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Carbon-negative products to engage society in climate action: The life cycle of olive oil

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ABSTRACT

Achieving carbon neutrality and addressing the need for ongoing carbon dioxide removal to meet the climate goal requires an urgent shift towards sustainable production and consumption practices. In this context, we turn our attention to the olive oil industry, a key food industry that strives towards more environmentally sustainable initiatives. Our study explores a novel approach that integrates bioenergy with carbon capture and storage (BECCS) into olive oil production. Employing Life Cycle Assessment, we assess the potential for carbon-negative olive oil production and its broader environmental implications. Our findings demonstrate that producing carbon-negative virgin olive oil is possible by powering the olive mill processes with BECCS based on olive prunings generated at the agricultural stage (up to −0.32 kg CO_2eq per 1-l bottle of virgin olive oil). However, collateral damages to acidification and eutrophication will also emerge, which can be mitigated through careful project planning tailored to local conditions. The path forward involves strategic investments, customized policies, collaboration between public and private sectors, and consumers' willingness to support carbon offset projects. Our work may contribute to unlocking the full potential of BECCS, offering a blueprint for other industries beyond the realm of olive oil production, ultimately catalyzing the realization of carbon-negative products.

1. Introduction

Advancing the Sustainable Development Goals (SDGs) requires an urgent shift towards more sustainable production and consumption patterns (UN, 2015). Focusing on climate action (SDG 13), there is a necessity to accelerate emission reductions to reach carbon neutrality by the midcentury and go net-negative afterward. This means that we need to remove the excess CO_2 from the atmosphere to avoid overshooting the temperature goal outlined in the Paris Agreement (IPCC, 2022). The amount of carbon dioxide removal (CDR) required is uncertain but ranges from 260 to 1030 Gt CO_2 (for median 5th–95th percentile) which poses a great challenge ahead (Masson-Delmotte, 2018).

Different methods have been proposed to support this unavoidable CDR ambition (Minx et al., 2017, 2018). The CDR options available include increasing natural carbon sinks and deploying technological solutions. The former refers to natural-based solutions storing the CO_2 in a biological form (vegetation, soils, and aquatic environment), which suffer from non-permanence issues and limited ability to contribute to net zero. The latter refers to engineered technologies mainly involving geological carbon sequestration, i.e., storing CO_2 in underground geologic formations ensuring its permanence out of the atmosphere in the long term, a crucial aspect for effective climate change mitigation.

As of the present day, Bioenergy with Carbon Capture and Storage (BECCS) stands as the preeminent CDR technological solution, garnering significant attention in the scientific community and beyond, as underscored by the Intergovernmental Panel on Climate Change (IPCC, 2023). BECCS hinges upon the utilization of well-established bio-based technologies that have been demonstrated at scale. These technologies facilitate the conversion of biomass resources into valuable and marketable products, such as electricity, heating, and various forms of chemicals and fuels (Bello et al., 2020). The distinctive allure of BECCS lies in the integration of these mature technologies with carbon capture and storage (CCS) systems which enable capturing the biogenic CO_2 through chemical reactions occurring during biomass conversion processes (combustion, fermentation, gasification, etc.). Subsequently, the captured CO_2 is transported and securely sequestered, thus precluding its release back into the atmosphere.

The inherent versatility of this BECCS concept, particularly when

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deployed for energy generation purposes (electricity or for heating applications), endows BECCS with great opportunities for integration into diverse production systems and industries (energy consumers)(Galán-Martín et al., 2022). The integration of BECCS into these operational frameworks allows for potentially generating marketable commodities that can be carbon-neutral or, in certain scenarios, carbon-negative (when negative emissions counterbalance all the positive emissions as evaluated across the entire life cycle of the production system). Such products could be considered premium due to their environmentally sustainable attributes. This distinctive competitive advantage could be a pivotal catalyst in accelerating the widespread adoption of BECCS and align with the imperative need for CDR to combat climate change and ensure a climate-resilient economy (IPCC, 2022).

Although CDR is acknowledged as an inevitable necessity, many barriers still hinder the large-scale deployment of CDR and BECCS (Minx et al., 2018). For instance, CDR is often perceived as something to come and is criticized as it may deter mitigation with future promises to remove the excess CO_2 (Anderson and Peters, 2016; Fuss et al., 2014). Moreover, specific concerns also arise regarding the BECCS alternative, which could exert pressure on the environment due to land-use impacts, water needs, and energy requirements (Fuss et al., 2018a; Jeswani et al., 2022). However, economic viability is perhaps the main obstacle today to the scale-up. Many approaches are being proposed to overcome this issue, such as voluntary payments, financial incentives and subsidies, carbon taxes, new industrial obligations, and developing new or adapting existing trading systems (Honegger et al., 2022; Honegger and Reiner, 2018). Nevertheless, to this day, the CDR and BECCS deployment has been relatively scarce, or at least not at the pace required to achieve the goals (Galán-Martín et al., 2021c).

The urgency of removing thousands of tons of CO_2 through BECCS underscores the importance of strategically leveraging regional resources. To achieve this, it is crucial to actively promote the implementation of innovative BECCS applications and business models across various economic sectors and activities considering the regional particularities and endowments (Tanzer et al., 2021).

