading facilities for the production of chemicals, and decentralization prefers more power plants due to the transportation limitations, the CO_2 emissions emitted from the treatment and upgrading of the organic waste in the studied region are similar. The centralized network emitted 793.60 million kg CO_2 in a year, where the decentralized network emitted 863.01 million kg CO_2/year. However, in the second decentralized scenario, the amount of CO_2 emission is significantly higher than scenario one, resulting in a discharge of 1124.07 million kg CO_2 during a year. It shows that enforcing the establishment of chemical production facilities in the decentralized network will results in a suboptimal scenario from the environmental perspective, leading to emitting substantial amounts of CO_2 emissions. As a consequence of the technical restrictions for the chemicals' production in the decentralized approach, the model attempts to cover the demand for chemical products by installing technologies with higher capacities for the reforming and hydrocracking of pyrolysis oil. However, this results in a lower production of chemicals than the centralized scenario, and lower generation of electricity than the base case decentralized case (scenario 1), but higher CO_2 emissions.

Regarding the CO_2 emissions from products transportation, the implementation of the centralized strategy involves two transportation stages, namely, transportation of waste from supply sources to treatment plants and shipment of final products from the processing locations to warehouses, resulting in the discharge of 88.81 and 1.09 million kg CO_2 in a year, respectively. The development of the decentralized network involves an additional transportation stage since intermediate products are transported from facilities processing the biowaste to upgrading facilities. Accordingly, the decentralized base case scenario emitted 113.76, 0.34, and 0.10 million kg CO_2 for shipping waste to the processing locations, the transportation of intermediate products to the upgrading facilities, and the transfer of final products to warehouses, respectively. It can be observed that the decentralized approach generates more emissions due to the increase in the number of transportations. However,

this is mainly due to the first stage, the transport of organic waste from the generation sources to the treatment plants, which is a common stage in both centralized and decentralized strategies. The proportion of emissions produced by the transportation of intermediate products is insignificant compared to the total transportation emissions, although it must be noted that the production of intermediate products in this scenario is lower than the centralized approach. In the second scenario of decentralization, the transportation emission of the first stage remains similar to the decentralized base case, discharging 101.73 million kg CO_2/year. In contrast, CO_2 emissions increased to 0.44 and 0.47 million kg CO_2 kg/year for the transportation of intermediate products and the transportation of final products to sale locations, respectively.
Comparing the assessed scenarios indicated that the centralized strategy is the approach with the lowest CO_2 emission generation. The main driver in the production of GHG emissions is the transportation of the waste to the processing facilities, where the shipment of intermediate products resulted in a marginal contribution to the emissions. The costs derived from the emission penalties for all scenarios are shown in Table 3.

6. Conclusions

In this research, mathematical models are developed to determine the optimal supply chains for the treatment and valorization of organic waste. Two strategies for the deployment of processing facilities are studied, including a centralized approach, in which all stages of the organic waste treatment are integrated into the same location, and a decentralized strategy, where different stages of the biomass processing are distributed across diverse areas allowing multiple exchanges of products between various locations. The proposed supply chain models are built based on the sustainable development objectives in which the economic, environmental, and social aspects are considered concurrently. The economic component of the model calculates the total cost of the network and net profit. Environmental impacts on industrial operations and transportation are considered and analyzed by measuring their effects on the ecosystems. Finally, the impact of the geographical location of facilities on the creation of employment opportunities for the local population and the improvement of the regional human development index of each region are analyzed to assess the social impact of the deployment of the bio-based waste treatment facilities.
The results showed that the centralized model for the deployment of organic waste treatment and upgrading facilities is the superior strategy in terms of economic performance and production of all types of chemicals, although it involves higher investment costs. However, the centralized approach had a lower capacity for electricity generation compared to the decentralized strategy. Therefore, the centralized approach is less efficient in terms of producing electricity than the decentralized model. This implies that the production of chemicals is the main driver of the profitability of the centralized network for the treatment of organic waste. In case the generation of electricity is the primary goal, a decentralized scheme should be taken into consideration since it generates a higher amount of power, involving a noticeably lower investment cost. However, its economic performance is more inferior to the centralized model.
Considering the emissions from transportation, the main driver for the generation of greenhouse gas emissions is the transportation of the waste to treatment facilities. Centralization increases the shipment of biomass feedstock from supply locations to treatment facilities over longer distances. However, since centralization benefits from high capacities and economies of scale, such as an increase in biomass utilization and energy efficiency and a decrease in the production cost, it can compensate for its transportation expenses and emissions. Investment in renewable energy sources is also associated with the formation of jobs and employment opportunities, regional development, and

the creation of a new source of income for the local communities, in addition to enhancing the market reliability of bioenergy industries and energy security. The results indicated that opening centralized and decentralized biomass treatment plants generated more than 22000 new jobs in all stages of the bioenergy supply chain.

A further study with more focus on incentive policies for the deployment of a bio-based waste treatment system is recommended. Moreover, a hybrid strategy combining centralized and decentralized supply chain models will need to be explored to assess its potentials for the design of optimal supply chain networks, considering the treatment and valorization of organic waste. Besides, the sensitivity analysis of the principal process parameters towards the design of a resilient network needs to be carried out. Another possible area of future research would be to investigate the strategic decision-making process on the location of the facilities in the target region to decide which centralized or decentralized scheme would be more beneficial.

