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Techno-economic and environmental assessment of inclusive, context-specific, and capability-sensitive agrarian biohubs for marine biofuels in Spain, Colombia, and Namibia using field residues☆

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ABSTRACT

This study presents a novel bottom-up approach to co-design inclusive biohubs based on field residues, namely olive tree pruning, coffee pulp, and acacia bush in Spain, Colombia, and Namibia, respectively, to produce "drop-in" marine biofuels (MBF) via hydrothermal liquefaction (HTL). The economic feasibility and environmental footprint of the designed biohubs are investigated through a detailed techno-economic and attributional-environmental life cycle assessment. This study introduces an early-stage, context-specific, capability-sensitive, and stakeholder-inclusive approach to conceptual design by integrating process simulations, process economics, and life-cycle environmental assessment. The outcomes indicate that an MBF yield of 5–10 wt% is achievable at a production cost of 1.2–3.9 EUR/$kg_{biocrude}$. The upgrading costs were estimated between 0.12 and 0.90 EUR/$kg_{bio\text{-}oil}$, resulting in a minimum fuel selling price (MFSP) of 0.94–4.45 EUR/kg_{MBF}, after fractionation, which is 1.05 to 5.50 times (without carbon credits) that of the current fossil marine fuel (0.8–0.9 EUR/kg_{MGO}). After mass allocation, the greenhouse gas (GHG) emissions of the derived MBF were estimated in the range of −43.4 to 10.9 g-CO_2 eq./$MJ_{marine\ biofuel}$, thereby indicating an immense potential to reduce global warming impacts. A sensitivity analysis showed that i) At smaller scales, the MFSP is found to be more sensitive to the HTL equipment costs than to feedstock prices; ii) The process economics could be improved through technological advancement and scale-up, and iii) Contextual factors plays crucial role in process design and sustainability of the biofuels. This study concludes that the proposed approach will aid in improving acceptability and in achieving global commercial-scale deployment of the bioeconomy.

Glossary

1,4-DCB	1,4-dichlorobenzene
BBVC	Biobased value chain
CAPEX	Capital Expenses
CFC	chlorofluorocarbons
CHP	Combined Heat and Power
CO	Colombia
CO_2 eq	Carbon dioxide equivalent
Cu	Copper
DM	Dry metric ton
dt	Dry ton
DTPD	Dry tons per day
e-LCA	Environmental Life Cycle Analysis

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eq	equivalents
ES	Spain
EUR	Euros
GHG	Greenhouse gas
GIS	Geographical Information System
GWP_{100}	Global warming potential (100 years)
HFO	Heavy Fuel Oil
HHV	Higher heating value
HTL	Hydrothermal Liquefaction
IEA	International Energy Agency
kg	kilogram
kWh	Kilo watt-hour
L	Litre

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(*continued*)

LHV	Lower heating value
m2a crop eq	Annual cropland
m3	Cubic meter
MBF	Marine biofuel
MFSP	Minimum fuel selling price
MGO	Marine Gas oil
MJ	Megajoule
MW	Megawatt
NA	Namibia
NOx	Nitrogen oxides
OPEX	Operating Expenses
PM2.5	Fine Particulate Matter with a diameter of less than 2.5 μm
SO2	Sulphur dioxide
SSD	Slow-stroke diesel engine
USD	United States Dollars

1. Introduction

Currently, biomass is the primary source of global renewable energy [1]. The wide range of global availability of biomass and local accessibility to affordable bioenergy will increase the above-mentioned share by a factor of 2 by 2030 [1]. The "hard-to-abate" shipping sector is one of the end-users that will be contributing to the increase in consumption of large-scale biofuels to meet the regulations [2]. Due to bunkering abilities and benefitting from existing infrastructure, "drop-in" biofuels are seen as short to mid-term solutions ahead of zero-carbon fuels. However, this growth and widespread global adoption of the biobased economy can only be achieved if the challenges in the commercial-scale deployment of (traditional) biobased value chains (BBVCs) are addressed. More specifically, the secure and sustainable mobilisation of field and processing residues must be ensured to de-risk commercialising lignocellulosic residue-based second-generation biorefineries.

Recently, according to the International Energy Agency (IEA), Biohubs have been identified as a potential way to successfully integrate biomass supply chains (especially for bioenergy), overcome the drawbacks of conventional BBVCs, and enable the commercial deployment of the bioeconomy globally [3]. Biohubs [or (community) hubs in general] act as an intermediary point where various activities such as collection, storage, pretreatment, and processing of biomass into intermediate products (such as pellets, briquettes, wood chips, bales, etc.) can be performed. By acting as processing points, biohubs will reduce the physical distance between the suppliers (biomass producers and growers) and end-users (biorefineries) and also enable them to robustly handle and process diverse biomass feedstocks in the region. However, predominantly, the literature focuses on valorising forestry residues in the global North from an economic feasibility perspective [4]. So far, the validation of this concept in global South countries with biomass feedstocks predominantly available as field residues, and where local social livelihood is interconnected, is yet to be investigated. This requires attention as the promise of biohubs can provide crucial input for global bioeconomy strategies.

Different researchers have studied the biohub concept in terms of economic performance. For example, Pradhan et al. (2022) investigated the economic feasibility of a "first of its kind" biohub in Canada with a 1500 DTPD plant to produce several bioproducts (firewood, bark, woodchips, regular pellets, torrefied pellets, biochar, and bio-oil) using various production pathways [5]. The cost of production of firewood, bark, wood chips, regular pellets, torrefied pellets, biochar, and bio-oil was reported to be 46 USD/dt, 13 USD/dt, 38 USD/dt, 118 USD/dt, 157 USD/dt, 87 USD/dt, and 0.49 USD/L, respectively [5]. However, the commercial perspective was not taken into consideration. In another study, Berry (2022) concludes that local biohubs had a preference while producing biochar, and (larger) regional biohubs in the case of pellets as products. This preference is mainly attributed to transportation costs for the former and operational efficiencies at a greater scale for the latter [6]. Lan et al. (2021) highlight that the minimum fuel selling price (MFSP) of the product is inversely related to the scale of the biorefinery and not necessarily to the capacity of the depots. The decentralised systems, although with higher MFSP based on their analysis, indicated other potential benefits such as supply chain risk mitigation and improved quality of processing feedstocks, which were not quantifiable in the study [7]. Thereby, emphasising the need for a much broader analysis of biohubs, with a focus on more than just economic and operational feasibility.

Very few works of literature have been reported to investigate the environmental or societal dimensions of sustainability for these biohubs.

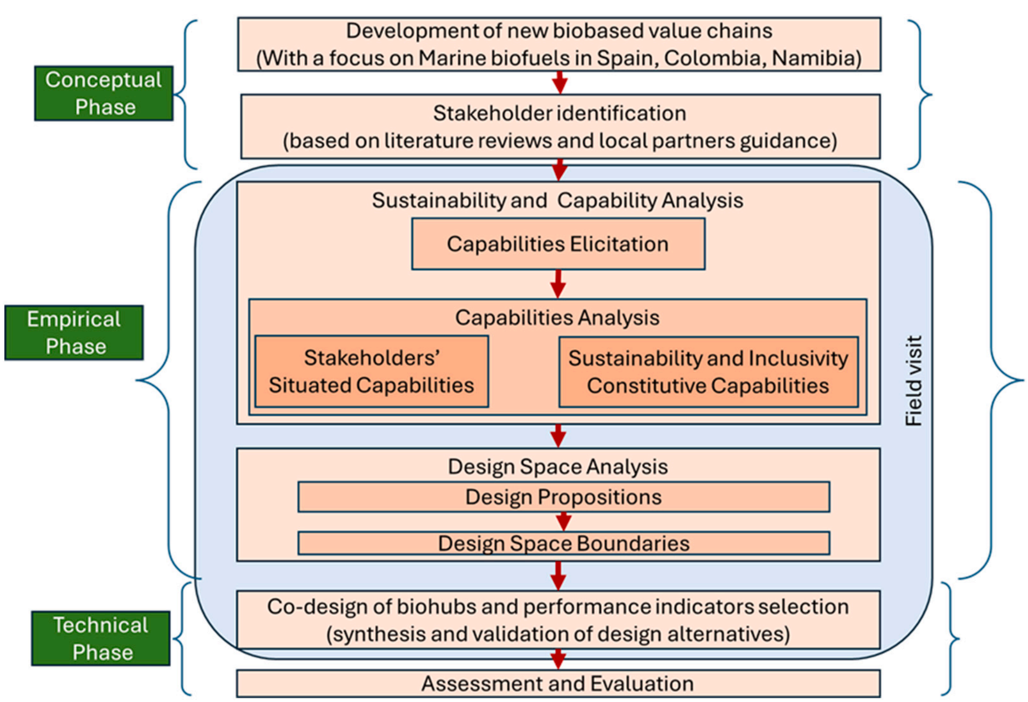

Fig. 1. Design Approach for Inclusive, context specific design of sustainable biohubs for marine biofuels using biobased residues.

Rai et al. (2024) investigated and reported the potential of three (two forestry and one non-forestry residue-based) biohubs to reduce GHG emissions by up to 90% based on the system configuration of biofuel value chains to defossilize hard-to-abate sectors [8]. Lan et al. (2020) performed a cradle-to-gate attributional LCA to investigate the effect of a multi-feedstock depot-based biobased supply chain. The environmental hotspots were identified as occurring during the biorefinery processing and depot feedstock preprocessing stages. The environmental impacts were insensitive to the depot size, biorefinery scale, and transportation [9]. For the social dimension, although BBVCs are supposed to be socio-technical systems, only a handful of literature has been found addressing the social impacts. These are incorporated in assessing the macro-socioeconomic impact of the value chains through various multi-criteria decision-making analyses [10]. There is still a large gap in addressing the social capabilities of these systems in terms of qualitative social perspectives such as inclusion, benefit sharing, and access to participation. These gaps become crucial when feedstocks such as agricultural residues are valorised but are more difficult to quantify and generalise as they merely relate to specific local and regional contexts. Moreover, the conceptual process designs of biohub lacks perspectives for potential environmental (such as mitigating soil, water, and air pollution) and social (such as inclusion and participation) benefits of valorising mismanaged or underutilised field residues beyond reduction in GHG emissions of bioproducts, especially in the upstream of the value chain, are currently lacking.

This investigation aims to address the above-mentioned knowledge gaps by integrating the technical (process and value chain design) aspects with non-technical (social values) elements. This study showcases an early-stage, context-specific, capability-sensitive, and stakeholder-inclusive approach to conceptual design of biohubs to answer the question *"How to design context-specific, and sustainable biohubs based on field residues with early-stage stakeholder inclusion?"* and assess their possible technical, economic, and environmental performance of an inclusive HTL-based biohub-implemented marine biofuel value chain in Spain, Colombia, and Namibia by addressing the problem statement *"What are the economic performance and environmental impacts of the co-designed inclusive field residue-based biohubs for marine biofuel production in Spain, Colombia, and Namibia?"*

The inclusive design approach presented here and the biohubs systems investigated are designed through the Capability Sensitive Design (CSD) approach by setting a design space (DS) and by deriving design prepositions (DPs) from participatory techniques [11–13]. The novel bottom-up approach developed in this paper for co-designing biohubs makes the system design inherently inclusive. Fig. 1 illustrates the designed approach incorporating concepts from engineering and social sciences for designing biobased value chains.

The non-forestry biohubs in this study for marine biofuel production via HTL focus on valorising underutilised or mismanaged lignocellulosic non-edible field biomass residues. Firstly, the Spain case study implements the olive tree pruning biomass, which is currently burned as a quick method of disposal, causing significant emissions of particulate matter to the air [14]. Secondly, in Colombia, the aim is to utilise the coffee pulp residues from the coffee sector, where no value chain for residue valorisation exists [15]. Finally, in Namibia, the focus is on encroacher bush (mainly *Acacia Mellifera*), which is currently posing an ecological threat by causing rapid groundwater depletion, destruction of natural savannah habitat, and drastically reducing the grazing capacity of the land. There has been no prior reported investigation on using these geospatial residue streams for the production of alternative "drop-in" biofuels for the marine segment of transportation. The problem statement is addressed by the following objectives: a) development of inclusive design approach; b) identifying design propositions for the context-specific biohubs through multiactor approach and participatory techniques; c) codesigning inclusive biohubs; d) develop process models in Aspen Plus for mass and energy balances; e) estimation of capital (CAPEX) and operating (OPEX) expenses of biohubs in Spain, Colombia, and Namibia for producing HTL marine biofuels; f) estimation of the minimum fuel selling price (MFSP) of the HTL biofuels; g) comparison of the calculated MFSP with general values reported in the literature; h) determination of environmental impacts of HTL biofuels; and i) key parametric sensitivity analysis that influence the MFSP of HTL biofuels.

2. Methodology

2.1. Case study scenarios for biohub development

2.1.1. Olive tree pruning in Spain

Spain is the leading producer of olive oil in the world, accounting for 40% of the global annual production [16]. The autonomous region of Andalusia, in the south of Spain, accounts for 80% of the national production with almost 1.5 million hectares of olive cultivation farm area [17]. The province of Jaen is the leading region for olive production in Andalusia and practices the traditional method of cultivation, which is both labour and resource-intensive [18]. Every year, in EU-28, the olive oil production value chain generates 21.4 million tons of field and processing residues, which are predominantly either underutilised or mismanaged [19]. Between 2004 and 2016, the average annual production of olive tree pruning biomass in Spain was estimated to be approximately 3.9 million tons, owing to 1.5–3 tons of pruning biomass per hectare per year [20]. Furthermore, the burning of pruning residues leads to economic costs and associated environmental risks due to potential wildfires and GHG emissions, thereby making the current disposal method unsustainable. Therefore, valorising this renewable source of energy will benefit associated small-scale farmers both economically and environmentally [21]. In recent years, the number of scientific investigations for valorising olive tree pruning biomass for bioenergy and bioproducts in the Mediterranean regions has increased [22–24]. However, there are no commercial-scale value chains established for olive pruning residues. Predominantly, the above-mentioned investigations focused on either biochemical conversion techniques to produce biochemicals and bioproducts or heat via thermochemical pathways.

This case study focuses on the province of Jaen. The large availability (approx. 1 million tons per year on a wet basis) of pruning residues [22], the geographical proximity to the end market segment at Port of Algeciras or Port of Gibraltar, stimulating bioenergy policies, and opportunities for strengthening rural economies, make the spatial choice of Jaen a promising region. This case study aims to valorise underutilised olive pruning biomass to produce marine "drop-in" biofuels using hydrothermal liquefaction technology, while improving the socio-economic status of the small-scale farmers.