As an illustrative and practical case, we here turn our attention to the food sector, specifically the olive oil agro-industry. This case study is appealing for two main reasons. First, it highlights that the principles of BECCS can be applied to enhance the environmental sustainability of food production where consumers play a central role (Lucas et al., 2021). Secondly, the olive oil industry is a key economic activity in many regional economies worldwide that generates substantial biomass throughout its value chain. This abundance of biomass represents a valuable opportunity for its utilization through biorefinery schemes coupled with CCS (BECCS systems). By tapping into this potential, additional revenues could be generated for farmers and industrial actors, while simultaneously facilitating CO_2 removal from the atmosphere (Galán-Martín et al., 2022). In particular, we here examine the olive oil production and focus on the olive tree prunings generated every year at the cultivation stage which are traditionally discarded or used as soil amendments. The article delves into an innovative initiative centered around utilizing pruning residues at the olive mill by integrating BECCS to meet the energy demands of the olive mill facility, potentially even producing surplus electricity as a co-product. The primary objective is to evaluate the potential of BECCS based on olive prunings retrofitted into the traditional production of virgin olive oil (VOO) to produce carbon-negative VOO while examining other environmental consequences. To evaluate the capacity for achieving net negative emissions and to comprehensively assess the environmental synergies and side-effects of carbon negative products we employ the Life Cycle Assessment (LCA) methodology (ISO, 2006a, 2006b). This methodology enables us to quantitatively measure the net greenhouse gas (GHG) emissions balance and other impacts beyond climate change considering all the upstream and downstream activities associated with the value chain. We found that producing carbon-negative VOO can be achieved by powering the olive mill operations with BECCS technology using olive prunings from the agricultural stage. Nevertheless, integrating BECCS may lead to negative impacts related to acidification and eutrophication which should be minimized. Our results have the potential to be extrapolated to other industries that incorporate BECCS as a source of energy for producing carbon-neutral and carbon-negative products to engage society in sustainable climate action. Overall, we argue that embracing innovative approaches that foster carbon-negative products can pave the way for a more sustainable and engage society in sustainable climate action.

2. Literature review

The olive agro-industry and production of olive oil production have been extensively analyzed in the last decade through the LCA methodology (Salomone et al., 2015). LCA is a standardized approach used for evaluating the environmental impacts associated with the complete life cycle of a product system (ISO, 2006a, 2006b). A noteworthy review of LCA studies focused on olive oil production was provided by Espadas-Aldana et al. (Espadas-Aldana et al., 2019), shedding light on the intricate and multifaceted nature of LCA investigations within the olive sector (Abdallah et al., 2022).

Several studies have focused on olive oil production in specific regions, such as Italy (Guarino et al., 2019), Spain (Fernández-Lobato et al., 2021), and Tunisia (Fernández-Lobato et al., 2022), identifying the predominant environmental hotspots associated with the agricultural phase. Other LCA investigations have delved into the diverse applications of co-products and wastes generated by the olive agro-industry. Many studies have also centered their focus on the valorization of olive pomace through various thermochemical processes as it constitutes the primary biomass, by weight, produced during the olive oil extraction process. For example, Cusenza and co-authors performed an environmental assessment of the pyrolysis of olive tree trimmings and olive pomace residues to energy (Cusenza et al., 2021). Ramos et al. conducted an assessment of various valorization techniques applied to olive pomace, including combustion, gasification, hydrothermal carbonization, and pyrolysis, aimed at the production of electricity, biochar, bio-oil, and syngas (Ramos and Ferreira, 2022). Another work considered a biorefinery system that converts the pomace into biodiesel while the glycerol byproduct was valorized into two distinct phosphate salts and triacetin (Khounani et al., 2021). Certain investigations have been dedicated to the treatment of wastewater, a pressing environmental concern in regions engaged in olive production (Chatzisymeon et al., 2013). Hence, a recent study performed the environmental evaluation of the anaerobic digestion of three-phase olive mill wastewater for energy production (Manthos et al., 2023). Other researchers focused on olive oil leaves valorization, shedding light on their potential to obtain antioxidants (Khounani et al., 2021) and other bioactive compounds considering different extraction techniques (Kritsotakis et al., 2022). Similarly, other works explored alternative approaches for managing waste materials, encompassing the manufacture of briquettes and pellets for domestic or industrial heating (Duman et al., 2020) or pyrolysis, and composting (Cusenza et al., 2021; Parascanu et al., 2018). Particularly noteworthy is a previous study that employed LCA to assess the carbon footprint (CF) of extra VOO, suggesting the potential to be carbon-negative products under specific conditions (Proietti et al., 2017). However, this study attributed the carbon stock in trees (excluding fruit contributions but including pruning) to one liter of olive oil. Caution is needed with such biogenic storage because it is subject to permanence issues reverting the process (e.g. fires, pests) and thus less reliable than geological CO_2 sequestration or long-term storage in materials (Tanzer et al., 2021).