Acknowledgements

Authors acknowledge funding from Junta de Castilla y León, Spain, under grant SA026G18 and grant EDU/556/2019.

Supporting Information

Supporting Information 1: the case for the production of intermediates, final products, and electricity at centralized conversion facilities, direct conversion of biomass to final products and power, the information related to the human development index.

Supporting information 2: Pareto front results, the geographic distances between supply chain entities, the residue to product ratio, type of waste generated in the shires of Castilla y León, the composition of the considered waste materials, details of all used conversion techniques, demand for products, human development index, unemployment rate.

Supporting Information 3: the utilized treatment approaches for each type of considered waste.

Nomenclature List

Sets:

b	Biomass type
c	Decentralized conversion facility receiving intermediates from decentralized pre-conversion plants to produce final product or energy
f	Final product
i	Intermediate product
j	Capacity level of upgrading technology
k	Capacity level of energy generation technology
m	Technology for production of intermediate products
n	Technology for production of energy products
o	By-product
p	Decentralized pre-conversion plant for production of intermediate products / centralized pre-conversion and conversion plant for production of intermediates, final, and energy products
r	Capacity level of intermediate production technology
s	Biomass supply location
t	Time period
u	Upgrading technology for production of final products
v	Skill level of workforce
w	Warehouse for storing final products
x	Transportation mode
z	Demand zone

Input Parameters:

A_{bst}	Amount of generated biomass b in supply location s in period t
CC_x	Container capacity of transport mode x

CR_c^{fac}, CR_p^{fac}	Capital recovery ratio for investment in decentralized conversion facility *c*, decentralized pre-conversion / centralized conversion plant *p*
CR_{mp}^{tech}, CR_{nc}^{tech}, CR_{np}^{tech}, CR_{uc}^{tech}, CR_{up}^{tech}	Capital recovery ratio for investment in intermediate technology type *m*, energy technology *n*, upgrading technology *u* in decentralized pre-conversion / centralized conversion plant *p*, decentralized conversion facility *c*
CD_{czt}, CD_{pzt}	Distribution cost of electricity from facility *c* / plant *p* to demand zone *z* in period *t*
CE^{tem}, CE^{pem}	Penalty cost for CO_2 emission emitted from transportation / processes
CH_{bpt}, CH_{ict}, CH_{ipt}, CH_{fwt}	Holding cost of biomass *b* in plant *p*, intermediate product *i* in plant *c*, *p*, final product *f* in warehouse *w* in period *t*
CIF_c, CIF_p	Investment cost to open facility *c*, *p*
CIT_{bmr}^{int}, CIT_{buj}^{upgr}, CIT_{iuj}^{upgr}, CIT_{bnk}^{ener}, CIT_{ink}^{ener}	Investment cost of technology type *m* with capacity level of *r* for processing biomass *b*, technology type *u* with capacity level of *j* for processing biomass *b* / intermediate *i*, technology type *n* with capacity level of *k* for processing biomass *b* / intermediate *i*
CL_{fzt}	Lost sale cost of product *f* requested by demand zone *z* in period *t*
CP_{bst}	Purchasing cost of biomass type *b* in supply location *s* in period *t*
CPB_{bmpt}	Processing cost of biomass *b* using technology *m* in decentralized pre-conversion / centralized conversion plant *p* in period *t*
CPB_{bupt}, CPI_{iuct}, CPI_{iupt}	Processing cost of biomass *b* using upgrading technology *u* in centralized conversion plant *p*, intermediate *i* using technology *u* in decentralized conversion plant *c* / centralized conversion plant *p* in period *t*
CPB_{bnpt}, CPI_{inct}, CPI_{inpt}	Processing cost of biomass *b* using upgrading technology *n* in centralized conversion plant *p* / intermediate product *i* using technology *n* in decentralized conversion plant *c* / centralized conversion plant *p* in period *t*
CT_{spxt}^{fix}, CT_{spxt}^{var}	Fixed and variable transportation costs from supply location *s* to plant *p* using transport mode *x* in period *t*
CT_{pcxt}^{fix}, CT_{pcxt}^{var}	Fixed and variable transportation costs from pre-conversion plant *p* to conversion plant *c* using transport mode *x* in period *t*
CT_{cwxt}^{fix}, CT_{cwxt}^{var}	Fixed and variable transportation costs from conversion plant *c* to warehouse *w* using transport mode *x* in period *t*
CT_{pwxt}^{fix}, CT_{pwxt}^{var}	Fixed and variable transportation costs from centralized plant *p* to warehouse *w* using transport mode *x* in period *t*
D_{sp}, D_{pc}, D_{cw}, D_{pw}	Distance from candidate supply location *s* to decentralized pre-conversion / centralized conversion plant *p*, from decentralized pre-conversion plant *p* to decentralized conversion plant *c*, from decentralized conversion plant *c* to warehouse *w*, from centralized plant *p* to warehouse *w*
D_{sp}^{limit}, D_{pc}^{limit}, D_{cw}^{limit}, D_{pw}^{limit}	Distance limit for transfer between supply location *s* and plant *p*, plant *p* and facility *c*, facility *c* and warehouse *w*, plant *p* and warehouse *w*
D_b^{max}, D_i^{max}	Maximum transportation distance for biomass / intermediate transportation
DB_{ozt}	Demand for by-product *o* in demand zone *z* in period *t*
DE_{zt}	Demand for electricity in demand zone *z* in period *t*
DF_{fzt}	Demand for final product *f* in demand zone *z* in period *t*
$E_{bim}^{CO_2}$, $E_{bom}^{CO_2}$, $E_{bfu}^{CO_2}$, $E_{ifu}^{CO_2}$, $E_{bn}^{CO_2}$, $E_{in}^{CO_2}$	CO_2 emission emitted during conversion of biomass *b* to intermediate product *i* / by-product *o* using technology *m*, biomass *b* / intermediate product *i* to final product *f* using technology *u*, biomass *b* / intermediate product *i* to electricity using technology *n*
ETC_{bnk}, ETC_{ink}	Capacity of energy generation technology *n* with capacity level *k* processing biomass *b*, intermediate *i*
F_{ct}^{econs}, F_{pt}^{econs}	Energy consumed by decentralized conversion plant *c*, centralized conversion plant *p* in period *t*
F_{ct}^{eloss}, F_{pt}^{eloss}	Loss factor of electricity during distribution in decentralized plant *c*, centralized plant *p* in period *t*
F_{bt}^{deter}	Deterioration rate factor of biomass *b* in period *t*
F_b^{loss}	Loss factor of biomass *b* during transportation
F_b^{mois}	Moisture content factor of biomass *b*
F_{bst}^{sus}	Sustainability factor for biomass *b* in supply location *s* in period *t*