2.1.2. Coffee sector in Colombia

With an average annual production of 800 kt of coffee between 2019 and 2023, Colombia is the third largest coffee producer in the world [25]. The sector spans over 800,000 ha (ha), involving about 550,000 families, with most (95%) of them cultivating less than 5 ha each [26]. More than 85% of the national coffee production happens in 10 departments with Huila leading the race with 18.37%, followed by Antioquia (15.81%), Tolima (13.29%), Cauca (10.46%), Caldas (7.78%), Risaralda (5.44%), Valle del Cauca (5.33%), Santander (5.21%), Nariño (4.32%), and Cundinamarca (2.77%) respectively [27]. With the suitable climate and soil conditions for coffee production, the coffee axis (locally known as the "*Eje Cafetero*") region in Colombia produces coffee in an agroforestry system along with other crops such as cacao, avocado, and banana. Unlike other coffee-producing countries, the Colombian coffee sector is very vertical, with only a few registered exporters authorised to export coffee beans [28]. Similarly, most Colombian coffee producers sell their coffee in a pre-processed state in comparison to unprocessed coffee cherries, such as in Costa Rica. This predominantly leads to wide variations in the quality, thereby affecting the uniformity of the final export product. The Colombian coffee sector also lacks the

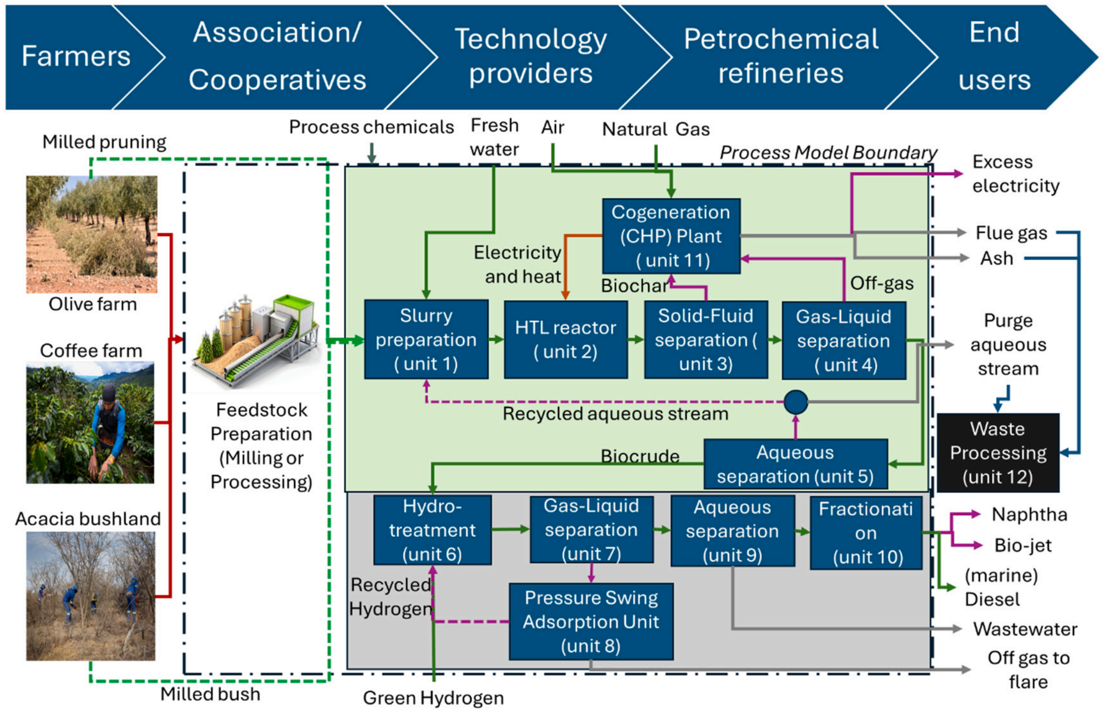

Fig. 2. Marine biofuel value chain with process model boundaries (with unit numbers indicating unit process or unit operation) and stakeholder groups across the value chain. The green highlight indicates the HTL biorefinery facility, and the grey highlight indicates the petrochemical facility. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

implementation of (cooperative-owned) mills with exporter access, thereby making the value chain longer and increasing the distance between the producers and the end consumer [28]. Therefore, new residue value chains with design strategies to enable centralised processing of coffee beans can address the above-mentioned drawbacks.

The wet processing method, which is commonly followed in the Colombian coffee sector, often generates large amounts of residues, posing health, environmental, and economic issues [29]. The supply chain accumulates about 900 g of residues per kg of harvested coffee cherries [30]. The main residues are pulp, mucilage, stems, husks, and coffee grinds. In Colombia, approximately 1.7 million tons of pulp, 0.6 million tons of mucilage, and 3.1 million tons of coffee cut stems are generated on an annual basis [15]. Currently, there are no commercial value chains for handling these residues except for occasional traditional uses such as firewood or compost, making them a promising source of renewable feedstock [31]. In this case study, we perform a first-of-a-kind investigation for developing a value chain to valorise coffee pulp residues for producing “drop-in” marine biofuels, with an additional focus on strengthening the existing coffee sector in the department of Risaralda in the *Eje Cafetero* region.

2.1.3. Encroacher bush in Namibia

In Namibia, the encroacher bush is causing a severe ecological threat [32]. The threats include depletion of groundwater, reducing biodiversity, limiting the grazing capacity of the land, and transforming savannah ecosystems into bushland, impacting human and wildlife. Around 45 million hectares (about one-third of the country) is bush encroached, at the loss of grass vegetation in the Savannah ecosystem [32]. Compared to the natural perennial grasses, these indigenous bushes deplete the groundwater at a much faster rate, reduce the grazing capacity of the land, restrict the movement of wildlife, and reduce the biodiversity of the region [32]. Due to various anthropological activities such as excessive animal browsing, increased atmospheric CO_2 concentration, and suppression of veld fires, the current estimate of the bush is approximately 400 million tons with an estimated annual growth rate of 3–4%, or 14 million tons per year [33]. Geographically, these encroached lands are present in nine of the fourteen regions of the country, with the most densely affected areas in the regions of Otjozondjupa, Oshikoto, Kavango West, and Omaheke [34]. Most of the Namibian population depends on agriculture, directly or indirectly, for their livelihood, with the majority being cattle farmers [35]. Therefore, valorising these abundant lignocellulosic renewable feedstocks can bring more than just economic benefits to the region. Currently, in addition to traditional uses such as firewood, fences, animal feed, etc., these bushes are used for charcoal production [34]. Namibia is one of the leading exporters of high-quality charcoal, obtained from encroacher bush, with a market size of 250 kt per year [36]. However, this value chain hardly consumes 2% of the total biomass available [37]. Therefore, there is a need for new value chains that can offtake the huge quantity of sustainably harvested biomass from bush-thinning activities to restore the savannah ecosystem.

With the increasing investments for infrastructural development in the country due to the discovery of fossil sources and new renewable energy projects, access to the port for exports in Walvis Bay, and the need for energy security and independence, encroacher bush is expected to play a significant role in Namibia's sustainable energy transition and development [38]. Commercially, Namibia Power Corporation (NAMPOWER) is currently constructing a 40 MW biomass power plant, which uses approximately 250,000 tons per year, using encroacher bush as the feedstock [39]. Furthermore, the potential for bush-based biochar production for soil amendment, protein-rich animal fodder, sustainable construction materials, and food production is a new area being explored. [40]. To complement these efforts, this case study focuses on the potential to implement value chains for using these bush lignocellulosic materials for marine biofuel production.

2.1.4. Design space (DS) and design propositions (DP)

This investigation was performed complementary to the work of Veen et al. (2024) within the project for developing sustainable and inclusive value chains for marine biofuels (CLEANSHIPPING) [13]. The

Table 1
Process parameters for the HTL conversion stage and the hydrotreatment upgrading stage.

Biorefinery			
Plant running time	8000 h		
Plant lifetime	15 years		
HTL			
	Spain [42]	**Colombia** [44]	**Namibia** [43]
Mass and Energy input			
Temperature	300 °C	320 °C	300 °C
Pressure	90 bars	120 bars	100 bars
Residence time	30 min	60 min	30 min
Catalyst	KOH	–	Na_2CO_3
Catalyst loading rate	5 wt% of biomass	–	5 wt% of biomass
Biomass/liquid ratio	0.1	0.05	0.1
Outlet yields			
Yields of biocrude, off-gas, aqueous stream, and biochar (in kg/100 kg DM feedstock)	39.5, 0.3, 48.2, and 12.0	24.8, 8.6, 52.8, and 14.0	31.7, 16.1, 44.4, and 7.9
Energy content of biocrude and biochar (in MJ/kg)	26.3 and 25.5	30.2 and 27.0	29.8 and 26.3
Hydrotreatment [50]			
Stage	Single stage		
Liquid hourly space velocity (LHSV), h^{-1}	0.22		
Catalyst (kg/ton bio-crude)	0.41		
Temperature	400 °C		
Pressure	106 bars		

interdisciplinary team visited the case study location for 5 weeks, during which diverse potential stakeholders were involved in the sectors of interest (such as producers, processors, farmer associations, unions, cooperatives, transport companies, technology developers, policy-makers, etc.) via participatory techniques such as semi-structured interviews and multi-stakeholder design workshops.

The semi-structured open interviews and the multi-stakeholder workshops resulted in the identification and validation of stakeholder capabilities and perspectives through a multiactor approach. The capabilities and values were further used to derive the design propositions for biohubs using field residues in the regions, considering the existing local contextual preferences, such as traditional biomass uses, values, capabilities, and capacities. The format of the interviews and the multi-stakeholder workshops organised for the three case studies is summarised in Appendix A1. The outcomes of the multi-actor approach for co-creation of biohubs led to the framing of both the Design Space (DS) (i.e., design aspects such as biomass feedstock choice, harvesting and collecting techniques, biorefinery technology, scale, and location, preference of intermediate or end products, logistical arrangements, co-processing with petrochemical industries, etc.) and the Design Propositions (DPs) (i.e., choice of design variables for each design aspect) for the potential biohubs systems valorising the residues in the chosen region of interest.

2.2. System boundaries and process modelling

2.2.1. Biohub system boundaries

The Biohub system boundaries encompass a wide range of activities: a) collection of crop/residue at the farm level, b) transportation of crop to the regional mill for processing or residues to the preprocessing facility for biomass preparation, c) transportation of pretreated residues to the biorefinery facility, d) conversion of biomass to biocrude using HTL at the biorefinery, e) transportation of HTL biocrude to the nearby petrochemical refinery for coprocessing, f) co-processing of HTL biocrudes in hydrotreaters present in existing petrochemical refinery, g) transfer of end product (marine biofuel) to the port bunker facilities using existing infrastructure, h) supply of utility systems (for electricity and water), and i) processing of waste streams at a waste processing facility. The preferred choices of the above-mentioned design variables were elucidated during the early-stage co-design process via DS and DPs identified in the section 2.1.4. The key features of the biohub systems are expected to be similar irrespective of the region of interest, such as the HTL process, the off-gas and biochar streams being sent to the onsite combined heat and power (CHP) plant, the (solid/liquid/gas) waste streams sent to a waste processing facility before disposal into the environment.

2.2.2. Process model battery limits and description

In this subsection, the process model battery limits for the biohub systems in the region of interests are being described. In process systems engineering, the process model battery limit defines the physical, operational, and commercial scope of activities within a facility. The Fig. 2 indicates the biorefinery process model boundaries in Spain, Colombia, and Namibia. The unit processes and operations performed as a part of liquefaction processes are highlighted in green, while the upgrading of biocrude, which is to be performed as co-processing in a petrochemical refinery is highlighted in grey. The unit processes and operations are numbered, which are subsequently used in process and system description. The biomass-to-biofuel conversion pathway includes two stages: the HTL conversion (units 1,2,3,4,5) and the Hydrotreatment upgrading stage (units 6,7,8,9,10). Various stakeholder groups who could potentially be involved directly in the new value chain is also depicted in Fig. 2.

2.2.2.1. Feedstock preparation. The biomass feedstocks are cleaned, sorted, and chipped in regional mills or preprocessing facilities before the HTL conversion process. The electricity consumption for the feedstock pre-processing, if performed, is obtained from the literature [41].

2.2.2.2. HTL biorefinery and hydrotreatment upgrading. In the HTL conversion process, the (pre-processed) prepared biomass is added to water (unit 1), and a slurry is formed. The slurry is pressurised (unit 2), up to 100 bars, through a series of pumps and further heated to around 300 °C, thereby making the slurry react under subcritical conditions. Upon completion of the residence time (5–60 min), the biomass is deconstructed into bio-crude, an aqueous phase with dissolved organics, an off-gas stream, and biochar. Table 1 shows the operating conditions, including the reactor temperature and pressure, along with the respective product yields. The experimental lab-scale data for the feedstock-conversion pathway are obtained from the literature [42–44]. The process performance of the experimental scale and the lab scale was assumed to be the same. Due to the lack of availability of HTL experimental data on olive pruning biomass, an assumption is made that olive pruning residues behave similarly to those of birchwood residues, owing to similar chemical composition in the feedstock [42]. This assumption is based on the preliminary results obtained from the work performed on the olive tree pruning biomass [45]. As the product yields of biocrude and biochar are comparable, and the similarity in feedstock (hardwood), the assumption is valid and will not have significant impact in the analysis. The reactor output (unit 2➔3) is fractionated using two solid-liquid-gas separating unit operations (units 3 and 4). Initially, the char is recovered using an ultrafilter. Due to a lack of evidence in the physiochemical properties of biochar and its unverified ability to act as a soil amendment, the biochar is sent to the cogeneration plant (unit 11) for producing process heat and electricity. Subsequently, upon depressurising, the off-gas stream containing some non-condensable gases is also sent to the cogeneration plant for valorisation. The liquid stream is subjected to a liquid-liquid separation (unit 5) where the aqueous phase with some dissolved organics is recovered. 75 wt% of the recovered aqueous stream is recycled back into the slurry preparation phase, thereby reducing the necessity of fresh water. The remaining 25% is

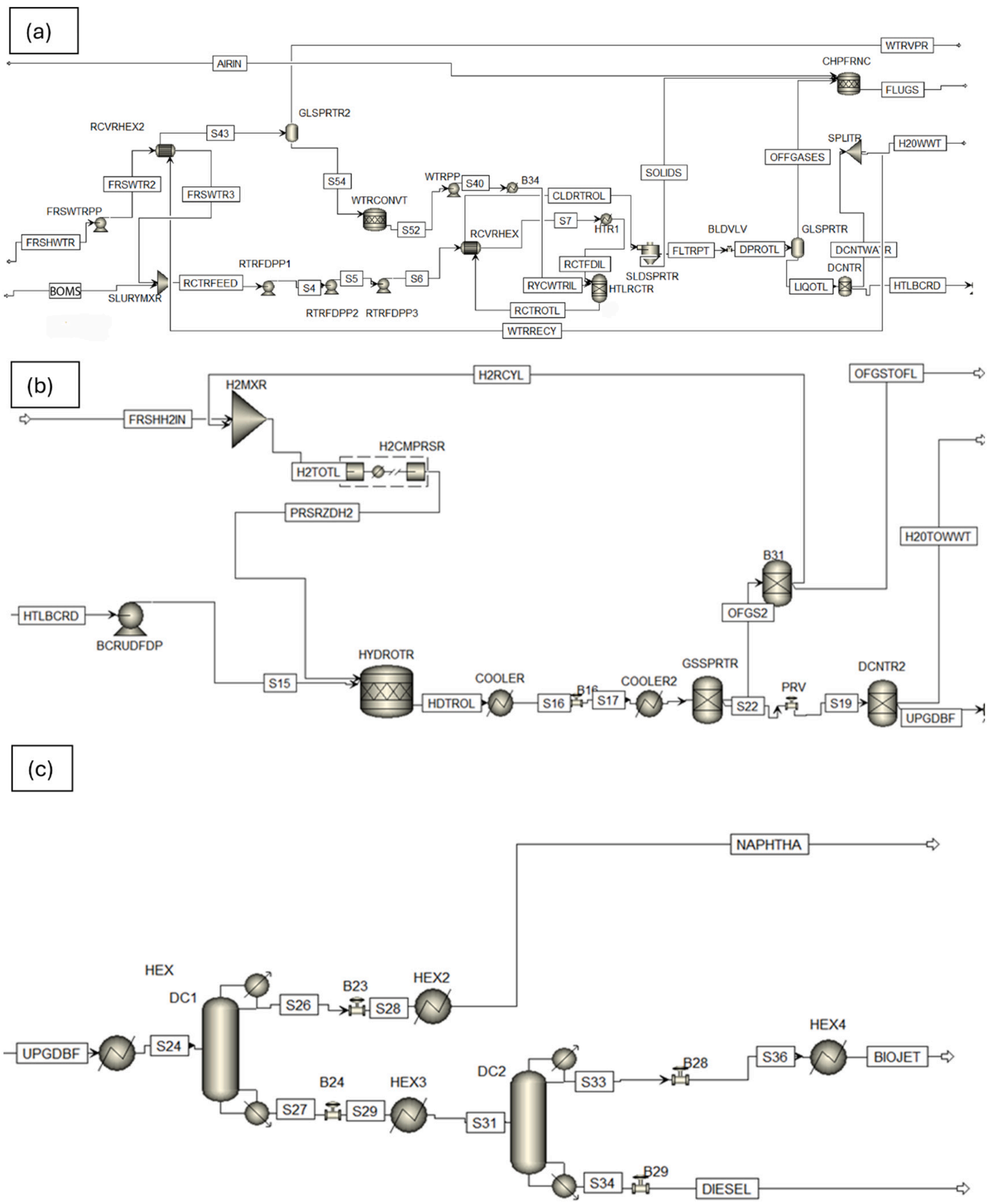

Fig. 3. Aspen Plus v12 process flow diagram of (a) HTL, (b) Hydrotreatment and (c) fractionation process.