Despite the considerable body of literature on the subject, a comprehensive analysis that encompasses the entirety of the VOO production process, including the valorization of olive biomass generated via BECCS is still lacking from the existing research landscape.

3. Methods

In this section, we start by providing a comprehensive explanation of an illustrative olive oil production system, along with its associated value chain. Building on the exemplary VOO production, we will introduce the scenarios that will be assessed in our study. Subsequently, we will introduce the LCA methodology as a fundamental tool to accurately quantify the CDR potential of any production system coupled with BECCS.

3.1. Case study: Virgin olive oil production

The production of VOO involves several steps, from harvesting the olives to extracting the pure olive juice by mechanical procedures. Each stage of the process involves different activities with particular emissions and environmental impacts which should be considered to assess the potential for carbon-negative VOO production.

Olive trees undergo photosynthesis, capturing inorganic CO_2 from the atmosphere which is subsequently sequestered as organic carbon in various parts of the tree, including branches, leaves, olives, and roots. The number of olive trees per hectare can vary depending on several factors (e.g. olive variety, climate, soil conditions, culture practices, etc.) ranging from around 100 trees ha^{-1} in traditional cultivation to 800 trees per hectare high-intensitive. However, most olive tree cultivation is intensive with a common planting density of around 250 trees ha^{-1} (Abdallah et al., 2022).

The cultivation phase may include activities such as soil preparation (e.g. tilling, and amending with organic matter), irrigation to ensure consistent moisture, fertilization to support growth and production, weed and pest control, and pruning. The latter is performed regularly (every two years) to shape the trees, remove dead, unproductive, or diseased branches, and ultimately encourage healthy growth and increase productivity. This pruning process generates a substantial amount of biomass in the form of branches and foliage (from 1.40 to 4.00 t ha^{-1} yr^{-1}) (Ruiz et al., 2017) which are usually underutilized representing a great option to be exploited for BECCS. To exploit olive tree prunings for energy production, several activities and processes are typically required including collection and harvesting, chipping or shredding, transportation, storage, and finally its use as feedstock for energy conversion systems, such as biomass boilers or biomass gasifiers to produce heat and electricity.

The olive harvesting marks the beginning of olive oil production. Depending on the crop type and mechanization possibilities, olives are handpicked or collected using vibrating machines, shaking the trees to dislodge the ripe fruit. On average, a mature olive orchard can produce from 2.00 to 5.00 t of olives per hectare per year (Galán-Martín et al., 2022). After harvesting, the olives are transported to the olive mill (usually by truck), where they undergo cleaning and washing to remove dirt, leaves, and other impurities. Water is commonly used in this process, which contributes to the overall water footprint of VOO production. The cleaned olives are then crushed to form a paste, and the olive oil is extracted, where the malaxation is a crucial step to break off the emulsions formed during the crushing stage and allow oil drops to coalesce. Then, the olive paste undergoes a centrifugation process to separate the oil from the olive pomace (semi-solid) in the two-phase extraction, along with wastewater in the pressing and three-phase extraction. This olive pomace could be further processed in another facility to obtain olive oil using chemicals and produce exhausted olive pomace residue. Additionally, heat needed at the olive mill is typically obtained by burning a portion of the olive pomace and olive pits generated during the process. After separation, the freshly extracted olive oil is stored in tanks before undergoing filtration to remove any remaining impurities. On average, it takes approximately 5.00 kg of fresh olives to produce one liter of VOO (Fernández-Lobato et al., 2021). Depending on the quality and purity of the VOO, it can be categorized as extra VOO when the acidity level is lower than 0.80 and there are no organoleptic defects. Finally, the last step is bottling and packaging for distribution. Polyethylene terephthalate (PET) and glass bottles are the predominant packaging solutions, with the former exhibiting superior environmental performance (Ferrara and De Feo, 2023).

Throughout the processes at the olive mill, energy is required to power the machinery. For example, electricity is needed to power the crushing machinery and stir the paste during malaxation, operate the centrifuges and pumps and filters or bottling machinery, labeling, and packaging processes. While VOO production is not an energy-intensive process, optimizing the equipment designs to reduce consumption or using renewable energy sources could substantially reduce the CF of VOO production. In this work, we will explore the use of carbon-negative electricity produced with BECCS based on olive tree pruning to assess the potential to reach a net negative GHG emissions balance considering all the life cycle activities.

3.2. Scenarios definition

Based on the previous description of the VOO production process (Section 3.1), we have defined five scenarios for analysis using the LCA methodology introduced later (Fig. 1). The first baseline scenario (S1 OIL-BAU) represents the conventional method of producing VOO, where the energy needed for olive mill operations is sourced from the national electrical grid. We consider that the heating needs in S1 are covered by burning residual biomass (olive pomace and pits) generated in the process in a cogeneration plant. In the second scenario (S2 OIL-BECCS), we incorporate the BECCS technology into the traditional VOO production process. Here, the energy requirements for the olive mill processes are satisfied by electricity and heating generated through the BECCS system based on olive tree pruning as the biomass source, making the olive mill self-sufficient. The third scenario (S3 OIL-BECCS) adopts an approach where all the prunings generated within the agricultural area are harnessed through BECCS. Any surplus electricity generated in this process is fed back into the electrical grid. Furthermore, to highlight the benefits of BECCS and emphasize the importance of accounting for biogenic CO_2 in permanent storage, we have introduced two additional scenarios analogous to S2 and S3 in terms of the production systems and the amount of pruning exploited, albeit without the CCS system (S2 OIL *w/o* CCS and S3 OIL *w/o* CCS). Consequently, in these scenarios, the biogenic CO_2 emissions from combusted prunings are released back into the atmosphere. These scenarios enable us to comprehensively assess the potential benefits of integrating BECCS technology and sustainable biomass sources to reduce carbon emissions and improve overall environmental sustainability.