F_x^{util}	Container utilization factor of transport mode *x*
FC_x^{bio}	Rate of biodiesel consumption in regular diesel fuel for transport mode *x*
FC_x^{reg}	Regular fuel consumption of transport mode *x*
$FE_x^{CO_2}$	Amount of CO_2 emission emitted from transport mode *x*
IC_{ct}, IC_{pt}	Input processing capacity of decentralized pre-conversion / centralized conversion plant *p* in period *t*, decentralized conversion facility type *c*
ITC_{bmr}	Capacity of intermediate technology *m* with capacity level *r* processing biomass *b*
NPF, NCF	Maximum number of decentralized pre-conversion / centralized conversion plants, maximum number of decentralized conversion facilities
NIT_m, NUT_u, NET_n	Maximum number of intermediate technology *m*, upgrading technology type *u*, energy generation technology type *n* in the entire network
PCB_{opt}^{min}, PCB_{opt}^{max}	Production capacity of decentralized / centralized plant *p* for producing by-product *o* in period *t*
PCE_{ct}^{min}, PCE_{ct}^{max}	Production capacity of decentralized facility *c* for producing electricity in period *t*
PCE_{pt}^{min}, PCE_{pt}^{max}	Production capacity of centralized plant *p* for producing electricity in period *t*
PCF_{fct}^{min}, PCF_{fct}^{max}	Production capacity of decentralized facility *c* for producing product *f* in period *t*
PCF_{fpt}^{min}, PCF_{fpt}^{max}	Production capacity of centralized plant *p* for producing product *f* in period *t*
PCI_{ipt}^{min}, PCI_{ipt}^{max}	Production capacity of decentralized / centralized plant *p* for producing product *i* in period *t*
R_{bim}^{conv}, R_{bom}^{conv}	Conversion rate of biomass *b* to intermediate product *i*, byproduct *o* using technology *m*
R_{ifu}^{conv}	Conversion rate of intermediate product *i* to final product *f* using technology *u*
R_{in}^{econv}	Conversion rate of intermediate product *i* to electricity using technology *n*
R_{bim}^{cons}, R_{bom}^{cons}, R_{ifu}^{cons}, R_{bfu}^{cons}, R_{in}^{econs}, R_{bn}^{econs}	Consumption rate of biomass *b* in a unit of intermediate product *i* / by-product *o* using technology *m*, intermediate product *i* / biomass *b* in a unit of final product *f* using technology *u*, intermediate product *i* / biomass *b* in a unit of electricity using technology *n*
RD_c, RD_p	Local development rate in candidate location *c*, *p*
RU_c, RU_p	Unemployment rate in candidate location *c*, *p*
SC_p^{bio}, SC_p^{int}, SC_c^{int}	Storage capacity for storing biomass in plant *p*, intermediates in plant *p*, *c*
S_{wft}^{fin}, S_{opt}^{byp}, S_{ct}^{elec}, S_{pt}^{elec}	Selling price of final product *f* in warehouse *w* in period *t*, by-product *o* in pre-conversion / centralized conversion plant *p*, electricity in decentralized facility *c* / centralized conversion plant *p* in period *t*
TC_{sxt}^{min}, TC_{pxt}^{min}, TC_{cxt}^{min}	Minimum transport capacity in supply location *s* / decentralized pre-conversion / centralized conversion plant *p* / decentralized facility *c* using transport mode *x* in period *t*
TC_{sxt}^{max}, TC_{pxt}^{max}, TC_{cxt}^{max}	Maximum transport capacity in supply location *s*/ decentralized pre-conversion plant *p*/ centralized conversion plant *p*/ decentralized conversion facility *c* using transport mode *x* in period *t*
UTC_{buj}, UTC_{iuj}	Capacity of upgrading technology *u* with capacity level *j* processing biomass *b*, intermediate *i*
V_b, V_i, V_f	Volume of biomass *b*, intermediate *i*, final product *f*
W_{vc}, W_{vp}	Hourly-based wage of workforce *v* in in facility *c*, *p*
WC_w	Capacity of warehouse *w* for storing final products
WH_{vc}, WH_{vp}	Annual working hours for workforce *v* in decentralized conversion facility *c* / centralized plant *p*
WF_{vc}^{min}, WF_{vp}^{min}, WF_{vc}^{max}, WF_{vp}^{max}	Minimum and maximum number of workforces in facility *c*, *p*
WT_{pt}, WT_{ct}	Working time in period *t* in decentralized pre-conversion / centralized conversion plant *p*, decentralized conversion facility *c*
WR_{vip}^{int}, WR_{vop}^{byp}, WR_{vfc}^{fin}, WR_{vfp}^{fin}, WR_{vc}^{elec}, WR_{vp}^{elec}	Required workforce with skill level *v* for producing a unit of product *i* / by-product *o* in decentralized pre-conversion / centralized conversion plant *p*, product *f* in decentralized facility *c* / centralized conversion plant *p*, energy products in decentralized facility *c* / centralized conversion plant *p*