purged to wastewater treatment facilities for proper treatment before being disposed of into the environment. Based on Albrecht et al. (2018), the dissolved organics in the aqueous phase is assumed to be 5 wt% of the total organic content in the reactor outlet [46]. The oil phase, commonly referred to as biocrude, is sent to upgrading (unit 6) for further treatment via hydrotreatment, where it is reacted with hydrogen to reduce the concentration of heteroatoms (such as N, S, and O). The HTL bio-crudes are reported to have superior quality compared to bio-oils obtained with other thermochemical conversion techniques [47]. Therefore, in this study, we consider the scenario where the HTL bio crudes are co-processed with fossil crudes in an existing oil refinery. Due to developments to establish green hydrogen production systems in the regions of investigation, it is assumed that green hydrogen will be procured for the hydrotreatment process [48]. Hydrotreating is one of the conventional processes used in the chemical industry to improve the quality of hydrocarbon streams, where hydrogen reacts with heteroatoms like nitrogen, sulphur, and oxygen over a bed of nickel-based catalysts [49]. In this analysis, a single-stage hydrotreatment process (unit 6) is implemented, which is operated at 400 °C and about 106 bar pressure [50]. The hydrogen is provided in twice more than the stoichiometric requirement (on a mass basis) to ensure complete hydrogenation of heteroatoms present in the biocrude [51]. The hydrotreater outlet is depressurised and cooled to ambient conditions and subjected to a gas-liquid separation (unit 7) to remove the gas stream. The separated gas stream still contains residual hydrogen, which is recovered in a pressure swing adsorption unit (unit 8) and further recycled back to the hydrotreater (unit 6). The liquid stream is subjected to an aqueous phase separation (unit 9) for the removal of residual water from the upgraded organic phase. The upgraded bio-oil is further fractionated (unit 10) in a series of distillation units to obtain naphtha, bio-jet, and diesel fractions based on the difference in boiling point.

2.2.2.3. Process simulation. The biofuel production pathway, including the HTL and the hydrotreating processes, is simulated using Aspen Plus v12.0, based on the experimental lab-scale data, as mentioned in the section 2.2.2.2, at steady state conditions, on the chosen feedstocks (olive tree pruning [42], coffee pulp [44], and *Acacia Mellifera* [43]). The modelling approach implemented in this study is robust for both processes, as the method can be used for the different feedstocks in the selected countries, and therefore, the accuracy of the models is not affected by the choice of location. The hydrotreatment was performed by co-processing HTL biocrude in existing petroleum refineries along with fossil crude. The HTL reactor and hydrotreater were modelled as a yield and stoichiometric reactor, respectively. The experimental conditions such as process temperature, residence time, pressure, biomass-water ratio were incorporated in the yield reactor. The Soave-Redlich-Kwong property estimation method is used for all unit operations, with the exception of the gas-liquid separators, in which the Non-Random Two-Liquid (NRTL) property method is used, accounting for vapour-liquid equilibrium description. For the HTL process, a yield reactor is used, operating at steady-state conditions. The HTL off-gas composition is assumed to be similar to that reported by Tews et al. (2014) [50]. The composition of the HTL organic bio-crude is modelled using model compounds reported in the literature [42–44]. In the hydrotreatment process, a single-stage stoichiometric reactor is used to simulate the reactions used to remove the heteroatoms (N, S, and O) from the HTL biocrude, under the experimental processing conditions from the literature, as indicated in Appendix A5. The hydrotreatment output stream (unit 6 ➔7) is further processed through gas-liquid (unit 7) and liquid-liquid separators (unit 9) to obtain the upgraded bio-oil. The bio-oil is further sent through a series of distillation columns (unit 10) to obtain fractions of Naphtha, bio-jet kerosene, and (marine) diesel based on their boiling points. The overall process flow diagram and the process conditions of the HTL and hydrotreatment can be found in.

Fig. 3 and Table 1, respectively.

2.2.3. Utilities

This subsection addresses the strategy implemented to meet the heat, energy, and water demands of the processes. The electricity demand was calculated for all the primary unit operations based on the Aspen Plus simulation (see Appendix A9) and literature data [41]. The heat demand was estimated using the energy balances (see Appendix A9 and A11) obtained from the process simulation based on the specific heat of substances and stream flow conditions. Heat exchangers have been implemented in the simulation to address heat recovery, such as using a hot HTL reactor outlet stream to heat the inlet biomass slurry in a heat exchanger. The excess energy demand, not satisfied by the process integration for heat recovery, was met by an onsite combined heat and power (CHP) plant, also known as a cogeneration plant, which uses off-gases and biochar from biofuel production. This reduces the grid dependency of the process and maximises the energy recovery of the biomass products. In the CHP stage, the co-products (biochar and off-gas) were burned in excess of air, and the flue gas is passed through a turbine and a condensing boiler for heat and electricity production. An 80% efficiency is assumed for both the turbine and the condensing boiler [41]. Stoichiometric reactions were used to determine the combustion products and the amount of heat contained in the flue gas. The excess energy is sold as electricity to the national grid. The total water demand includes the water used in the process and for steam production in the heating system. The methodology used to calculate the total water demand is same as reported in Tanzer et al. (2019) [41]. The total water demand was calculated based on the assumption that demand for freshwater make-up and boiler blowdown was 22% and 3% of the steam demand, respectively [41].

2.3. Techno-economic assessment

In this section, the methodology for estimating the technical performance indicators, capital, and operating expenses of the value chain design in the three case study scenarios is described. The key technical indicators are the overall yield of the final liquid fuel (Y_{MBF}), the quality of the final liquid product (higher heating value and moisture content), and the energy efficiency ($EE_{Process}$) of the process. Similarly, the key economic indicator that is used in this study is the minimum fuel selling price (MFSP) to compare the economic performance of the alternative biofuels in the three case studies and also against their respective fossil counterparts in the regions of interest. The detailed capital and operating expenses estimation procedure can be found in Appendix A6.

2.3.1. Technical performance analysis

The technical performance of the overall process can be defined using performance indicators. The process performance indicators estimated in this investigation are:

The **overall yield (Y_{MBF})** of the marine "drop-in" biofuel is defined as the mass fraction of the amount of liquid marine biofuel produced per kilogram of dry biomass processed ($kg_{MBF}/kg_{drybiomass}$).

The **carbon yield (Yc)** of the marine "drop-in: biofuel is defined as the mass fraction of the amount of Carbon captured in liquid marine biofuel in comparison to the total carbon input from the biomass

The **quality** of the marine "drop-in" biofuel is estimated by the higher heating value (HHV) obtained from aspen simulation, which is associated with the energy content of the fuel and the moisture content of the biofuel. These are obtained through Aspen simulations.

Energy efficiency ($EE_{process}$), which is defined as the percentage of sum of useful energy output (HTL biocrude, biochar, off gas, aqueous phase) obtained divided by the total energy supplied through biomass and natural gas. The energy content of aqueous phase is calculated by the total HHV of the biocrude content present in the water phase.

$$Energy\ efficiency = \left(\frac{Total\ Energy_{HTL\ biocrude+electricity+offgas+aqueous\ phase}}{Total\ Energy_{biomass+natural\ gas}}\right)\cdot 100 \quad (1)$$

2.3.2. Capital expenses (CAPEX)

The economic estimation starts with calculating the capital expenses. The procedure, commonly known as the factor method, is used to determine the total purchased equipment costs (TPEC) of major equipment and process units based on the literature [41,50]. The required equipment sizes were calculated using the stream flows from the process mass balances and are scaled to the respective needed capacities using the capacity–costs relation shown in Eq. (2).

$$C_{new} = \left(\frac{S_{new}}{S_{ref}}\right)^{z}\cdot C_{ref} \quad (2)$$

with C_{ref} as the cost of equipment at the reference capacity (S_{ref}), and C_{new} as the new equipment costs for the new needed capacity (S_{new}), with 'z' as the scaling cost factor for the respective equipment (ranging from 0.65 to 0.75) [41].

The project lifetime considered is 15 years with an average installation factor of 2.5 [41]. Due to the relatively novel application of the technology in the locations, a contingency factor of 0.5 is included, against the conventional factor of 0.2 for a commercial-scale facility [41]. The working capital (which includes the operational expenses before revenue generation) is calculated with sales revenue estimation using retail market prices of fossil fuels and electricity, as mentioned in Appendix A6.3.1. The "drop-in" marine biofuels were compared against marine gas oil (MGO for both economic and environmental performance. The regional production cost differences between the literature

Table 2
Composition of Capital expenses (CAPEX) estimation based on Seider (2017) [53] and Tews et al. (2014) [50].

Abbreviation	Definition	Factor/Formula
FCI	**Fixed capital investments include**	**FCI = dc + ic + cf + cc**
dc	Direct capital costs include	dc = TPEC + inst
TPEC	*Total production equipment costs*	*The sum of all scaled equipment costs*
inst	*Installation costs (labour and materials)*	*2.5 · TPEC*
ic	Indirect costs	0.34 · dc
cf	Contractor's fee	0.23 · TPEC
cc	Capital contingency	0.5 · TPEC
WC	**Working capital**	0.2 · sales revenue
SC	**Startup costs**	0.07 · FCI
LF	**Location factor**	0.9 (Spain), 0.8 (Colombia), 1.2 (Namibia)
CAPEX	**TOTAL CAPITAL INVESTMENT**	**CAPEX = LF · (FCI + WC + SC)**

data and the specific case study regions are eliminated by using location factors [41,52] (also in Table 3). The sales revenue is calculated on an annual basis, by multiplying the annual production of biofuels with the selling price of MGO at respective locations. The calculation scheme of capital expenses is shown in Table 2**:**

In this study, the HTL biocrude is assumed to be co-processed in petroleum refineries in the respective locations. Therefore, we do not consider the capital expenses associated with the upgrading and fractionation stage of the value chain based on the perspective of the transition of petrochemical refineries to renewable biofuels in the future.

2.3.3. Operating expenses (OPEX)

Table 3 indicates the calculation assumptions made for estimating the operational costs of the process and the biohubs. The operational costs consist of a fixed fraction and a variable fraction. The latter part includes country-specific expenses associated with feedstock procurement, catalysts and chemicals, utilities, waste processing, and transport. The feedstock procurement costs relate to the price of raw materials at the end gate of the pre-processing facility in the biohubs. The transport costs were calculated based on the fixed and variable transport costs incurred for transporting the raw materials and intermediates between processing facilities. The distance between these facilities is calculated using driving distances from online GIS tools such as Google Maps. The fixed variable expenses fractions consist of labour costs, taxes, insurance, maintenance, and plant overheads [41]. A contingency factor of 0.2 was used against the direct production costs to account for the unforeseen costs of a conversion technology at the lower Technology Readiness Level [41].

Labour costs are estimated based on a scenario with three 8-h shifts, employing 6 workers per shift for the HTL conversion process [54]. The costs for chemicals, catalysts, and landfilling activities are obtained from the literature. The waste processing costs, which include wastewater treatment and off-gas cleaning treatment, were estimated based on methods reported in the literature. However, certain costs related to operating expenses, such as catalyst and electricity consumption costs, for the upgrading stage have been taken into consideration, as can be seen in Appendix A6.3. The variable expenses due to fractionation are not considered in this study, as it is assumed to be cofractionated with the fossils.

2.3.4. Minimum fuel selling Price (MFSP)

Based on the capital and operational expenses, the minimum fuel selling price (MFSP) was estimated. Eq. 3 presents the formula for calculating the MFSP, where it is the unit price of the final product is when the total annual sales revenue equals the total annual operating expenses.

Table 3
Composition of Operating expenses (OPEX) estimation methodology [53].