3.3. Life cycle assessment

This study conducts a comprehensive LCA of an innovative approach that integrates BECCS into the production of VOO. The LCA was carried out considering four phases following the ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b). In the first phase, the goal and scope are defined. The goal of this study is to evaluate the potential of producing carbon-negative VOO by integrating BECCS at the olive mill. The functional unit (FU) was specified as the production of "one liter of VOO, packaging included" as defined in the Product Category Rule 2010:07 in accordance with the ISO standard 14025:2006 (ISO, 2006c). A cradle-to-gate model was implemented for the VOO production, encompassing all stages of VOO production, from olive cultivation to the delivery of the final product to consumers at the olive mill gate (see detailed description of the VOO production in Section 3.1). More precisely, the study includes i) all activities related to olive cultivation such as planting, fertilization, pest control, and irrigation; ii) activities associated with the olive picking and pruning harvesting: iii) transportantion of olives and prunings from the orchard to the mill; iv) all processes for two-phase extraction of VOO; and v) the packaging of VOO bottles. Fig. 2 shows the system boundaries in our study.

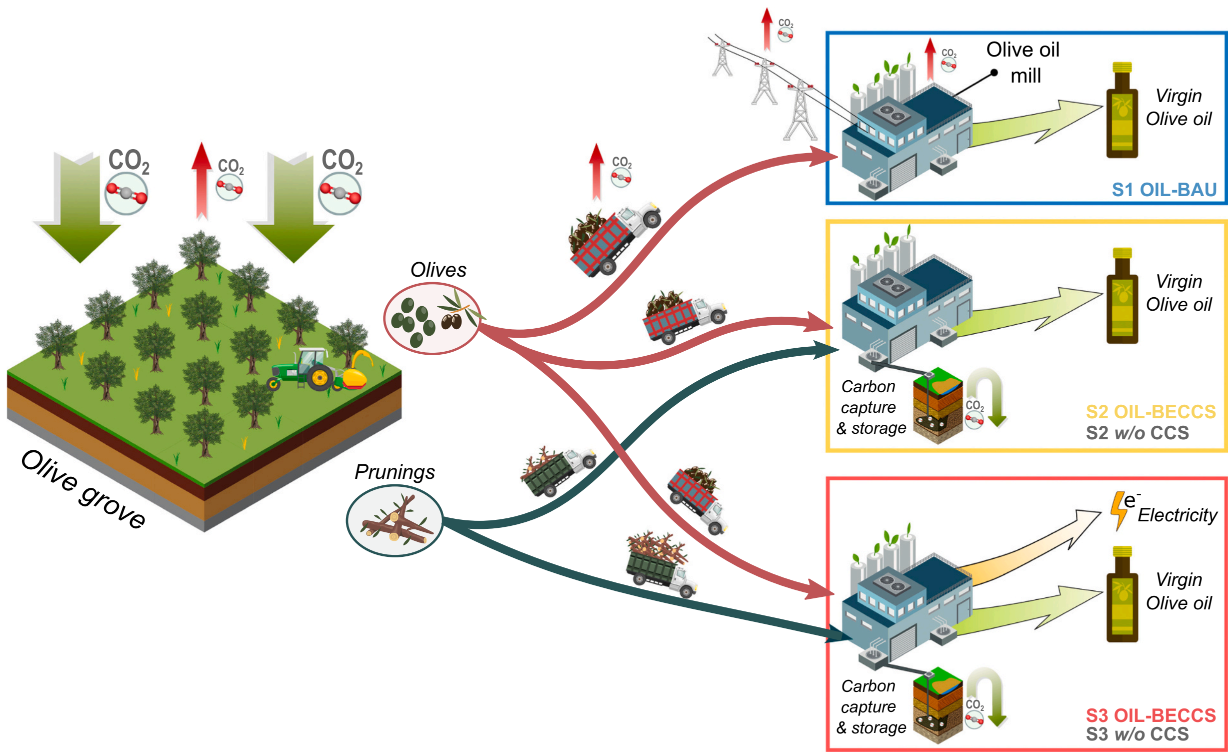

Fig. 1. Conceptual framework and scenarios evaluated in this work. The hypothesis aims to investigate the possibility of achieving carbon-negative virgin olive oil production by utilizing olives and olive tree prunings from a specific olive grove area.