Positive continuous variables:

a_{ompt}^{byp}	Amount of by-product *o* produced by intermediate technology *m* in plant *p* in period *t*

a_{bnkp}^{cap}, a_{inkc}^{cap}, a_{inkp}^{cap}	Amount of capacity of energy generation technology *n* with capacity level *k* to process biomass *b*, intermediate *i* in plant *c*, *p*
a_{bujp}^{cap}, a_{iujc}^{cap}, a_{iujp}^{cap}	Amount of capacity of upgrading technology *u* with capacity level *j* to process biomass *b*, intermediate product *i* in plant *c*, *p*
a_{bmrp}^{cap}	Amount of capacity of intermediate technology *m* with capacity level *r* to process biomass *b* in plant *p*
a_{bspxt}^{cent}	Amount of biomass type *b* transferred from supply location *s* to centralized pre-conversion and conversion plant *p* via transport mode *x* in period *t*
a_{bspxt}^{dec}	Amount of biomass type *b* transferred from supply location *s* to decentralized pre-conversion plant *p* via transport mode *x* in period *t*
a_{nct}^{elec}, a_{npt}^{elec}	Amount of electricity produced by energy generation technology *n* in decentralized conversion facility *c* / centralized conversion plant *p* in period *t*
a_{bnpt}^{ener}, a_{inct}^{ener}, a_{inpt}^{ener}	Amount of biomass *b*, intermediate product *i* sent to energy generation technology *n* in decentralized conversion facility *c* / centralized plant *p* in period *t*
a_{czt}^{esold}, a_{pzt}^{esold}	Amount of sold electricity sent from plant *c* / *p* to demand zone *z* in period *t*
a_{fuct}^{fin}, a_{fupt}^{fin}	Amount of final product *f* produced by upgrading technology *u* in decentralized conversion facility *c* / centralized conversion plant *p* in period *t*
a_{bmpt}^{int}	Amount of biomass *b* sent to intermediate technology *m* in plant *p* in period *t*
a_{bpt}^{inv}	Amount of inventory level of biomass *b* in plant *p* in period *t*
a_{ict}^{inv}, a_{ipt}^{inv}	Amount of inventory of intermediate *i* in decentralized conversion facility *c* / decentralized pre-conversion plant *p* / centralized conversion plant *p* in period t
a_{fwt}^{inv}	Amount of inventory of final product *f* in warehouse *w* in period *t*
a_{impt}^{int}	Amount of intermediate *i* produced by intermediate technology *m* in plant *p* in period *t*
a_{fzt}^{lost}	Amount of lost sale of product *f* in demand zone *z* in period *t*
a_{fwzt}^{sold}	Amount of sold final product *f* from warehouse *w* to demand zone *z* in period t
a_{opzt}^{sold}	Amount of sold by-product *o* from plant *p* to demand zone *z* in period *t*
a_{fcwxt}^{trans}, a_{fpwxt}^{trans}	Amount of final product *f* transferred from plant *c*, *p* to warehouse *w* via transport mode *x* in period *t*
a_{ipcxt}^{trans}	Amount of intermediate product *i* transferred from decentralized pre-conversion plant *p* to conversion facility *c* via transport mode *x* in period *t*
a_{bupt}^{upgr}, a_{iuct}^{upgr}, a_{iupt}^{upgr}	Amount of biomass *b*, intermediate *i* sent to upgrading technology *u* in facility *c*, *p* in period *t*
a_{fxt}^{use}	Amount of used biodiesel by transport mode *x* in period *t*
$ep_{ct}^{CO_2}$, $ep_{pt}^{CO_2}$	Amount of CO_2 emission from industrial processes incurred by plant *c*, *p* in period *t*
$et_{spxt}^{CO_2}$, $et_{pcxt}^{CO_2}$, $et_{cwxt}^{CO_2}$, $et_{pwxt}^{CO_2}$	Amount of CO_2 emission by transportation from supply location *s* to decentralized pre-conversion plant *p* / centralized pre-conversion and conversion plant *p*, decentralized pre-conversion plant *p* to decentralized conversion plant *c*, decentralized conversion plant *c* to warehouse *w*, centralized conversion plant *p* to warehouse *w* using transport mode *x* in period *t*