Symbol	Description	Factor or formula	References
DPC	**Direct Production Costs, including**	**DPC = VC + LC + M**	
VC	Variable costs, including	VC = *F* + *T* + *U* + *Wt*	
F	feedstock[a]	Olive pruning residue: 100 EUR/ton Coffee pulp residue: 48 EUR/ton Acacia Wood chips: 68 EUR/ton [33] Green Hydrogen, ES: 3.1 EUR/kg [55], CO: 3.1 EUR/kg [55], NA: 2.0 EUR/kg [56]	This study
U	Utilities	Natural Gas, ES: 1389 EUR/ton [54], CO: 641 EUR/ton [57], NA: 1389 EUR/ton [54] Water, ES: 0.08 EUR/ton [58], CO: 0.08 EUR/ton [58], NA: 0.28 EUR/ton [59] Electricity, ES: 28.6 EUR/GJ [60], CO: 36.1 EUR/GJ [61], NA: 29.7 EUR/GJ [62]	
T	Transport	Truck Transport, fixed = 12 EUR/ton (ES), 6 EUR/ton (CO), 12 EUR/ton (NA) Truck transport, variable = 0.27 EUR/ton-km (ES), 0.16 EUR/ton-km (CO), 0.27 EUR/ton-km (NA)	This study
Wt	Waste treatment	Waste processing: gas: 6.00 EUR/ton (ES), 6.00 EUR/ton (CO), 6.00 EUR/ton (NA) Waste processing: water, black: 0.60 EUR/ton (ES), 0.60 EUR/ton (CO), 0.60 EUR/ton (NA) Waste processing: solids: 135 EUR/ton (ES), 135 EUR/ton (CO), 135 EUR/ton (NA)	Based on [63]
LC	Labour costs, including	LC = *Dw* + *Sv*	
Dw	Direct wage and benefits	12 EUR/h (ES, NA), 6 EUR/h (CO)	This study
Sv	Supervision and supplies	50% *Dw*	
M	Maintenance of equipment	10% of FCI	
OC	**Operating Contingency**	**20% of DPC**	
PO	**Plant Overhead**	**70% of *LC***	
FC	**Fixed charges, including**	**FC = lt + i + d**	
lt	Local taxes	1.5% (ES), 1.5% (CO), 1.5% (NA) of fixed capital costs	This study
i	Insurance	1.0% (ES), 1.0% (CO), 1.0% (NA) of annual total sales revenue	This study
d	Linear depreciation	14.0% (ES) [64], 28.0% (CO) [65], 25.0% (NA) [66] of fixed capital costs	
GE	**General administrative overhead expenses**	**10% of annual total sales revenue**	
OPEX	**Total Operating Expenses**	**OPEX = DPC + OC + PO + FC + GE**	

[a] *feedstock price includes the transportation costs from the farm to the pre-processing or the HTL facility.*

$$MFSP = \frac{OPEX - Annual\ sales\ revenue\ from\ byproducts}{Annual\ biofuel\ production\ capacity} \quad (3)$$

Similar to Tanzer et al. (2019), the annualized CAPEX is not included in the MFSP calculation, however the CAPEX is considered in terms of manufacturing expenses (such as maintenance, depreciation, and taxes)

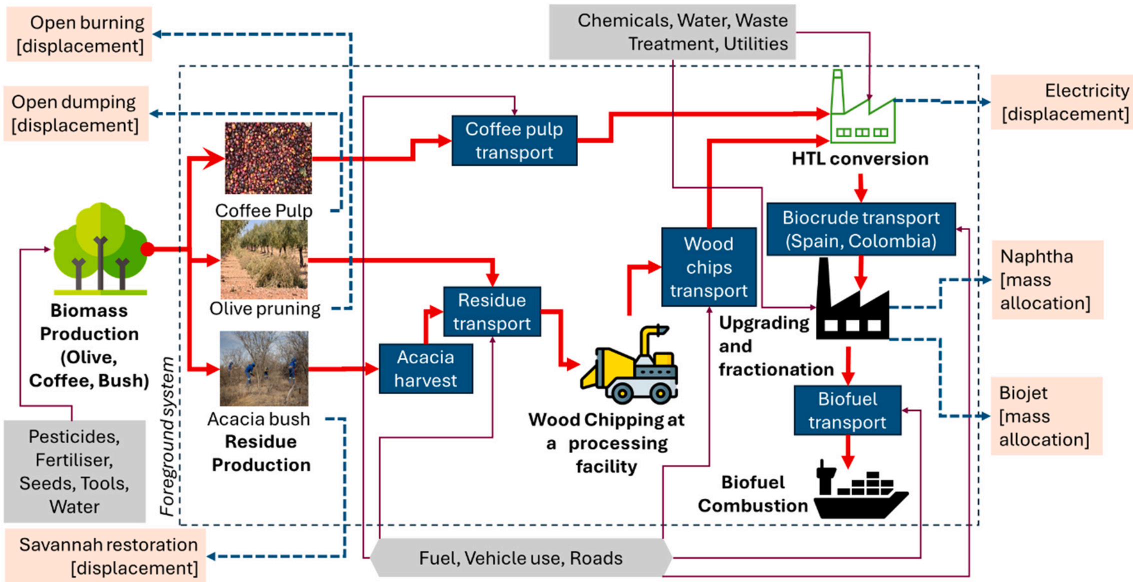

Fig. 4. System boundaries of marine biofuel environmental life cycle assessment. Weighted red line: Main process stream flow, Dashed blue line: Co-product/avoided emissions [allocation method], and purple weighted line: inputs from background system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[41]. This assumption could possibly lead to underestimation of real time MFSP but allows the study to compare with literature values. Due to unknown properties of biochar to be implemented for purposes such as soil amendment, in this study, the biochar produced is assumed to be burned in a cogeneration plant to produce electricity for the facilities. Excess electricity, if produced, is sold to the national grid at its wholesale retail market price. The MFSP of HTL marine drop-in biofuels was compared against the MGO prices from 2023 at the Port of Gibraltar (for the Spain case study), Port of Buenaventura (Colombia), and Port of Walvis Bay (Namibia). The MGO prices in Gibraltar, Colombia, and Namibia are shown in Appendix A6.3.3.

2.3.5. Sensitivity analysis

A sensitivity analysis was performed to understand the impact of four commonly reported factors due to their large variability and low resolution on the available data: a) feedstock price, b) HTL equipment costs, c) biocrude yield, and d) installation factor. These parameters were varied by ±50% to evaluate their impact on the overall process economics through the sensitivity on MFSP of marine "drop-in" biofuel.

2.4. Environmental life cycle assessment (e-LCA)

2.4.1. Goal and scope

To evaluate the environmental performance of the "drop-in" biofuels produced in the designed biohubs, an attributional life cycle assessment (a-LCA) is conducted to quantify the environmental footprint. The analysis is performed from a "Cradle-to-grave" approach following the international standard for e-LCA, ISO 14040, with the Functional Unit of 1 megajoule (MJ) of the drop-in marine biofuel [67,68]. The environmental performance of the HTL "drop-in" biofuel is compared against the emissions from the life cycle of fossil-based marine gas oil (MGO) as a benchmark to contextualise the impact of the biofuels' environmental emissions.

The LCA inventory consists of and accounts for all stream emissions from each process and their respective upstream supply chain [67,68]. Fig. 4 illustrates the system boundaries for the marine biofuel production. This includes sourcing of feedstocks, production of biooil and fractionation, and consumption of biofuel fractions (incl. Marine biofuel), from feedstock extraction up until final waste processing. However, the inventory does not include any emissions related to infrastructure development, construction, and equipment manufacturing, as these activities are proven to have minor contributions [41]. The foreground systems include biomass pre-treatment, biofuel production, upgrading, combustion, and transportation between these elements of the value chain. The background systems include biomass production and its upstream activities, such as cultivation.

As all of the feedstocks are either agricultural residues or have a short-term biomass cultivation period ($\leq$ 5 years), the biogenic CO_2 during the biofuel combustion is considered to have a net-zero GWP. The emissions from each process stage are obtained using the characterisation factors. The mass flows and energy consumptions are obtained from the Aspen simulations (see Appendices A8, A9, and A11), which are then multiplied by their corresponding emission characterisation factors obtained from the ecoinvent database from SimaPro software, as mentioned in Appendix A7.

2.4.2. Inventory

The life cycle stages of biohubs are biomass production, biomass transport, biomass pretreatment, pretreated residue transportation, HTL conversion, biocrude transport, hydrotreatment, upgraded biofuel transport, and biofuel combustion. The life cycle stages are described below, and the inventory results are available in Appendix A7.

Residue production, as can be seen in Fig. 4, includes the crop cultivation phase, harvest, and residue generation activities. The data for the activities were obtained from the ecoinvent database and literature reports. The environmental burdens associated with the generation of agricultural residues are assumed to be zero in all the scenarios due to their low (<10%) economic value in comparison with the main (cash) crop [69]. However, emissions related to biomass extraction (such as harvesting of the Acacia bush) and biomass pretreatment (such as chipping) are considered in this study. We also assume no soil carbon change due to the sustainable harvest of Acacia and Olive tree pruning residues [38,70]. Avoided emissions due to the current utilisation of olive pruning burning, coffee pulp disposal in open fields, and regrowth of savannah grasses after acacia harvest have been taken into consideration via system expansion (refer to Appendix A7).

Transport emissions are estimated using the emissions factors data, as mentioned in Appendix A7, obtained from the literature reports and the ecoinvent data. In case of non-availability of country-specific data (such as in Namibia), alternative data from neighbouring countries or the continent was used, as can be seen in Appendix A7. The emissions are associated with residue transport from the farm to the pretreatment facility and subsequently to the HTL facility in trucks (except for Namibia, where they would be transported by Rail). The HTL biocrudes are considered to be transported either through liquid tanker trucks (Spain) or pipelines (Namibia and Colombia). The transport of the final "drop-in" biofuel is performed using the existing infrastructures of the petrochemical refineries via pipelines.

The **biofuel production stage** includes pretreated biomass conversion via HTL and biocrude upgrading via hydrotreatment in an existing petrochemical refinery. The emissions related to foreground processes are estimated from the simulated process models (i.e., the mass and energy balances in Appendices A8, A9, and A11), and the background data includes upstream emissions of utilities, water, and waste disposal (see Appendix A7). According to the ISO methodology, system expansion, also known as allocation by displacement, is implemented to allocate emissions among the biocrude and electricity sold to the grid from the CHP plant. The electricity from the biorefinery is assumed to replace the electricity produced from existing conventional sources, and therefore, the allocated impacts of biofuel are determined by deducting the impacts of displaced electricity, as shown in Appendix A7. Due to similarity in mass and energy distribution among the fractionated products, the multifunctionality while allocating environmental emissions has been addressed by mass allocation.

The emissions related to **fuel combustion** in an internal combustion engine are very limited for lignocellulosic-based HTL drop-in biofuels, and therefore, it is assumed to be the same across all the case studies, based on experimental measurements, as mentioned in Appendix A7. For the reference material, as a conventional shipping fuel, MGO is chosen in this investigation. Due to a lack of data for MGO, the data is obtained from the ecoinvent database for heavy fuel oil (HFO) and modified based on higher heating values for the two fuels according to Comer and Osipova (2021) [71].

2.4.3. Impact categories

Given that the scope of the study is to evaluate the environmental footprint of marine biofuel from the perspective of the IMO 2020 regulation [72], the life cycle impacts are evaluated through the ReCiPe 2016 Midpoint (Hierarchist) method, with its 18 impact categories, listed as follows: Climate change (in kg CO_2 eq to air), Ozone depletion (in kg CFC-11 to air), Ionizing radiation (in kBq Co-60 to air), Fine particulate matter formation (in kg PM2.5 to air), Photochemical oxidant formation: ecosystem quality (in kg NO_x to air), Photochemical oxidant formation: human health (in kg NO_x to air), Terrestrial acidification (in kg SO_2 to air), Freshwater eutrophication (in kg P to freshwater), Human toxicity: cancer (in kg 1,4- DCB to urban air), Human toxicity: non-cancer (in kg 1,4- DCB to urban air), Terrestrial ecotoxicity (in kg 1,4- DCB to industrial soil), Freshwater ecotoxicity (in kg 1,4- DCB to fresh), Marine ecotoxicity (in kg 1,4- DCB to marine water), Land use (in m^2*yr annual crop land), Water use (in m^3 water consumed), Mineral resource scarcity (in kg Cu), Fossil resource scarcity (in kg oil), and Marine eutrophication (in kg N eq).

3. Results and discussions

In this section, the approach to context-specific, inclusive, capability-sensitive conceptual design of biohubs in the case study locations is discussed in section 3.1 using design propositions. The techno-economic and environmental performance of the developed biohub designs has been evaluated in section 3.2 and section 3.3, respectively. Finally, a sensitivity analysis of the MFSP of the biofuels on some of the key performance indicators has been discussed in the section 3.4.

3.1. Design space and design propositions

During the stakeholder interviews and multistakeholder workshop, the preferences for biohub design have been identified. The Design Space was classified and discussed through various design elements. For instance, the design aspect of feedstock included elements such as the choice of feedstocks, processing, and logistics. The design characteristics were elucidated based on stakeholders' perspectives and common agreement about the current needs that are to be addressed, as well as motivating features for biohub implementation in the future. Finally, design propositions were elucidated based on the norms of the capability approach [13] and design choices made by stakeholders. More detailed aspects of the translation of design propositions to technical design choices are reported in our previous work [73].

3.1.1. Spain

In this subsection, the design propositions for olive residue based biohubs is mentioned in Table 4 and the biohub design is illustrated in Fig. 5. Based on the elucidated design proposition, Fig. 5 shows the configuration of biohub based on olive tree pruning residues in Andalusian region of Spain. The top image shows the location of biohubs in the regions of Cazorla, Jaen, Villacarillo, and Linares producing the woodchips of olive tree pruning. The latter is processing a HTL facility in the region of Ubeda, where HTL biocrude is produced. The HTL biocrude is transported to the CEPSA San Roque refinery via trucks, where it is upgraded and then consumed in the port of Gibraltar. The bottom image indicates the structure of biohub, Jaen as an example, including the olive plantations and the primary mills for processing the pruning residues. The detailed elucidation of design propositions from the design characteristics for respective design elements under specific design space is

Table 4
Design Space and Design Propositions for biohubs in Spain.

Design Space	Design Propositions
Spain [73]	
Feedstock	- Use Crude olive pomace as the primary feedstock
	- Olive tree pruning biomass, Olive leaves, and Exhausted olive pomace can be utilised as feedstocks if they can bring more economic revenue than existing uses.
	- Central wood chipping facility at cooperative-owned primary mills
	- Farmers can bring either pruned or chipped biomass
	- Potential to use third parties for pruning, chipping, and transportation for farms with ageing owners.
Biorefinery	- Centralised HTL facility
	- Upgrading at San Roque refinery
	- Off gas and biochar valorisation for energy requirements through a cogeneration plant.
	- Ubeda is preferred over Jaen due to the proximity to farms.
	- Transportation fuels
	- Oleochemicals
Benefits	- At least 75% of the pruning biomass is available
	- 100% of the pruning biomass is available when farmers are enabled to grow other cover crops (such as grasses)
	- Valorisation of Crude olive pomace in large quantities can reduce soil and air pollution due to surface run-offs and open-pond storage
	- Minimum selling price of olive tree pruning residues should be 70 EUR/ton

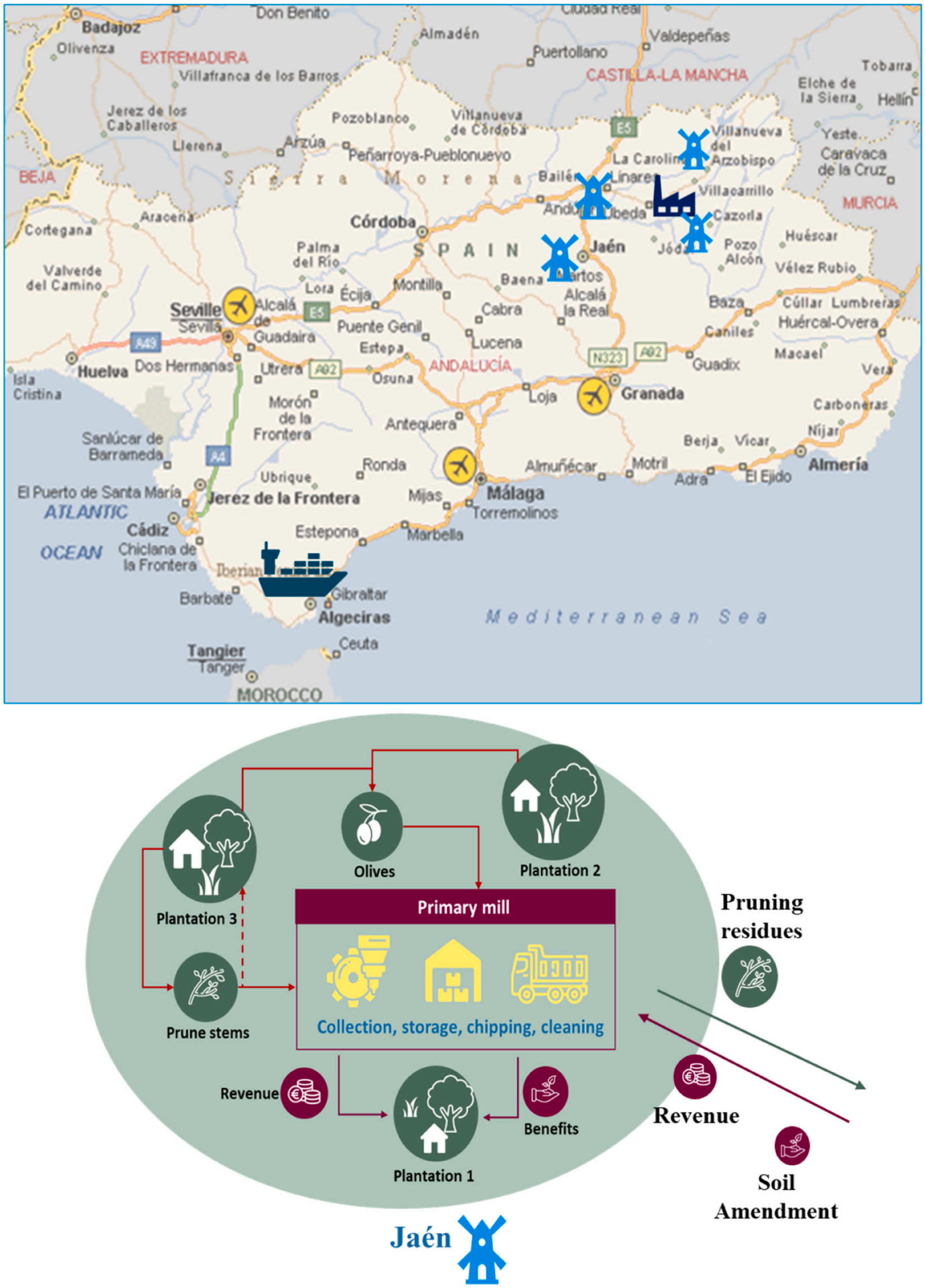

Fig. 5. Biohub configuration in Andalusian region of Spain.

mentioned in the Appendix A13.