Our study excludes the distribution of the bottles of VOO to the consumers and the use phase which is usually used for salad dressing or cooking but includes the end-of-life of packaging materials. Note that the GHG emissions associated with the use phase of VOO are minimal when compared to the emissions generated during the earlier stages of its life cycle and could be neglected (Espadas-Aldana et al., 2019). Hence, note that whether a BECCS-industry system could result in net negative emissions or not (physical removal of GHG emissions from the atmosphere) can only be assessed through a cradle-to-grave accounting of all GHG emissions (Tanzer et al., 2021).

Moreover, for simplicity and to avoid allocation methods with our multi-product system, all environmental impacts and burdens are allocated to the main product of interest which is the 1-l bottle of VOO although other marketable co-products such as the olive pomace, the olive stones, and electricity (the later only in case of S3 S3 OIL-BECCS) are delivered at the olive mill.

The second phase involves conducting a comprehensive Life Cycle Inventory (LCI) in which all inputs (e.g. water, energy, chemicals) and outputs (e.g. emissions, waste) associated with each stage of the product system are compiled. This includes data on olive grove management practices, energy consumption during VOO extraction, bioenergy production from olive tree prunings, and emissions associated with carbon capture and storage. Data for the study were collected from secondary sources, primarily existing literature and databases. All collected data were utilized to construct the LCI for each stage of VOO production. Specifically, we obtained data for mass and energy balances of VOO production systems from the literature (Fernández-Lobato et al., 2021; Guarino et al., 2019) (as outlined in Table 1). Data for the background system were retrieved from the Ecoinvent v3.9.1 (Wernet et al., 2016) database accessed via SimaPro v9.5.0.0 (Goedkoop et al., 2016). We employed the "At the Point of Substitution" (APOS) system model and, for the activities, we select datasets for Spain ([ES]), Euorope ([RER]), and global ([GLO]) or the Rest of the World ([RoW]) datasets when the former are unavailable.

The scenarios under consideration (described in Section 3.2 and illustrated in Fig. 1) vary depending on how the energy demands of the olive mill processes are satisfied and the extent to which the pruning residue available is utilized. Considering the FU of a 1-l bottle of VOO, the total electricity and heating requirements are 0.21 kWh of electricity and 0.52 MJ, respectively (Table 1). In the S1 OIL-BAU (conventional VOO production), the electricity is sourced from the Spanish grid, while the heating needs are met through the combustion of olive prunings (without CCS). To model this heating input, we adapted the Ecoinvent v3.9.1 dataset "Electricity, high voltage {ES}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | APOS, U" (Wernet et al., 2016) by replacing the biomass input with olive prunings. The modeled activity encompasses heat production utilizing olive pruning chips in a co-generation plant, including the infrastructure, the wood input, and all substances needed for operation (lubricating oil, organic chemicals, sodium chloride, chlorine, and decarbonized water) as well as the emissions to air and the disposal of the ashes. The biomass input is computed as 0.84 kg kWh^{-1}, assuming a lower heating value of 18.9 MJ kg^{-1} (on dry mass) and a thermal efficiency of 0.45.

With regards to the olive prunings, the LCI is detailed in Table 2. Data for background processes were acquired from the Ecoinvent v3.9.1 database (Wernet et al., 2016), while the foreground relied on insight gathered through interviews with practitioners about current practices and similar activities from Ecoinvent v3.9.1 (Wernet et al., 2016). Pruning of olive trees involves the use of hand-held gasoline-driven power saws, creating swathes of branches that are then chipped to reduce their volume and increase density for efficient transportation by tractors and trucks. The amount of power sawing and chipping per harvested pruning assumes average input and productivity as in the dataset "Wood chips, wet, measured as dry mass {RoW}| hardwood forestry, birch, sustainable forest management | APOS, U" sourced from Ecoinvent v3.9.1 (Wernet et al., 2016). We assume transportation by an agricultural tractor of 1 km followed by transportation by lorry to the olive oil mill of 50 km. The amount of biogenic CO_2 embodied in the