Positive integer variables:

n_{spxt}	Number of transfers from supply location *s* to plant *p* using transport mode *x* in period *t*
n_{pcxt}	Number of transfers from decentralized pre-conversion plant *p* to decentralized conversion facility *c* using transport mode *x* in period *t*
n_{cwxt}	Number of transfers from decentralized conversion facility *c* to warehouse *w* using transport mode *x* in period *t*
n_{pwxt}	Number of transfers from centralized conversion plant *p* to warehouse w using transport mode *x* in period *t*
wf_{vc}, wf_{vp}	Number of workers with skill level *v* at plant *c*, *p*

Binary variables:

y_{spxt}^{mode}	Equal 1 if transportation mode *x* from supply location *s* to decentralized pre-conversion / centralized conversion plant *p* is selected in period *t*
y_{pcxt}^{mode}	Equal 1 if transportation mode *x* from decentralized pre-conversion plant *p* to decentralized conversion facility *c* is selected in period *t*
y_{cwxt}^{mode}	Equal 1 if transportation mode *x* from decentralized conversion facility *c* to warehouse *w* is selected in period *t*
y_{pwxt}^{mode}	Equal 1 if transportation mode *x* from centralized conversion plant *p* to warehouse *w* is selected in period *t*
y_{cwxt}^{ship}	Equal 1 if there is a shipment from location *c* to *w* using transport mode *x* in period *t*

y_{spxt}^{ship}	Equal 1 if there is a shipment from location s to p using transport mode x in period t
y_{pcxt}^{ship}	Equal 1 if there is a shipment from location p to c using transport mode x in period t
y_{pwxt}^{ship}	Equal 1 if there is a shipment from location p to w using transport mode x in period t

Boolean variables:

Y_{p}^{cent}	True if centralized pre-conversion and conversion plant p is selected; Otherwise False
Y_{c}^{conv}	True if decentralized conversion facility c is selected; Otherwise False
Y_{p}^{dec}	True if decentralized pre-conversion plant p is selected; Otherwise False
Y_{nkp}^{elec}	True if energy generation technology n with capacity level k to process biomass is installed in centralized conversion plant p; Otherwise False
Y_{nkc}^{ener}	True if energy generation technology n with capacity level k to process intermediates is installed in decentralized conversion facility c; Otherwise False
Y_{ujp}^{fin}	True if upgrading technology u with capacity level j to process biomass is installed in centralized conversion plant p; Otherwise False
Y_{mrp}^{int}	True if intermediate technology m with capacity level r to process biomass is installed in decentralized plant p; Otherwise False
Y_{mrp}^{pre}	True if intermediate technology m with capacity level r to process biomass is installed in centralized plant p; Otherwise False
Y_{ujp}^{prod}	True if upgrading technology u with capacity level j to process intermediates is installed in centralized plant p; Otherwise False
Y_{nkp}^{pwr}	True if energy generation technology n with capacity level k to process intermediates is installed in centralized conversion plant p; Otherwise False
Y_{ujc}^{upgr}	True if upgrading technology u with capacity level j to process intermediates is installed in decentralized conversion facility c; Otherwise False

References

(1) Hong, B. H.; How, B. S.; Lam, H. L. Overview of sustainable biomass supply chain: from concept to modelling. *Clean Technol. Environ. Policy* **2016**, *18*(7), 2173-2194.

(2) Mihai, F. C. Waste collection in rural communities: Challenges under EU regulations. A case study of Neamt County, Romania. *J. Mater. Cycles Waste Manag.* **2018**, *20*(2), 1337-1347.

(3) Elghali, L.; Clift, R.; Sinclair, P.; Panoutsou, C.; Bauen, A. Developing a sustainability framework for the assessment of bioenergy systems. *Energy Policy* **2007**, *35*(12), 6075-6083.

(4) Maina, S.; Kachrimanidou, V.; Koutinas, A. A roadmap towards a circular and sustainable bioeconomy through waste valorization. *Curr. Opin. Green Sustainable Chem.* **2017**, *8*, 18-23.

(5) Ba, B. H.; Prins, C.; Prodhon, C. Models for optimization and performance evaluation of biomass supply chains: An Operations Research perspective. *Renewable Energy* **2016**, *87*, 977-989.

(6) Zabaleta, I.; Rodic, L. Recovery of essential nutrients from municipal solid waste - Impact of waste management infrastructure and governance aspects. *Waste Manage.* **2015**, *44*, 178-187.