3.1.2. *Colombia*

In this subsection, the design propositions for coffee pulp residue based biohubs is mentioned in Table 5 and the biohub design is illustrated in Fig. 6. Based on the elucidated design proposition, Fig. 6 shows the configuration of biohub based on coffee pulp residues in the Eje Cafetero region of Colombia. The top image shows the location of biohubs in the different regions of Risaralda and Caldas such as Marsella, Belalcazar, Filadelfia, Mistrato etc. producing the coffee pulp from centralised coffee bean processing. The residues are processed in a centralised HTL facility located in a major city of the department such as Pereira or Manizales where HTL biocrude is produced. The HTL biocrude is transported to the Sebastopol refinery via trucks, where it is upgraded and then consumed in the port of Buenaventura by pipeline. The bottom image indicates the structure of biohub, Santa Rosa Cabal as an example, including the coffee agroforestry plantations and the central processing facility for processing coffee beans using wet processing

Table 5
Design Space and Design Propositions for biohubs in Colombia.

Design Space	Design Propositions
Colombia	
Feedstock	- Valorisation of residues from the coffee sector is an example for other sectors, such as cacao. - The coffee sector is well structured and organised for collective sectoral impact in the country - Centralised facility to process cash crops (such as coffee, cacao) for uniformity in the processing of beans and can act as a logistical point for residue collection - Located one per region in the department and owned by an association/cooperative/federation - Farmers are willing to bring residues to the processing facility free of cost.
Biorefinery	- Biofuels - Food and pharmaceutical products - Bio-degradable plastics - A technology with existing "proof of concept" - Water recycling and off-gas valorisation techniques to be implemented. - Biochemical transformation is preferred due to existing knowledge and expertise - Promising Thermochemical technologies can be considered. - Technologies can be integrated with the Sebastopol refinery - HTL facility in Pereira - Upgrading at the Sebastopol refinery
Benefits	- Any resource recovery strategy from residues is beneficial - By-product valorisation to make the system "fossil-free" and enhance primary agriculture is encouraged. - Implement replicable and scalable solutions. - Associations/cooperatives owned common processing facilities for better control of processing

method. The detailed elucidation of design propositions from the design characteristics for respective design elements under specific design space is mentioned in the Appendix A13.

3.1.3. Namibia

In this subsection, the design propositions for acacia bush based biohubs is mentioned in Table 6 and the biohub design is illustrated in Fig. 7. Based on the elucidated design proposition, Fig. 7 shows the configuration of biohub based on acacia bush in the Otjozondjupa region of Namibia. The top image shows the location of biohubs in the different regions of Otjozondjupa such as Okhakarara, Grootfontein, Okahandja etc. producing the acacia wood chips from centralised wood chips processing facility. The wood chips are processed in a centralised HTL facility located in Walvis Bay where HTL biocrude is produced. The HTL biocrude is transported to the petroleum refinery via pipeline, where it is upgraded and then consumed in the port of Walvis Bay. The bottom image indicates the structure of biohub, Otjiwaraango as an example, including the communal and commercial farms, and the central processing facility or the biomass industry park for processing acacia wood chips. The detailed elucidation of design propositions from the design characteristics for respective design elements under specific design space is mentioned in the Appendix A13.

More details regarding the biohub configurations are summarised in the Table 7**.** For Spain, the feedstock availability is conservatively assumed to be 50% (or 450,000 tons per annum) of the produced pruning biomass in the province of Jaen, accounting for cover crop application. In the department of Risaralda in Colombia, 100% (or 83,000 tons per annum) feedstock availability is assumed due to the absence of any utilisation practices. Finally, in Namibia, a mobilisation of 250,000 tons per annum (2.5% of the total availability) of acacia wood is considered as a feedstock supply capacity. Additionally, for the "first-of-its-kind" biohub concepts considered in this investigation, the scales of the HTL facilities resulting from the biomass availability stated above for the three locations are therefore 1265 DTPD, 211 DTPD, and 692 DTPD of biomass feedstock in Spain, Colombia, and Namibia, respectively.

3.2. Techno-economic performance of "drop-in" marine biofuel production from biomass

Table 8 summarises the key technical performance indicators (like capacity, conversion yields, and product distribution) resulting from the process model as described in sections 2.2.2 and 2.2.3 in combination with the Biohubs' characteristics identified and described in section 3.1.

Initially, technical performance is investigated based on the mass and energy balances obtained from the process simulations. In the HTL conversion stage, the final biocrude yield obtained ranges from 0.27 to 0.38 kg/kg DM. The Colombian HTL biocrude showed lower yields and higher calorific content owing to prolonged exposure of biomass to elevated temperature (320 °C) over higher residence time (60 min) favouring deoxygenation, formation of volatiles and soluble components [74]. The processes implementing catalysts (i.e., KOH for olive pruning in Spain and Na_2CO_3 for acacia bush in Namibia) produce a higher yield of biocrude in comparison to the non-catalytic process (such as Colombian HTL process). The homogenous alkaline catalysts improved the deoxygenation reaction during liquefaction by promoting cracking and condensation, resulting in a decreased oxygen content in bio-oil, which is beneficial for subsequent bio-oil hydrogenation and deoxygenation processes [74]. The biomass to biocrude yield obtained from Aspen modelling is found to be slightly higher than that of experimental values, owing to the recovery of organics present in the aqueous recyclate. The quality of biocrude, especially the energy content of biocrude (HHV), obtained via modelling (39–43 MJ/kg), was found to be higher than that reported in the literature based on experimental studies (30–36 MJ/kg) [42–44], owing to the higher efficiency of aqueous phase separation from HTL biocrude in the aspen simulation. It is crucial to note that due to assumptions made (such as biocrude composition and separation efficiencies of liquid-liquid unit operations), the HHV obtained from the modelled might be overestimated. The average electricity consumption (kW/kg_{feed}) for the HTL processes is found to be at least 45% lower than that reported in the literature, owing primarily to the reduced working volumes due to recycling of the output HTL-aqueous streams [41,75,76]. In terms of energy efficiency, all the HTL processes are self-sufficient (not fossil-dependent, no natural gas consumption as can be seen in Table 8), when the off-gas and biochar produced are fully used in the cogeneration plant. The heat from the cogeneration plant was utilised to satisfy the process's internal heat demand. Excess electricity from the cogeneration plant is sold to the national grid to displace fossil-based electricity. The major sinks for heat loss are found to be the flue gas and wastewater streams. This could be inferred from the reduced overall process energy efficiency for the coffee-residue-based case study, with only 68% compared to the other two case studies, as seen in Appendix A11. The large differences in waste streams (in Table 8) generated and excess electricity produced are owed to the differences in quantity (Appendix A9) and energy content of the by-products (see Table 1).

In the hydrotreatment stage, based on the stoichiometric, complete hydrogenation of identified HTL biocrude components is assumed. To

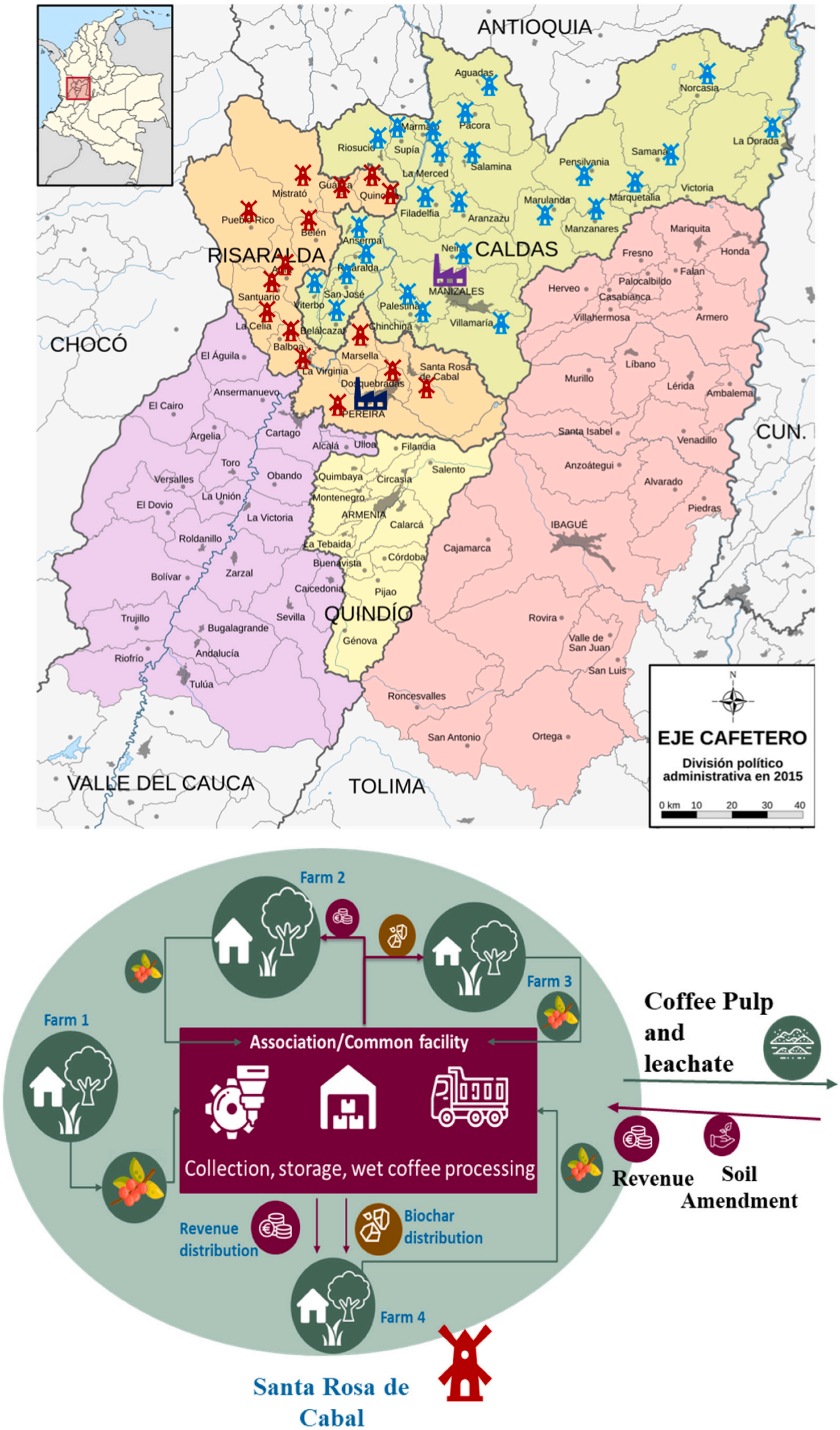

Fig. 6. Biohub configuration in the Eje Cafetero region of Colombia.

Table 6
Design Space and Design Propositions for biohubs in Namibia.

Design Space	Design Propositions
Namibia	
Feedstock	- *Acacia Mellifera*, as it is one of the most abundant - Commercial farmers providing 70–80% feedstock demand with 20–30% ad-hoc supply from communal farmers - Choice to be made based on the region of interest and farmers' capabilities. - Forest Stewardship Council (FSC) -certified feedstocks as proof of sustainable feedstock extraction - The harvest should be done after obtaining a harvest permit and performing an impact assessment. - Communal farmers should have community forest management practices in place - Wood chips will be the nature of the feedstock - Biomass Park concept for wood processing facility - Common wood-chipping facilities will be placed near the biomass site, and with high population density - Road or Rail transport for feedstock transportation from the Biomass Park to the HTL facility
Biorefinery	- Biofuels - Green hydrogen - Wood chips as the chosen nature of feedstock, as they can also be used for wood pellets and animal fodder - Wood chipping at regional, decentralised locations - HTL with water recycling methods. - Ability to integrate with existing value chains and future projects. - Biomass parks in the regions of Otjiwarongo, Tsumeb, Okhakarara, Grootfontein - HTL facility at Walvis Bay
Benefits	- Additional income, especially during drought seasons - Almost all families can benefit from the sustainable bush valorisation - Reclamation of Savannah lands, especially for game movement and livestock farming - Improved soil inorganic and organic health - Increased groundwater availability - Inclusive and equal participation of different biomass providers in a commercial value chain - By-products to be valorised as per the needs of local contexts, such as soil amendment, energy production, or water purification

ensure complete hydrogenation, hydrogen is supplied in excess (200 wt %) of the stoichiometric quantity. The hydrogen consumption in this study was found to be at least 50% less than that of the assumed values in the literature [41,77]. The reduced hydrogen consumption could be attributed to the presence of lower heteroatoms (such as N, S, and O) content in modelled biocrude from the HTL conversion stage. The upgraded oil yield obtained from the respective HTL biocrude is found to be dependent on the percentage of impurities (hetero atoms) present in the biocrude, indicated with the lowest biocrude to bio-oil yield for coffee residues (81%) and highest for olive tree pruning biomass (94%). In the process simulation, due to the stream composition and thermodynamic behaviour of stream components, upon distillation, the upgraded oil from olive pruning and coffee pulp yields a larger fraction of diesel in comparison to that of acacia-based bio-oil, as represented by the yield of naphtha, biojet, and "drop-in" marine biofuel in Table 8. The difference in fractionation yield is attributed to the presence of a high number of lower-boiling-point components in the bio-oil, which end up in the naphtha fraction. With respect to energy distribution, the majority of the input energy is contained in HTL biocrude (40–59%), followed by combustion losses (15–32%), aqueous recyclate (15–19%), process energy (3–8%) and salable electricity (1–5%). Detailed distribution of energy balance and utilities demand can be found in Appendices A11 and A12 respectively.