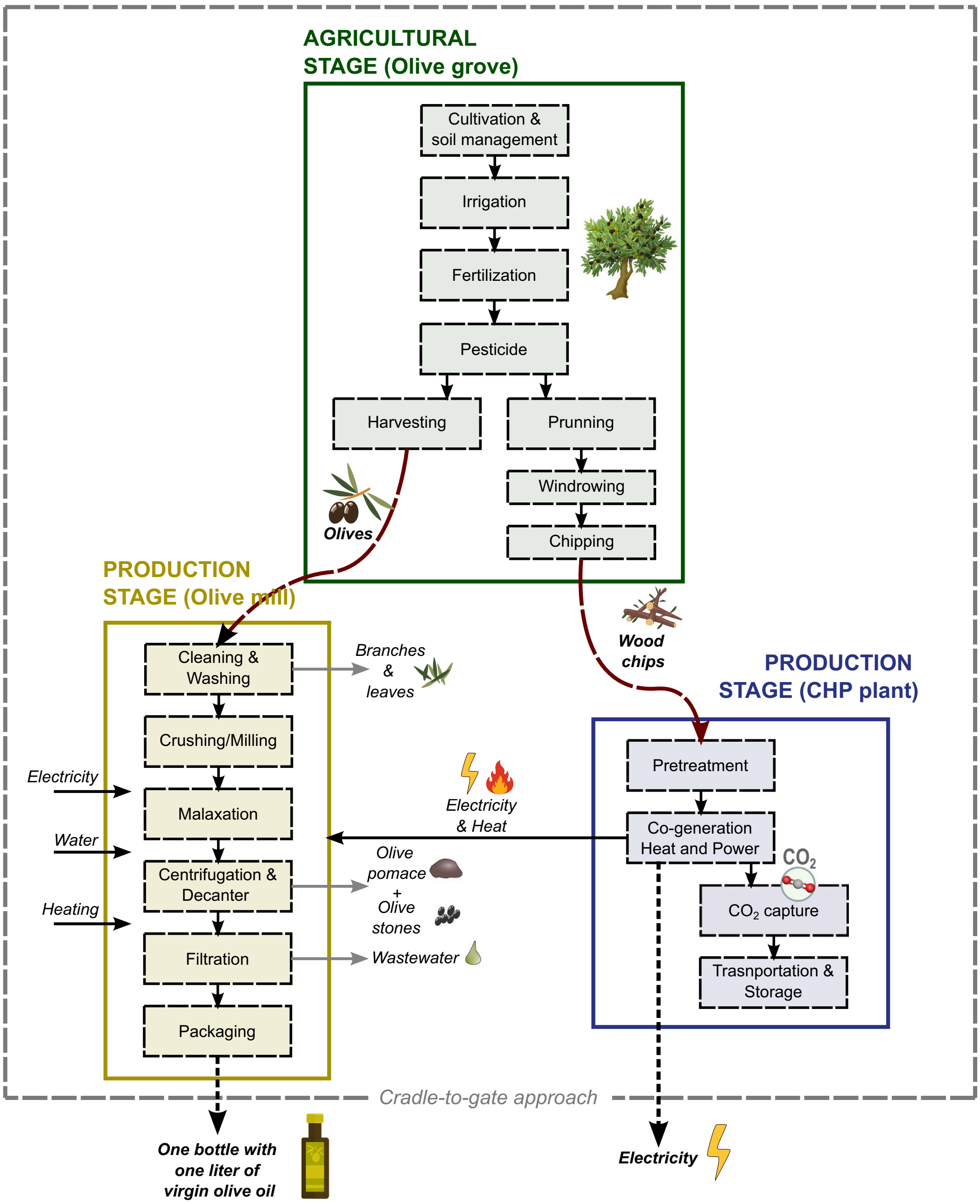

Fig. 2. Cradle-to-gate life cycle model, system boundaries, and main processes for virgin olive oil production.

olive prunings biomass (modeled as a negative entry in the system, Table 2) is estimated considering a water content of 27.60 % and carbon content on a dry basis of 49.40 % according to Phyllis2 (ECN, 2014). All land-related aspects, such as land occupation and transformation, changes in land use, and activities associated with olive tree cultivation (e.g. fertilizer application, pesticide use, and irrigation) are attributed to the olive fruits.

The alternative scenarios integrate the BECCS technology into the traditional VOO production process. In the S2 OIL-BECCS (energetically self-sufficient), all the energy demands are met with BECCS based on olive prunings, without dependence on external energy supplies. Considering that the BECCS system consumes 1.03 kg of pruning per kWh delivered, the S2 OIL-BECCS scenario would require 0.37 kg of pruning material to satisfy its energy demand. This pruning input represents only a small portion (26 %) of the total pruning available related to the FU of a 1-l bottle of VOO which is estimated to be 1.40 kg. This value is computed considering that 5.00 kg of olives are required per liter of VOO and assuming conservative olive and prunings yields of 5.00 t ha^{-1} and 1.40 t ha^{-1}, respectively. In contrast, in the S3 OIL-BECCS scenario, all the prunings available are fully utilized, generating 1.35 kWh to cover all the energy needs of the olive mill (totaling 0.36 kWh per FU) and delivering +0.99 kWh of surplus electricity to the grid. Note that we adopt a conservative approach by accounting for 1.40 t of prunings per hectare, although it can potentially be increased to 4.00 t per hectare (Ruiz et al., 2017) thus potentially producing more surplus electricity delivered to the grid. Regarding the modeling of the BECCS system, the LCI is primarily based on the work by Galán-Martín et al. (Galán-Martín et al., 2021a), adapting it to our specific context by considering olive prunings as input raw material (Table 2). Detailed information on the BECCS system and the complete LCI are accessible through a publicly available repository (Galán-Martín et al., 2021b). The activity is rooted in the Ecoinvent v3.9.1 dataset “Electricity, high

Table 1
Inventory of elementary flows for the production of 1-l bottle of virgin olive oil together with their respective activity names in Ecoinvent v3.9.1 (Wernet et al., 2016).