(7) Nizami, A. S.; Rehan, M.; Waqas, M.; Naqvi, M.; Ouda, O. K. M.; Shahzad, K.; Miandad, R.; Khan, M.Z.; Syamsiro, M.; Ismail, I.M.I.; Pant, D. Waste biorefineries: enabling circular economies in developing countries. *Bioresour. Technol.* **2017**, *241*, 1101-1117.

(8) World Energy Council. World Energy Resources. UK, London. **2016**.

(9) Gold, S., & Seuring, S. Supply chain and logistics issues of bio-energy production. *J. Clean. Prod.* **2011**, *19*(1), 32-42.

(10) Mohammadi, M.; Harjunkoski, I. Performance Analysis of Waste-to-Energy Technologies for Sustainable Energy Generation in Integrated Supply Chains. *Comput. Chem. Eng.* **2020**, 106905.

(11) Ghosh, S. K. Biomass & bio-waste supply chain sustainability for bio-energy and bio-fuel production. *Procedia Environ. Sci.* **2016**, 31, 31-39.

(12) Karak, T.; Bhagat, R. M.; Bhattacharyya, P. Municipal solid waste generation, composition, and management: the world scenario. *Crit. Rev. Environ. Sci. Technol.* **2012**, *42*(15), 1509-1630.

(13) Lou, X. F.; Nair, J. The impact of landfilling and composting on greenhouse gas emissions–a review. *Bioresour. Technol.* **2009**, *100*(16), 3792-3798.

(14) Sharma, B.; Ingalls, R. G.; Jones, C. L.; Khanchi, A. Biomass supply chain design and analysis: Basis, overview, modeling, challenges, and future. *Renew. Sustain. Energy Rev.* **2013**, *24*, 608-627.

(15) European Commission. Sustainable and optimal use of biomass for energy in the EU beyond 2020. **2017**.

(16) Lohri, C. R.; Diener, S.; Zabaleta, I.; Mertenat, A.; Zurbrügg, C. Treatment technologies for urban solid biowaste to create value products: a review with focus on low-and middle-income settings. *Rev. Environ. Sci. Biotechnol.* **2017**, *16*(1), 81-130.