The economic performance of the biohubs is specified in Table 9. The total production costs of biocrude are found to be largely influenced by the scale, biocrude yield, and capital costs. Due to the large scale, the MFSP of biofuel in the Spanish case study is significantly lower due to economies of scale. Due to lower yields of bio-oil from coffee pulp, more feedstock is needed, thereby increasing the capital costs and negatively influencing the MFSP of biofuel obtained.

The HTL reactor is the major contributor to the total equipment costs, followed by the pre-treatment facility (if present) and cogeneration plant. The biocrude production costs are estimated in the range of 1260.2–3911.3 EUR/$ton_{biocrude}$ in comparison to 0.6 EUR/$kg_{Brent\ crude}$ [78]. Overall, for the three case studies, the capital depreciation (24–58%), maintenance costs (12–19%), feedstock price (5–20%), and catalysts (4–10%) contribute majorly to the production costs, as can be seen in Appendix A10. With co-processing, the upgrading production costs are in the range of 125–921 EUR/$ton_{bio\text{-}oil}$, with biocrude transportation contributing a significant proportion in Spain (65%) and Colombia (68%), as can be inferred from the table in Appendix A10. The upgrading costs compare well with the reported values of 0.5–0.97 EUR/$L_{bio\text{-}oil}$ in the literature [75,76]. Moreover, the production costs of final "drop-in" marine biofuel, on an energy content (HHV) basis, are found to be (32.19–112.24 EUR/GJ) and are higher than marine gas oil (19.38 EUR/GJ, in 2024 at Port of Gibraltar). However, except for coffee pulp owing to its small scale, these values are lower or within the range (17–50 EUR/GJ) of drop-in marine biofuels obtained from other thermochemical conversion pathways [41,79–83]. Finally, the ratio of the minimum fuel selling price of "drop-in" marine biofuel to that of its fossil equivalent (marine gas oil, MGO) is found to be in the range of 1.05–5.54. This value is highly sensitive to the changes in the (regional) market price of MGO. The cost incurred due to the avoided emission of fossil CO_2 is not considered in this investigation, which, in addition, might lead to more cost-competitive cases for alternative biofuels. Moreover, the economic performance of the Spanish and Namibian HTL biofuels can significantly benefit from the scaling opportunities, through economies of scale, as only 50% and 2.5% respectively of the feedstock is assumed for the processing capacity [73]. Similarly, apart from technical improvements in terms of better biocrude yield by using catalysts, the economic performance of the Colombian HTL biofuels can be improved by processing multiple feedstocks from the agro-forestry system or implementing the value chain in other departments (such as Huila or Antioquia), where the coffee production is significantly higher than the considered department of Risaralda.

3.3. Environmental performance of "drop-in" marine biofuel production from biomass

The allocated environmental impacts of the "drop-in" marine biofuel production (in a well-wake approach) are shown in Table *10*. The GWP for the investigated scenario is estimated to be 10.9, −43.37, and − 7.24 g-CO_2 eq/$MJ_{\text{“drop-in” marine biofuel}}$ for Spanish, Colombian, and Namibian scenarios, respectively. This translates to a reduction of 89.6%, 141.3%, and 106.9% in GHG emissions in comparison with fossil MGO. These values are within the range reported in the literature [51,69,84]. In other impact categories, all three alternative renewable fuels performed lesser than their fossil counterparts for Ozone formation (terrestrial ecosystem), Marine eutrophication, Land use, and water consumption. This could be attributed to the emissions due to biomass handling phase and the system definition that includes waste streams handling, which are absent in fossil production. For biomass phase, the emissions predominantly arise from activities such as biomass transportation and preprocessing. The consumption of water for HTL process, which is

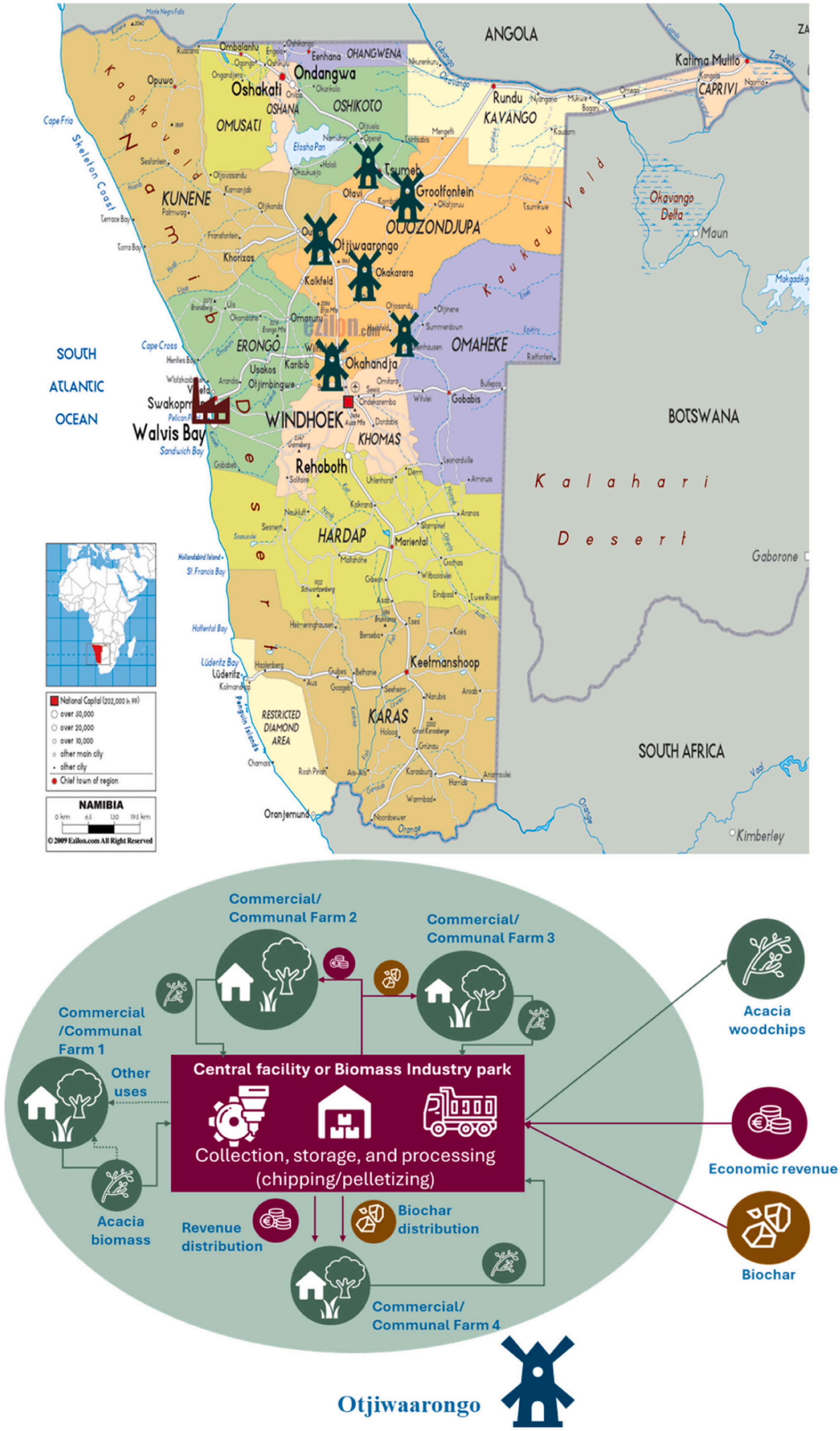

Fig. 7. Biohub configuration in the Otjozondjupa region of Namibia.

Table 7
Biohub design configuration details at different stages of biohub in Spain, Colombia, and Namibia.

	Case-study locations		
Biohub stages	Spain	Colombia	Namibia
Feedstock	Olive tree pruning	Coffee Pulp	*Acacia Mellifera*
Harvesting and transport from the farm to the pre-processing facility	Farmers bring pruned biomass to their associated primary mills using their existing infrastructure and get paid at the gate.	Farmers bring coffee cherries to a centralised processing facility (possibly owned by a cooperative or association)	Farmers use suitable and dedicated harvesting techniques. Trailers and Trucks are used to transport the raw feedstock.
Pre-processing facility location	Primary mills will act as a processing facility, within a 10 km distance from olive farms	Coffee pulp will be generated in a new centralised coffee processing facility. One per region in the Department.	One new pre-processing facility in major cities with considerable population density, within a 100 km radius.
Transportation selection from pre-processing facility to the HTL Facility	Wood chips are transported in 16–32-ton trucks with an average distance of 45 km.	Coffee pulp is transported in 7.5–16-ton trucks with a refrigeration system, with an average distance of about 75 km.	Wood chips are transported in a freight train over a distance of 450 km.
HTL Location	Ubeda	Pereira	At the refinery site in Walvis Bay
HTL biocrude transportation to an upgrading facility	Biocrude is transported via Liquid tanker trucks over a distance of about 320 km.	Biocrude is transported via Liquid tanker trucks over a distance of 380 km.	HTL and Upgrading at the same site
Upgrading Location	Compañía Española de Petróleos, Sociedad Anónima (CEPSA) San Roque refinery	Sebastopol refinery	Joedilla Refinery
Marine biofuel (MBF) transport	MBF is transported via an existing pipeline over a distance of 15 km.	MBF is transported via a yet-to-be-constructed pipeline over a distance of 100 km.	MBF is transported via a yet-to-be-constructed pipeline over a distance of 20 km.
End-use Location	Port of Gibraltar	Puerto Berrío	Port of Walvis Bay

absent in fossil counterpart, leads to increase in water consumption. The Spanish and Namibian biofuels also performed relatively poorly in the impact category of mineral resource scarcity and ecotoxicity (freshwater and marine) due to the consumption of inorganic catalysts during the HTL phase. Finally, the Spanish scenario also causes freshwater ecotoxicity that can be attributed to the additional fertiliser consumption due to the utilisation of pruning biomass, which would otherwise generate ash on burning, which acts as organic fertiliser.

The stagewise GWP or GHG emissions contribution toward the final product is shown in Fig. 8. For the Spanish scenario, HTL catalysts (KOH) consumption contributes majorly to GHG emissions, accounting for 50%. In the Colombian context, with -130 g-CO_2 eq/ $MJ_{\text{drop-in biofuel}}$, the avoided emissions from decomposition and soil pollution, in form of methane, due to open-field conventional disposal of coffee pulp significantly reduced the overall GWP of the coffee-pulp-based HTL biofuel. Finally, in Namibia, based on system expansion, the increased CO_2 uptake due to the restoration of savannah grasses and the excess electricity from biochar valorisation, sold to the grid, reduced the GHG

Table 8
Technical performance indicators for the “drop-in” marine biofuel production.

	Case-study location		
Technical Parameters (unit)	Spain	Colombia	Namibia
Overall biofuel production Process			
Feedstock processing capacity (in DTPD)	1265	211	692
% of total regional feedstock processed in a year	50%	100%	2.5%
Drop-in marine biofuel output (in ktpa)	58.11	5.58	17.06
HTL conversion			
Liquefaction catalyst	KOH	–	Na_2CO_3
Biomass to biocrude yield (kg/kg DM)	0.38	0.27	0.33
Biocrude quality			
HHV (in MJ/kg)	43.05	41.32	39.45
LHV (in MJ/kg)	39.81	38.08	36.43
Water content (in wt%)	2.5	3.4	2.6
Natural gas consumption (kg/kg DM)	0	0	0
Water consumption (kg/kg DM)	3.09	8.29	3.09
Electricity utilisation (kWh/kg DM)	0.06 (HTL)/ 0.09 (Upgrading)	0.14 (HTL)/ 0.11 (Upgrading)	0.06 (HTL)/ 0.09 (Upgrading)
Excess Electricity (kWh/kg DM)	0.04	0.23	0.20
Waste streams			
Off-gas (kg/kg DM)	1.52	2.87	1.31
Liquids (wastewater) (kg/kg DM)	2.66	6.11	2.62
Solids (ash) (kg/kg DM)	0.00	0.1	0.04
Internal Heat Use (MJ/MJ biofuel)	0.02	0.99	0.26
Carbon yield (in %)	68.04	50.38	67.52
Process energy efficiency (in %)	77	68	77
Hydrotreatment			
Green Hydrogen demand (kg/kg DM)	0.02	0.01	0.01
Biocrude to upgraded bio-oil yield	0.94	0.81	0.91
Fractionation			
upgraded bio-oil to “Drop-in” marine biofuel yield	0.36	0.37	0.25
“Drop-in” marine biofuel to biomass yield (kg/kg DM)	0.14	0.08	0.07
Light Naphtha to biomass yield (kg/kg DM)	0.06	0.03	0.11
Biojet to biomass yield (kg/kg DM)	0.14	0.10	0.10
Drop-in marine biofuel quality			
HHV (in MJ/kg)	43.03	43.05	37.68
LHV (in MJ/kg)	39.66	39.9	34.96
Water content (in wt%)	1.9%	0	0

Table 9
Economic performance of the marine biofuel production in the case study locations.

	Case-study locations		
Economic Parameter	Spain	Colombia	Namibia
Capital costs			
Total Purchased equipment costs (TPEC) (in million Euros), includes (contribution%)	93.0	42.5	59.5
Feedstock pretreatment	5.9 (6.3%)	0	3.5 (5.9%)
HTL reactor system	82.1 (88.3%)	39.3 (92.5%)	52.1 (87.6%)
Cogeneration plant	5.0 (5.4%)	3.2 (7.5%)	3.9 (6.6%)
Total Installed costs (TIC) (in million Euros)	139.5	63.8	89.3
Indirect costs (in million Euros)	79.1	36.1	50.6
Fixed capital investment (FCI) (in million Euros)	379.6	173.5	243.0
Total capital investment (TCI) (in million Euros)	442.2	192.9	275.8
Location-adjusted TCI (in million Euros)	398.0	154.3	331.0
Operating costs (in million Euros per year) includes			
Variable operating costs (in million Euros per year)	71.2	7.2	26.3
Of which, Feedstock	45.1	3.6	16.3
Of which, Water	0.1	0.05	0.2
Of which, Hydrogen	0.03	0.003	0.005
Of which, Liquefaction Catalyst	14.9	–	3.61
Of which, Hydrotreatment Catalyst	6.4	0.7	2.85
Of which, Wastewater treatment	0.7	0.3	0.2
Of which, Gas cleaning	3.8	1.2	1.8
Of which, Ash disposal	0.13	0.98	1.35
Of which, Biocrude Transportation	16.87	0.34	0
Capital depreciation	55.0	42.6	82.1
Total Annual Operating Costs (in million Euros per year)	224.1	73.5	162.7
Biocrude Production costs, EUR/ton$_{biocrude}$	1260.2	3911.3	2136.4
Upgrading costs of biocrude to biooil, EUR/ton$_{biooil}$	125.0	920.8	225
Total production costs of upgraded biooil, expressed as EUR/ton$_{product\ mix}$	1385.2	4832.1	2361.4
Annual Sales Revenue (in million Euros per year)	123.7	10.3	43.0
Of which, marine biofuel	51.7	4.5	13.6
Of which, biochar	0	0	0
Of which, electricity	0	0.01	0.01
Of which, naphtha	15.8	1.06	14.68
Of which, biojet	56.1	4.79	14.6
MFSP of MBF (in EUR/ton)	940.4	4447.1	1935.9
MBF MFSP: MGO ratio	1.05	5.54	2.4

Table 10
Environmental impacts of "drop-in" marine biofuels.