Elementary flow	Amount	Dataset
Inputs:		
Olives (kg)	5.00	*Own activity.
Electricity for Cleaning & Washing (kWh)	2.20×10^{-2}	#Alternative electricity sources depending on the scenario.
Water for Cleaning & Washing (kg)	2.92×10^{-3}	Tap water (tap water production, conventional treatment)
Electricity for Crushing & Milling (kWh)	7.81×10^{-2}	#Alternative electricity sources depending on the scenario.
Electricity for Malaxation (kWh)	2.08×10^{-2}	#Alternative electricity sources depending on the scenario.
Heating for Malaxation (MJ)	5.23×10^{-1}	†Alternative heating sources depending on the scenario.
Water for Malaxation (kg)	7.92×10^{-4}	Tap water (tap water production, conventional treatment)
Electricity for Centrifugation & Decanter (kWh)	7.71×10^{-2}	#Alternative electricity sources depending on the scenario.
Electricity for Filtration (kWh)	$1.52\ 10^{-2}$	#Alternative electricity sources depending on the scenario.
Bottling & Packaging (kg)	$5.26\ 10^{-2}$	Polyethylene terephthalate, granulate, bottle grade, production
Outputs:		
1 bottle of 1 l of virgin olive oil (p)	1.00	–

[*] Own activity modeled by removing the wood waste treatment from the Ecoinvent v3.9.1 activity Olive {ES}| olive production.

[#] The electricity needs for the processes at the olive mill can be met either with electricity from the Spanish grid (Activity Electricity, medium voltage {ES}| market for |) or with BECCS based on olive prunings (Own activity modeled from Galán-Martín et al. (Galán-Martín et al., 2021a)).

[†] The heating needs for the processes could be from the cogeneration plant based on olive prunings without CCS (activity adapted from Ecoinvent v3.9.1) or from the BECCS activity (own activity modeled from Galán-Martín et al. (Galán-Martín et al., 2021a)).

Table 2
Inventory of elementary flows for 1 kg of olive tree prunings (measured as dry mass) together with their respective activity names in Ecoinvent v3.9.1 (Wernet et al., 2016).

Elementary flow	Amount	Dataset
Inputs:		
Carbon dioxide, in air (kg)	−1.43	*Modeled as a negative entry of carbon dioxide fossil.
Power sawing (hr)	1.99×10^{-5}	Power sawing, without catalytic converter (market for)
Swath cutting (ha)	7.14×10^{-4}	Swath, by rotary windrower (processing)
Wood chipping (hr)	3.70×10^{-5}	Wood chipping, chipper, mobile, diesel, at forest road (market for)
Wood chipping (hr)	2.21×10^{-5}	Wood chipping, forwarded with terrain chipper (market for)
Transport, freight (tkm)	5.00×10^{-2}	Transport, freight, lorry 3,5–7,5 metric ton, euro6 (market for)
Transport in tractor (tkm)	0.10×10^{-2}	Transport, tractor and trailer, agricultural (market for)
Outputs:		
Olive tree chips (kg)	1.00	–

[*] The amount of CO_2 embodied in the olive prunings biomass is estimated considering a water content of 27.60 % and carbon content of 49.40 % on a dry basis according to Phyllis2 (ECN, 2014).

voltage {ES}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | APOS, U" (Wernet et al., 2016) considering olive prunings as biomass input. Assuming perfect combustion, the BECCS plant generates 1.53 kg of biogenic CO_2 per kWh of electricity produced (considering the carbon content of prunings of 49.40 % and ratio of 0.841 kg of chips per kWh generated). However, the integration of the CCS system incurs an efficiency penalty, attributed to the high energy demands of the CCS unit (electricity needs for the MEA unit operation and CO_2 compression to 110 bar). This means that to deliver 1.00 kWh with the BECCS, 1.23 kWh are produced and 1.84 kg of biogenic CO_2 is generated by combusting the pruning chips that enters the MEA unit. Input and output data for the CCS infrastructure (compression, transportation, and geological storage) were derived from the literature (Oreggioni et al., 2017; Wildbolz, 2007). Our CCS system considers monoethanolamine as the capture solvent, with an assumed capture efficiency of 90 %. Overall, 1.69 kg of biogenic CO_2 is captured per kWh delivered with the BECCS system and transported via pipeline 200 km to be securely stored in a deep saline aquifer.

The third phase is the Life Cycle Impact Assessment (LCIA) which calculates the potential environmental impacts by converting the inventory flows into a set of impact indicators. The LCI data was built in SimaPro v9.5.0.0 (Goedkoop et al., 2016) software taking the background data from Ecoinvent v3.9.1 (Wernet et al., 2016). We followed an attributional methodology to quantify a set of midpoint impact indicators. In particular, we employed the characterization factors based on the ReCiPe 2016 (Huijbregts et al., 2016) Hierarchist perspective. For the analysis, we focus on the Global Warming (GW) category (expressed in kg of CO_2eq) accounting for all upstream and downstream direct and indirect emissions associated with the system. This choice allows determining the GHG emissions balance and calculating the CF. Notably, the biogenic CO_2 emission (to air) in the ReCiPe 2016 (v1.03) is provided with a characterization factor of zero for the GW category, meaning that the biogenic carbon uptakes and emissions are considered neutral. Hence, to account for the biogenic CO_2 permanent sequestration with BECCS, the CO_2 embodied in the biomass input (i.e. olive tree prunings for BECCS) is modeled as a negative entry of fossil CO_2 fossil. This negative entry reflects that the biogenic CO_2 was previously sequestered from the atmosphere during the growth of the biomass, contributing as a carbon-negative component in the overall emissions accounting. For a production system, to be carbon-negative, the total quantity of atmospheric GHG removed and permanently stored should be greater than the total quantity of those emitted to the atmosphere in the life cycle., thus leading to an actual decrease in atmospheric CO_2 through the physical removal and ensuring storage of carbon dioxide.