(17) Basu, P. Gasification theory and modeling of gasifiers. In Biomass gasification and pyrolysis: Practical design and theory. Elsevier Inc. **2010**, 117-165.
(18) Nakatsuka, N.; Kishita, Y.; Kurafuchi, T.; Akamatsu, F. Integrating wastewater treatment and incineration plants for energy-efficient urban biomass utilization: A life cycle analysis. *J. Clean. Prod.* **2020**, *243*, 118448.
(19) Lohri, C. R.; Rajabu, H. M.; Sweeney, D. J.; Zurbrügg, C. Char fuel production in developing countries–A review of urban biowaste carbonization. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1514-1530.
(20) Zhang, Q.; Chang, J.; Wang, T.; Xu, Y. Review of biomass pyrolysis oil properties and upgrading research. *Energy Convers. Manag.* **2007**, *48*(1), 87-92.
(21) Wright, M. M.; Daugaard, D. E.; Satrio, J. A.; Brown, R. C.; Hsu, D.D. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. National Renewable Energy Laboratory (NREL). Technical Report NREL/TP-6A20-46586. **2010**.
(22) Li, W.; Dang, Q.; Brown, R. C.; Laird, D.; Wright, M. M. The impacts of biomass properties on pyrolysis yields, economic and environmental performance of the pyrolysis-bioenergy-biochar platform to carbon negative energy. *Bioresour. Technol.* **2017**, *241*, 959-968.
(23) Patel, A.; Agrawal, B.; Rawal, B. R. Pyrolysis of biomass for efficient extraction of biofuel. *Energy Sources Part A* **2020**, *42*(13), 1649-1661.
(24) Ben-Iwo, J.; Manovic, V.; Longhurst, P. Biomass resources and biofuels potential for the production of transportation fuels in Nigeria. *Renew. Sustain. Energy Rev.* **2016**, *63*, 172-192.
(25) Molino, A.; Chianese, S.; Musmarra, D. Biomass gasification technology: The state of the art overview. *J. Energy Chem.* **2016**, *25*(1), 10-25.
(26) Molino, A.; Larocca, V.; Chianese, S.; Musmarra, D. Biofuels production by biomass gasification: A review. *Energies* **2018**, *11*(4), 811.
(27) Martín, M.; Grossmann, I. E. Optimal integration of renewable based processes for fuels and power production: Spain case study. *Appl. Energy* **2018**, *213*, 595-610.
(28) Kirkels, A. F.; Verbong, G. P. Biomass gasification: Still promising? A 30-year global overview. *Renew. Sustain. Energy Rev.* **2011**, *15*(1), 471-481.
(29) Chaemchuen, S.; Zhou, K.; Verpoort, F. From biogas to biofuel: materials used for biogas cleaning to biomethane. *ChemBioEng Rev.* **2016**, *3*(6), 250-265.
(30) Martín-Hernández, E.; Sampat, A. M.; Zavala, V. M.; Martín, M. Optimal integrated facility for waste processing. *Chem. Eng. Res. Des*. **2018**, *131*, 160-182.
(31) Martín-Hernández, E.; Guerras, L. S.; Martín, M. Optimal technology selection for the biogas upgrading to biomethane. *J. Cleaner Prod*. **2020**, 122032.
(32) Capra, F.; Magli, F.; Gatti, M. Biomethane liquefaction: A systematic comparative analysis of refrigeration technologies. *Appl. Therm. Eng.* **2019**, *158*, 113815.
(33) Mata-Alvarez, J. (Ed.). Biomethanization of the organic fraction of municipal solid wastes. IWA publishing. Padstow, Cornwall, UK. **2003**.
(34) Mussatto, S. I.; Dragone, G.; Guimarães, P. M.; Silva, J. P. A.; Carneiro, L. M.; Roberto, I. C.; Vicente, A.; Domingues, L.; Teixeira, J. A. Technological trends, global market, and challenges of bio-ethanol production. *Biotechnol. Adv.* **2010**, *28*(6), 817-830.
(35) Gupta, A.; Verma, J. P. Sustainable bio-ethanol production from agro-residues: a review. *Renew. Sustain. Energy Rev.* **2015**, 41, 550-567.
(36) Sarris, D.; Papanikolaou, S. Biotechnological production of ethanol: biochemistry, processes and technologies. *Eng. Life Sci.* **2016**, *16*(4), 307-329.
(37) Abo, B. O.; Gao, M.; Wang, Y.; Wu, C.; Ma, H.; Wang, Q. (2019). Lignocellulosic biomass for bioethanol: an overview on pretreatment, hydrolysis and fermentation processes. *Rev. Environ. Health* **2019**, *34*(1), 57-68.
Alayet, C.; Lehoux, N.; Lebel, L.; Bouchard, M. Centralized supply chain planning model for multiple forest companies. *INFOR* **2016**, *54*(3), 171-191.
(38) Vohra, M.; Manwar, J.; Manmode, R.; Padgilwar, S.; Patil, S. Bioethanol production: Feedstock and current technologies. *J Environ Chem Eng* **2014**, *2*(1), 573-584.
(39) Nugroho, Y. K.; Zhu, L. Production Planning, Scheduling, and Process Control System in Microalgae and Biogas Supply Chain. *Ind. Eng. Chem. Res.* **2019**, *58*(5), 1941-1956.
(40) Patel, M.; Oyedun, A. O.; Kumar, A.; Doucette, J. The development of a cost model for two supply chain network scenarios for decentralized pyrolysis system scenarios to produce bio-oil. *Biomass Bioenergy* **2019**, *128*, 105287.
(41) Chen, C. W.; Fan, Y. Bioethanol supply chain system planning under supply and demand uncertainties. *Transp. Res. E Logist. Transp. Rev*. **2012**, *48*(1), 150-164.
(42) Emara, I. A.; Gadalla, M. A.; Ashour, F. H. Supply chain design network model for biofuel and petrochemicals from biowaste. *Chem. Eng. Trans.* **2016**, *52*, 1069-1074.
(43) Ling, W. C.; Verasingham, A. B.; Andiappan, V.; Wan, Y. K.; Chew, I. M.; Ng, D. K. An integrated mathematical optimisation approach to synthesise and analyse a bioelectricity supply chain network. *Energy* **2019**, *178*, 554-571.