		Spain	Colombia	Namibia	Fossil MGO
Impact category	Unit	per MJ	per MJ	per MJ	Per MJ
Global warming	kg CO_2 eq	1.09E-02	−4.34E-02	−7.24E-03	1.05E-01
Stratospheric ozone depletion	kg CFC11 eq	7.37E-09	1.12E-08	5.57E-09	4.38E-08
Ionizing radiation	kBq Co-60 eq	1.35E-03	3.49E-05	−3.36E-05	1.59E-03
Ozone formation, Human health	kg NO_x eq	−3.01E-04	3.52E-05	5.14E-05	2.47E-04
Fine particulate matter formation	kg $PM_{2.5}$ eq	−1.06E-05	2.99E-05	1.04E-05	3.82E-04
Ozone formation, Terrestrial ecosystems	kg NO_x eq	1.44E-03	6.10E-04	1.81E-03	2.54E-04
Terrestrial acidification	kg SO_2 eq	−3.78E-05	3.04E-05	−1.53E-05	1.15E-03
Freshwater eutrophication	kg P eq	4.70E-06	2.97E-07	−7.05E-06	1.78E-06
Marine eutrophication	kg N eq	2.57E-06	2.07E-06	2.05E-06	1.43E-07
Terrestrial ecotoxicity	kg 1,4-DCB	6.47E-02	4.71E-02	1.21E-01	4.52E-01
Freshwater ecotoxicity	kg 1,4-DCB	7.83E-04	1.66E-04	9.00E-04	2.72E-04
Marine ecotoxicity	kg 1,4-DCB	1.00E-03	2.35E-04	1.16E-03	7.01E-04
Human carcinogenic toxicity	kg 1,4-DCB	3.32E-04	1.05E-04	−4.35E-04	6.82E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	−5.25E-01	8.95E-03	1.39E-02	1.51E-02
Land use	m^2a crop eq	3.39E-03	4.43E-04	2.42E-02	2.35E-04
Mineral resource scarcity	kg Cu eq	9.42E-05	2.71E-05	1.94E-04	4.14E-05
Fossil resource scarcity	kg oil eq	2.37E-03	9.63E-05	−2.40E-03	5.86E-02
Water consumption	m^3	1.36E-03	6.59E-04	1.26E-03	1.07E-05

environmental footprint of acacia-based HTL marine biofuel with an impact of −69.55 g-CO_2 eq/ $MJ_{\text{drop-in biofuel}}$.

3.4. Sensitivity analysis

Fig. 9 shows the sensitivity analysis of the MFSP of HTL biofuels. A sensitivity analysis is performed to understand the effect of some key parametric indicators on the MFSP of marine biofuel, as mentioned in section 2.3.5. Process yield is chosen as parameter for analysing uncertainties for the assumptions made while using experimental data for process simulations. As illustrated in, the MFSP is more sensitive to the HTL process yield. Process yield can be either improved by changing or optimizing the choice of (non-expensive) HTL catalyst (such as NaOH, Ca (OH)2), catalyst loading, processing conditions, and reactor design (such as continuous mode etc.) or reduced due to losses during scale up and specific feedstock type. With other parameters as a constant, a reduction of process yields by 50% leads to almost 100% increase in the MFSP of HTL biofuels across all the scenarios. Similarly, the MFSP is

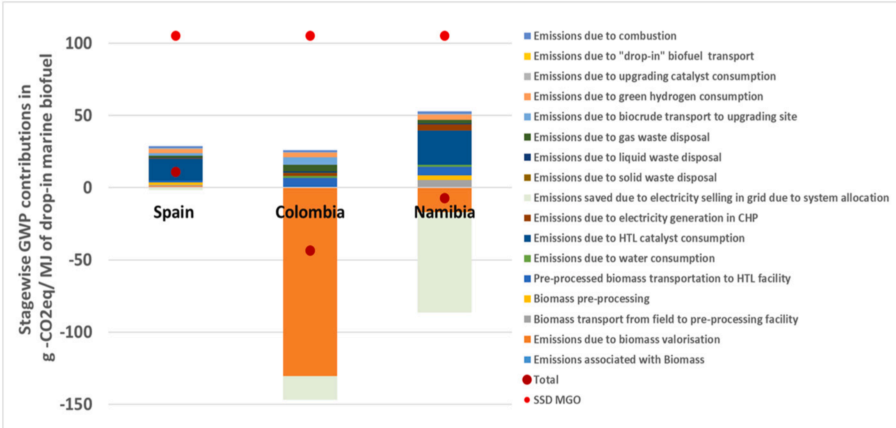

Fig. 8. Stagewise GWP contributions in g-CO_2 eq/MJ of drop-in marine biofuel.

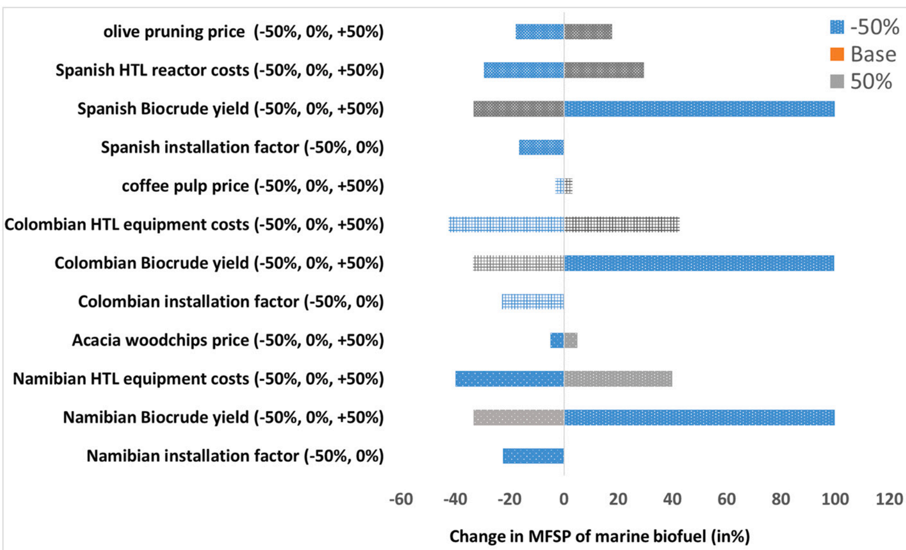

Fig. 9. Sensitivity analysis of the MFSP of HTL "drop-in" biofuels. Grey (increase of parametric value from the base case by 50%), Blue (decrease of parametric value from the base case by 50%). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sensitive to changes in equipment costs than feedstock price. Thus, a 50% change in HTL equipment costs has a proportionate effect of 29%, 43%, and 40% in the Spain, Colombia, and Namibia scenarios, respectively, due to operations and maintenance. Similar changes in feedstock price led to a direct change of only 18%, 3%, and 5% for olive pruning-based, coffee pulp-based, and acacia-based biohubs. To address the higher HHV of biocrudes obtained via modelling, compared to experimental values, a sensitivity analysis was performed (for scenario with lower HHV that requires more hydrogen for upgrading) by increasing the amount of hydrogen required to upgrade the HTL biocrudes to 10 times the base scenario. However, the MFSP of Spanish, Colombian, and Namibian MBF changed only by 0.2%, 0.03%, and 0.04% respectively. With an increase in scale, the sensitivity of MFSP toward equipment and feedstock costs is found to narrow down, but the former predominantly dominates at smaller scales. This could be attributed to the need for a high-pressure reactor system and a low TRL level of HTL, impacting the capital costs at smaller scales. This trend also indicates the potential for the reduction in MFSP when the facilities are scaled up to a commercial scale (with a processing capacity of 2000 DTPD). At the designed capacities, except for the Spanish scenario, with a 50% reduction in HTL equipment costs, the MFSP of marine biofuel is still significantly higher than that of its fossil counterpart. In terms of biocrude yield, if it can be increased by +50% due to process improvements such as catalysts or process optimisation, the MFSP of biofuels in all the case studies can be reduced by 33%. Likewise, the reduction in the installation factor by +50%, to account for uncertainty, led to a reduction of MFSP of the marine biofuels by 16%, 22%, and 22% in Spain, Colombia, and Namibia, respectively.

4. Conclusion and recommendations

This "first-of-a-kind" study conceptually co-designed agrarian biohubs for HTL-based "drop-in" marine biofuel production utilising field biomass residues in the form of olive pruning, coffee pulp, and encroacher bush in Spain, Colombia, and Namibia, respectively, using capability-sensitive design. The early-stage inclusion of potential stakeholders and a novel bottom-up co-design approach identified opportunities and showstoppers for implementing bio-based value chains during the conceptual phase. However, stakeholders' perspective on the final results for validation has not been carried out and is highly recommended in the future. The detailed process simulation indicated that the choice of biomass feedstock directly impacts the final biofuel distribution (Naphtha/bio-jet/biodiesel) of the product mix obtained through the HTL process. For the designed scenarios, without consideration of carbon credits, the alternative marine biofuels were expensive (1.05–5.5×) than their fossil counterparts. Therefore, a more detailed investigation on the impact of carbon credits on the economic performance of the biohubs is recommended in the future. The biofuels had significant positive environmental GWP impacts, with a potential reduction of at least 89% GHG emissions in comparison to fossils. The MFSP of the biofuels was found to be more sensitive to the HTL process yields, equipment costs, thereby indicating the potential for improvement in economic performance upon scale-up and technological advances due to process optimisation or mass/heat integration.

Future research should focus on the technical viability of the HTL process to valorise multiple diverse feedstocks simultaneously to benefit from economies of scale in the region with high biomass availability, with varied nature of feedstocks, such as in an agroforestry system. The proposed biohubs should also be investigated using other biochemical conversion techniques for producing fine or speciality chemicals, which could improve the feasibility in regions like Colombia. The current investigation should further be supported with a macro-socioeconomic assessment and a multi-criteria decision analysis based on the context-specific selection and weightage of performance indicators to evaluate the trade-offs of the decision-making process during the design phase. Based on environmental performance, the impact of carbon credits, the incorporation of renewable energy systems such as solar or wind-based electricity, and the technical viability of biochar as a soil amendment need to be further explored to improve the sustainability of the biohubs. If proven, the use of biochar for soil amendment can bring local social benefits and improve soil health, thereby more detailed analysis on the best use of HTL byproducts is recommended for improving the socio-economic footprint of biohubs. Overall, sustainably and inclusively designed biohubs have the potential to offer opportunities beyond climate change mitigation by improving the existing agro-systems and strengthening the rural economies.

CRediT authorship contribution statement

Sivaramakrishnan Chandrasekaran: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patricia Osseweijer:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **John Posada:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors of this manuscript declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cej.2026.173069.

Data availability

Shared the data repository link

Agrarian Biohubs for drop-in marine biofuels: A techno-economic and environmental assessment for Spain, Colombia, and Namibia using field residues (Original data) (4TU research data)

References

[1] International Energy Agency, Renewables 2024 [Online]. Available: www.iea.org, 2024.
[2] C.-W.C. Hsieh, C. Felby, Biofuels for the Marine Shipping Sector Biofuels for the Marine Shipping Sector an Overview and Analysis of Sector Infrastructure, Fuel Technologies and Regulations, 2017.
[3] S. Nasso, B. Sweazey, Bio-hubs as keys to successful biomass supply for the bioeconomy report from joint IEA bioenergy task 43 and Natural Resources Canada workshop held in Ottawa, IEA Bioenergy 1 (2020) 1–30.
[4] M. Valipour, et al., Integrating bio-hubs in biomass supply chains: Insights from a systematic literature review, Aug. 15, Elsevier Ltd. (2024), https://doi.org/10.1016/j.jclepro.2024.142930.
[5] P. Pradhan, M. Akbari, R.M. Sebastian, A. Dwivedi, A. Kumar, Development of Techno-Economic Model for Assessment of Bio-Hubs in Canada Final Report, Edmonton, May 2022.
[6] Dr.M.D. Berry, A case study addressing the economic and operational feasibility of establishing Biohubs in the Private Native Forests of SouthEast Queensland 1 (2022) 1–9.
[7] K. Lan, et al., Techno-economic analysis of decentralized preprocessing systems for fast pyrolysis biorefineries with blended feedstocks in the southeastern United States, Renew. Sust. Energ. Rev. 143 (2021), https://doi.org/10.1016/j.rser.2021.110881.
[8] A. Rai, R. Monaghan, Environmental Sustainability Studies of Biohub Archetypes, Jan. 2024.
[9] K. Lan, L. Ou, S. Park, S.S. Kelley, Y. Yao, Life cycle analysis of decentralized preprocessing Systems for Fast Pyrolysis Biorefineries with blended feedstocks in the southeastern United States, Energ. Technol. 8 (11) (2020), https://doi.org/10.1002/ente.201900850.
[10] P. Rafiaani, T. Kuppens, M. Van Dael, H. Azadi, P. Lebailly, S. Van Passel, Social sustainability assessments in the biobased economy: Towards a systemic approach, Elsevier Ltd. (Feb. 01, 2018), https://doi.org/10.1016/j.rser.2017.06.118.
[11] M.P. Parada, L. Asveld, P. Osseweijer, J.A. Posada, Setting the design space of biorefineries through sustainability values, a practical approach, Biofuels Bioprod. Biorefin. 12 (1) (2018) 29–44, https://doi.org/10.1002/bbb.1819.
[12] M. Palmeros Parada, P. Osseweijer, J.A. Posada Duque, Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design, Ind. Crop. Prod. 106 (2017) 105–123, https://doi.org/10.1016/j.indcrop.2016.08.052.
[13] S. van der Veen, L. Asveld, P. Osseweijer, Designing bio-based value chains for social justice: the potential of capability sensitive design, Energy Res. Soc. Sci. 117 (2024), https://doi.org/10.1016/j.erss.2024.103724.
[14] J.M. Romero-García, J.C. López-Linares, M. del M. Contreras, I. Romero, E. Castro, Exploitation of olive tree pruning biomass through hydrothermal pretreatments, Ind. Crop. Prod. 176 (2022), https://doi.org/10.1016/j.indcrop.2021.114425.
[15] A. Duarte, J.C. Uribe, W. Sarache, A. Calderón, Economic, environmental, and social assessment of bioethanol production using multiple coffee crop residues, Energy 216 (2021), https://doi.org/10.1016/j.energy.2020.119170.
[16] D. Yang, Special features 22 Food Outlook [Online]. Available: https://openknowledge.fao.org/handle/20.500.14283/cc1154en, 2024.
[17] C.R.R. Pleguezuelo, V.H.D. Zuazo, J.R.F. Martínez, F.J.M. Peinado, F.M. Martín, I.F.G. Tejero, Organic olive farming in Andalusia, Spain. A review, Springer-Verlag France. (Apr. 01, 2018), https://doi.org/10.1007/s13593-018-0498-2.
[18] L. Fernández-Lobato, B. Ruiz-Carrasco, M. Tostado-Véliz, F. Jurado, D. Vera, Environmental impact of the most representative Spanish olive oil farming systems: a life cycle assessment study, J. Clean. Prod. 442 (2024), https://doi.org/10.1016/j.jclepro.2024.141169.
[19] J. Berbel, A. Posadillo, Review and analysis of alternatives for the valorisation of agro-industrial olive oil by-products, MDPI (Jan. 17, 2018), https://doi.org/10.3390/su10010237.
[20] J.F. García Martín, M. Cuevas, C.H. Feng, P.Á. Mateos, M.T. García, S. Sánchez, Energetic valorisation of olive biomass: Olive-tree pruning, olive stones and pomaces, MDPI AG. (May 01, 2020), https://doi.org/10.3390/PR8050511.
[21] J. Martín-García, J.A. Gómez-Limón, M. Arriaza, Conventional versus organic olive farming: which has a better economic performance? Agric. Food Econ. 11 (1) (2023) https://doi.org/10.1186/s40100-023-00292-5.
[22] M. del M. Contreras, I. Romero, M. Moya, E. Castro, Olive-derived biomass as a renewable source of value-added products, *Elsevier Ltd.*, Oct. 01, 2020, https://doi.org/10.1016/j.procbio.2020.06.013.
[23] E. Ruiz, J.M. Romero-García, I. Romero, P. Manzanares, M.J. Negro, E. Castro, Olive-derived biomass as a source of energy and chemicals, John Wiley and Sons Ltd. (Nov. 01, 2017), https://doi.org/10.1002/bbb.1812.
[24] S. Fanourakis, J.M. Romero-García, E. Castro, L. Jiménez-Esteller, Á. Galán-Martín, Economic and environmental implications of carbon capture in an olive pruning tree biomass biorefinery, J. Clean. Prod. 456 (2024), https://doi.org/10.1016/j.jclepro.2024.142361.