(44) Shabani, N.; Akhtari, S.; Sowlati, T. Value chain optimization of forest biomass for bioenergy production: a review. *Renew. Sustain. Energy Rev.* **2013**, *23*, 299-311.
(45) Meyer, D. A.; Cattrysse, D.; Rasinmäki, J.; Van Orshoven, J. Methods to optimise the design and management of biomass-for-bioenergy supply chains: A review. *Renew. Sustain. Energy Rev*. **2014**, *31*, 657-670.
(46) Nunes, L. J. R., Causer, T. P.; Ciolkosz, D. Biomass for energy: A review on supply chain management models. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109658.
(47) Jong, D. S.; Hoefnagels, R.; Wetterlund, E.; Pettersson, K.; Faaij, A.; Junginger, M. Cost optimization of biofuel production-The impact of scale, integration, transport and supply chain configurations. *Applied Energy* **2017**, *195*, 1055-1070.
(48) Yue, D.; You, F.; Snyder, S. W. Biomass-to-bioenergy and biofuel supply chain optimization: Overview, key issues and challenges. *Comput. Chem. Eng.* **2014**, *66*, 36-56.
(49) Särkilahti, M.; Kinnunen, V.; Kettunen, R.; Jokinen, A.; Rintala, J. Replacing centralised waste and sanitation infrastructure with local treatment and nutrient recycling: Expert opinions in the context of urban planning. *Technol. Forecasting Social Change* **2017**, *118*, 195-204.
(50) Ghasemi, P.; Khalili-Damghani, K.; Hafezolkotob, A.; Raissi, S. A decentralized supply chain planning model: a case study of hardboard industry. *Int. J. Adv. Manuf. Technol.* **2017**, *93*(9-12), 3813-3836.
(51) Thiriet, P.; Bioteau, T.; Tremier, A. Optimization method to construct micro-anaerobic digesters networks for decentralized biowaste treatment in urban and peri-urban areas. *J. Clean. Prod.* **2020**, *243*, 118478.
(52) You, F.; Wang, B. Life cycle optimization of biomass-to-liquid supply chains with distributed–centralized processing networks. *Ind. Eng. Chem. Res.* **2011**, *50*(17), 10102-10127.
(53) Sharifzadeh, M.; Garcia, M. C.; Shah, N. Supply chain network design and operation: Systematic decision-making for centralized, distributed, and mobile biofuel production using mixed integer linear programming (MILP) under uncertainty. *Biomass Bioenergy* **2015**, *81*, 401-414.
(54) Kuznetsova, E.; Cardin, M. A.; Diao, M.; Zhang, S. Integrated decision-support methodology for combined centralized-decentralized waste-to-energy management systems design. *Renew. Sustain. Energy Rev.* **2019**, *103*, 477-500.
(55) Claassen, R.; Bowman, M.; McFadden, J.; Smith, D.; Wallander, S. Tillage Intensity and Conservation Cropping in the United States (No. 1476-2018-5723). **2018**.
(56) Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC. **2009**. Available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32009L0030:EN:NOT. Accessed on July 2020.
(57) Grossmann, I. E.; Trespalacios, F. Systematic modeling of discrete-continuous optimization models through generalized disjunctive programming. *AIChE Journal* **2013**, *59*(9), 3276-3295.
(58) Basu, P. Biomass gasification and pyrolysis: practical design and theory Academic press. 2010.
(59) Sikarwar, V. S.; Zhao, M.; Clough, P.; Yao, J.; Zhong, X.; Memon, M. Z.; Shah, N.; Anthony, E.J.; Fennell, P. S. An overview of advances in biomass gasification. *Energy Environ. Sci.* **2016**, 9(10), 2939-2977.
(60) United Nations Development Programme. Human Development Index (HDI). **2020**. http://hdr.undp.org/en/content/human-development-index-hdi. Accessed on July 2020.
(61) European Environment Agency. EU Emissions Trading System (ETS) data viewer. **2020**. Available at: https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1. Accessed on June 2020.
(62) Junta de Castilla y León. Explotaciones Ganaderas de Bovino. **2020**. https://datosabiertos.jcyl.es/web/jcyl/set/es/medio-rural-pesca/ganaderia_bovino_2017/1284707647175. Accessed on July 2020.
(63) Junta de Castilla y León. Explotaciones Ganaderas de Porcino. **2020**. https://datosabiertos.jcyl.es/web/jcyl/set/es/medio-rural-pesca/ganaderia-porcino/1284707659296. Accessed on July 2020.
(64) United States Department of Agriculture. Animal Feeding Operations. **2011**. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/plantsanimals/livestock/afo/. Accessed on July 2020.
(65) United States Department of Agriculture. Agricultural Waste Management Field Handbook. United States Department of Agriculture (USDA). **2009**.
(66) Junta de Castilla y León. Superficie de Cultivo por Término Municipal. **2020**. https://agriculturaganaderia.jcyl.es/web/es/estadistica-informacion-agraria/superficies-cultivo-termino-municipal.html. Accessed on July 2020.
(67) Koopmans, A.; Koppejan, J. Agricultural and forest residues-generation, utilization and availability. Regional consultation on modern applications of biomass energy. **1997.**
(68) Junta de Castilla y León. Plan Integral de Residuos de Castilla y León. **2014**. Available at https://medioambiente.jcyl.es/web/jcyl/MedioAmbiente/es/Plantilla100/1284312829695/_/_/_. Accessed on July 2020.
(69) Junta de Castilla y León. Estadística Energética en Castilla y León. Resumen Anual 2017. **2017**.
(70) Comisión Nacional de los Mercados y la Competencia. Informe de Supervisión del Mercado Minorista de Gas en 2018 por Comunidades Autónomas. **2019**. Available at https://www.cnmc.es/expedientes/isde01619. Accessed on July 2020.

(71) Comisión Nacional de los Mercados y la Competencia. Estadística de productos petrolíferos CNMC. **2020**. Available at https://www.cnmc.es/estadistica/estadistica-de-productos-petroliferos-cnmc. Accessed on July 2020.
(72) Esri. World Topographic Map". 2013. https://www.arcgis.com/home/item.html?id=30e5fe3149c34df1ba922e6f5bbf808f . Accessed on December 2020.
(73) IRENA. Renewable energy technologies: cost analysis series. Biomass for power generation. International Renewable Energy Agency. **2012**. Available at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-BIOMASS.pdf Accessed on October, 2020.
(74) Business Insider. CO_2 European Emission Allowances. **2020.** Available at: https://markets.businessinsider.com/commodities/co2-european-emission-allowances. Accessed on June 2020.
(75) European Commission. EU Emissions Trading System (EU ETS). **2020**. Available at: https://ec.europa.eu/clima/policies/ets_en#tab-0-1. Accessed on June 2020.
(76) European Council. Council Directive 2009/29/EC of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community. Official Journal L 140, p. 63, **2009**.
(77) Transport and Environment, **2010**. Understanding the effects of introducing lorry charging in Europe.