[25] FNC, Coffee Statistics, Accessed: Mar. 02. [Online]. Available: https://federaciondecafeteros.org/wp/coffee-statistics/?lang=en, 2024.
[26] Lady Gomez, Coffee Annual, Bogota, May 2024.
[27] FEDECAFE, Coffee Statistics. https://federaciondecafeteros.org/wp/coffee-statistics/?lang=en, 2023.
[28] K. Rubio-Jovel, Coffee production networks in Costa Rica and Colombia: a systems analysis on voluntary sustainability standards and impacts at the local level, J. Clean. Prod. 445 (2024), https://doi.org/10.1016/j.jclepro.2024.141196.
[29] S. Garcia-Freites, M. Röder, P. Thornley, Environmental trade-offs associated with bioenergy from Agri-residues in sub-tropical regions: a case study of the Colombian coffee sector, Biomass Bioenergy 140 (2020), https://doi.org/10.1016/j.biombioe.2020.105581.
[30] J.A. Gil-Gómez, L.M. Florez-Pardo, Y.C. Leguizamón-Vargas, Valorization of coffee by-products in the industry, a vision towards circular economy, Springer Nature. (Sep. 01, 2024), https://doi.org/10.1007/s42452-024-06085-9.
[31] A. Wronka, G. Kowaluk, The Use of Biomass in Colombia Based on Experience from CELISE Project Secondment the Coffee Case, 2024.
[32] A. Schick, P.L. Ibisch, Namibian 'Bush Encroachment' in Context: An Ecological Perspective on Current and Future Dryland Greening, its Causes and Consequences, Apr. 2021.
[33] F. Flesch, G. Ohlde, N. Senanayake, M. Monschin, K. Wilhelm, Road Map to a Biomass Industrial Park Biomass Partnership with Namibia [Online]. Available: www.stoffstrom.org, Jun. 2021.
[34] C. Birch, A. Middleton, L. Harper-Simmonds, P. Lindeque, Benefits of bush control in Namibia. A national economic study for Namibia and a case for the Otjozondjupa region, Report for the Economics of Land Degradation Initiative 1 (2016) 1–52 [Online]. Available: www.eld-initiative.orgwww.eld-initiave.org.
[35] REPUBLIC OF NAMIBIA, Strategy for the Transformation of the Agri-Food Sector, 2025.
[36] MEFT, National Strategy on the Sustainable Management of Bush Resources 2022-2027 2 National Strategy on the Sustainable Management of Bush Resources, 2022.
[37] NAMIBIA CHARCOAL ASSOCIATION, Charcoal_Factsheet, Jul. 2018.
[38] T. A. I. MINISTRY OF HIGHER EDUCATION, The Namibia Sustainable BIOECONOMY Strategy, Windhoek, Jun. 2024.
[39] B. Mingeli, J. Mukena, PROJECT FACT SHEET 40MW OTJIKOTO BIOMASS POWER STATION, May 2024.
[40] UNIDO, Strategic Action Plan for Sustainable Bush Value Chains in Namibia Funded By [Online]. Available: www.unido.org, 2019 www.adobestock.com.
[41] S.E. Tanzer, J. Posada, S. Geraedts, A. Ramírez, Lignocellulosic marine biofuel: Technoeconomic and environmental assessment for production in Brazil and Sweden, J. Clean. Prod. 239 (2019), https://doi.org/10.1016/j.jclepro.2019.117845.
[42] L. Nazari, Z. Yuan, S. Souzanchi, M.B. Ray, C. Xu, Hydrothermal liquefaction of woody biomass in hot-compressed water: catalyst screening and comprehensive characterization of bio-crude oils, Fuel 162 (2015) 74–83, https://doi.org/10.1016/j.fuel.2015.08.055.
[43] T. Minowa, T. Kondo, S.T. Sudirjo6, Thermochemical liquefaction of INDONESIAN biomass residues, Biomass Bioenergy 14 (1997) 517–524, https://doi.org/10.1016/S0961-9534(98)00006-3.
[44] J. Remón, F. Ravaglio-Pasquini, L. Pedraza-Segura, P. Arcelus-Arrillaga, I. Suelves, J.L. Pinilla, Caffeinating the biofuels market: effect of the processing conditions during the production of biofuels and high-value chemicals by hydrothermal treatment of residual coffee pulp, J. Clean. Prod. 302 (2021), https://doi.org/10.1016/j.jclepro.2021.127008.
[45] S. Misar, Drop-in Biofuels from Olive Residues Towards Sustainable Biofuels in the Maritime Sector a Case Study in Spain, Delft University of Technology, Delft, 2022. Accessed: Oct. 01, 2022. [Online]. Available: https://repository.tudelft.nl/record/uuid:33d6c94c-3c6f-48a3-9952-1b709fceec82.
[46] K. Albrecht, et al., Final Report for the Project Characterization and Valorization of Aqueous Phases Derived from Liquefaction and Upgrading of Bio-Oils, Jul. 2018.
[47] S. van Dyk, J. Su, J.D. Mcmillan, J. (John) Saddler, Potential synergies of drop-in biofuel production with further co-processing at oil refineries, John Wiley and Sons Ltd. (2019), https://doi.org/10.1002/bbb.1974.
[48] C. Hank, M. Holst, C. Thelen, Site-Specific, Comparative Analysis for suitable Power-to-X pathways and Products in Developing and Emerging Countries [Online]. Available: https://www.researchgate.net/publication/372952190, 2023.
[49] T.H. Pedersen, C.U. Jensen, L. Sandström, L.A. Rosendahl, Full characterization of compounds obtained from fractional distillation and upgrading of a HTL biocrude, Appl. Energy 202 (2017) 408–419, https://doi.org/10.1016/j.apenergy.2017.05.167.
[50] I. Tews, et al., Biomass Direct Liquefaction Options: TechnoEconomic and Life Cycle Assessment, Jul. 2014.
[51] K.F. Tzanetis, J.A. Posada, A. Ramirez, Analysis of biomass hydrothermal liquefaction and biocrude-oil upgrading for renewable jet fuel production: the impact of reaction conditions on production costs and GHG emissions performance, Renew. Energy 113 (2017) 1388–1398, https://doi.org/10.1016/j.renene.2017.06.104.
[52] U.S. Intratec, Plant Location Factors, Accessed: Jun. 06. [Online]. Available: https://www.intratec.us/products/industry-economics-worldwide/plant-location-factor/united-states-plant-location-factor, 2023.
[53] W.D. Seider, D.R. Lewin, J.D. Seader, S. Widagdo, R. Gani, K.M. Ng, Product and Process Design Principles - Synthesis, Analysis, and Evaluation (4th Edition), 4th ed., John Wiley & Sons, 2017.
[54] C.C. da Silva, Techno-Economic and Environmental Analysis of Oil Crop and Forestry Residues Based Integrated Biorefineries in Brazil, PD Engg thesis,, Delft University of Technology, 2016.
[55] V.M. Maestre, A. Ortiz, I. Ortiz, Decarbonizing the Spanish transportation sector by 2050: design and techno-economic assessment of the hydrogen generation and supply chain, Int. J. Hydrog. Energy 48 (99) (2023) 39514–39530, https://doi.org/10.1016/j.ijhydene.2023.05.154.
[56] D. Franzmann, et al., Green hydrogen cost-potentials for global trade, Int. J. Hydrog. Energy 48 (85) (2023) 33062–33076, https://doi.org/10.1016/j.ijhydene.2023.05.012.
[57] Colombia Natural Gas Prices, Accessed Dec. 13 (2023) [Online]. Available: https://www.globalpetrolprices.com/Colombia/natural_gas_prices/.
[58] P. Martinez, M. Blanco, Sensitivity of agricultural development to water-related drivers: the case of Andalusia (Spain), Water (Switzerland) 11 (9) (2019), https://doi.org/10.3390/w11091854.
[59] A. Nehemia, Namwater Corporation Limited: Bulk Water Supply Tariffs Determined in Terms of the Namibia Water, Windhoek. Accessed: Feb. 13, 2025. [Online]. Available: https://www.lac.org.na/laws/2012/5025.pdf, Aug. 2012.
[60] Statista, Average Monthly Electricity Wholesale Price in Spain, Accessed: Jul. 01. [Online]. Available: https://www.statista.com/statistics/1267552/spain-monthly-wholesale-electricity-price/, 2023.
[61] Colombian Energy Prices, Accessed: Jan. 27,. [Online]. Available: https://www.globalpetrolprices.com/Colombia/electricity_prices/, 2024.
[62] Namibia Fuel Prices, Electricity Prices, Accessed: Jan. 21. [Online]. Available: https://www.globalpetrolprices.com/Namibia/, 2024.
[63] G.D. Ulrich, T. Vasudevan Palligarnai, How to Estimate Utility Costs [Online]. Available: www.mueller-gmbh.com, 2006.
[64] Spain Long Term Interest Rate, Accessed: Feb. 20. [Online]. Available: https://ycharts.com/indicators/spain_long_term_interest_rates#:~:text=Spain%20Long%20Term%20Interest%20Rate%20is%20at%203.23%25%2C%20compared%20to,or%20close%20to%2010%20years, 2024.
[65] Colombia Long term Interest Rate, Accessed: Mar. 01. [Online]. Available: https://www.investing.com/economic-calendar/colombian-interest-rate-decision-497, 2025.
[66] Namibia Interest Rate, Accessed: Mar. 15. [Online]. Available: https://www.focus-economics.com/country-indicator/namibia/interest-rate/#:~:text=Policy%20Interest%20Rate%20in%20Namibia,information%2C%20visit%20our%20dedicated%20page, 2024.
[67] ISO, ISO 14040:2006 Environmental Management — Life Cycle Assessment — Principles and Framework, 2006.
[68] ISO, ISO 14044:2006 Environmental Management — Life Cycle Assessment — Requirements and Guidelines, 2006.
[69] Y. Nie, X. Bi, Life-cycle assessment of transportation biofuels from hydrothermal liquefaction of forest residues in British Columbia, Biotechnol. Biofuels 11 (1) (Feb. 2018), https://doi.org/10.1186/s13068-018-1019-x.
[70] E.V. Taguas, et al., Opportunities of super high-density olive orchard to improve soil quality: management guidelines for application of pruning residues, J. Environ. Manag. 293 (2021), https://doi.org/10.1016/j.jenvman.2021.112785.
[71] B. Comer, L. Osipova, Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies 1, Blackwell Publishing Ltd, 2021, pp. 1–12. COI:20.500.12592/wftjdj.
[72] IMO, Fourth IMO GHG Study 2020 Full Report, 2021.
[73] S. Chandrasekaran, A.M. Vidal, E. Castro, P. Osseweijer, J. Posada, Techno-economic feasibility of olive residue-based biohubs for marine biofuel production: a capability-sensitive and context-specific approach in the Mediterranean region, Energy Conversion and Management: X 26 (2025), https://doi.org/10.1016/j.ecmx.2025.101038.
[74] R. Bao, et al., A Review of Hydrothermal Biomass Liquefaction: Operating Parameters, Reaction Mechanism, and Bio-Oil Yields and Compositions, Am. Chem. Soc. (May 16, 2024), https://doi.org/10.1021/acs.energyfuels.4c00240.
[75] Y. Zhu, et al., Microalgae Hydrothermal Liquefaction and Biocrude Upgrading: 2022 State of Technology [Online]. Available: https://www.ntis.gov/about, 2023.
[76] L. Snowden-Swan, et al., Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2022 State of Technology [Online]. Available: https://www.ntis.gov/about, 2022.
[77] Y. Nie, X.T. Bi, Techno-economic assessment of transportation biofuels from hydrothermal liquefaction of forest residues in British Columbia, Energy 153 (2018) 464–475, https://doi.org/10.1016/j.energy.2018.04.057.
[78] Business Insider, Oil (Brent) Price, Accessed: Jan. 16. [Online]. Available: https://markets.businessinsider.com/commodities/oil-price, 2024.
[79] K.F. Tzanetis, J.A. Posada, A. Ramirez, Analysis of biomass hydrothermal liquefaction and biocrude-oil upgrading for renewable jet fuel production: the impact of reaction conditions on production costs and GHG emissions performance, Renew. Energy 113 (2017) 1388–1398, https://doi.org/10.1016/j.renene.2017.06.104.
[80] E.M. Lozano, S. Løkke, L.A. Rosendahl, T.H. Pedersen, Production of marine biofuels from hydrothermal liquefaction of sewage sludge. Preliminary techno-

economic analysis and life-cycle GHG emissions assessment of Dutch case study, Energy Convers. Manag. X, vol. 14 (2022), https://doi.org/10.1016/j.ecmx.2022.100178.

[81] Y. Zhu, et al., Microalgae Conversion to Biofuels and Biochemical via Sequential Hydrothermal Liquefaction (SEQHTL) and Bioprocessing: 2020 State of Technology [Online]. Available: https://www.ntis.gov/about, 2021.

[82] S. Li, Y. Jiang, L.J. Snowden-Swan, J.A. Askander, A.J. Schmidt, J.M. Billing, Techno-economic uncertainty analysis of wet waste-to-biocrude via hydrothermal liquefaction, Appl. Energy 283 (2021), https://doi.org/10.1016/j.apenergy.2020.116340.

[83] Z. Sa, T. Rahardjo, C. Valkenburg, L.J. Snowden-Swan, S.B. Jones, M.A. Machinal, Techno-Economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels, 2011.

[84] E.M. Lozano, S. Løkke, L.A. Rosendahl, T.H. Pedersen, Production of marine biofuels from hydrothermal liquefaction of sewage sludge. Preliminary techno-economic analysis and life-cycle GHG emissions assessment of Dutch case study, Energy Convers. Manag. X, vol. 14 (2022), https://doi.org/10.1016/j.ecmx.2022.100178.