To gain a comprehensive understanding of the environmental implications, we also consider both midpoint and endpoint indicators of ReCiPe 2016 (Huijbregts et al., 2016). In particular, we examined a range of mid-level categories that refer to particular environmental problems, including ionizing radiation (kBq Co-60eq), fine particulate matter formation (kg PM2.5eq), terrestrial acidification (kg of SO_2eq), freshwater eutrophication (kg of Peq), freshwater ecotoxicity (kg of 1,4-DCBeq), terrestrial ecotoxicity (kg of 1,4-DCBeq.), land use (m^2a of crop eq) and water consumption (m^3). Finally, we also assess the three endpoint categories which refer to broader consequences of environmental stressors on human health (expressed in DALYs, disability-adjusted life years), ecosystems (expressed in species·yr which represents the local species loss integrated over time), and natural resources (expressed in USD2013 which represents the extra costs involved for future mineral and fossil resource extraction) (Huijbregts et al., 2016).

Finally, the last phase consists of interpreting the results. By analyzing the obtained results, we gain insights into the broad environmental implications of carbon-negative VOO production.

4. Results and discussion

4.1. The carbon footprint (net GHG emissions balance)

We start by assessing the CF (life cycle GHG emissions balance) of five different scenarios for VOO production (see description of scenarios in Section 3.2 and Fig. 1). Fig. 3 provides a visual comparison of these five scenarios. The CF of each scenario is represented by a stacked bar showing the contribution of each stage in the value chain to the overall

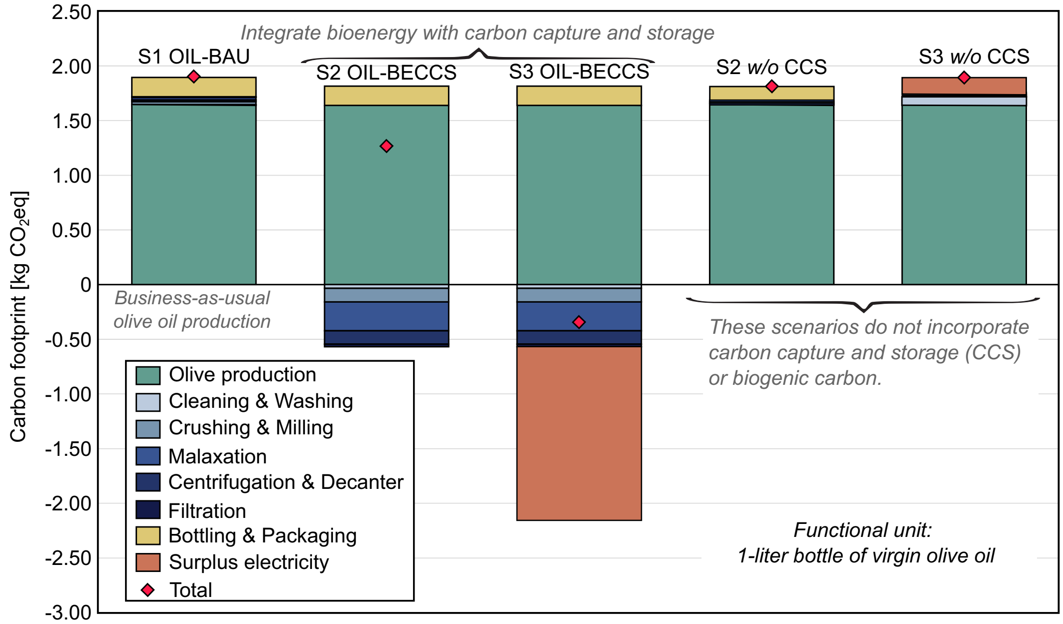

Fig. 3. Carbon footprint (kg CO_2eq per 1-l bottle of virgin olive oil) of the conventional production of virgin olive oil (S1 OIL-BAU scenario), the two scenarios integrating bioenergy with carbon capture and storage (BECCS) at the olive mill (S2 OIL-BECCS and S3 OIL-BECCS) and their analogous without carbon capture and storage (S2 w/o CCS and S3 w/o CCS).

CF.

The S1 OIL-BAU scenario serves as our baseline reference point, representing conventional VOO production utilizing industry-standard methods. This scenario exhibits the highest CF among the five scenarios, yielding +1.93 kg of CO_2eq emissions per 1-l bottle of VOO. Our findings align with prior research in the literature, which has shown that CF can vary between 1.00 and 4.00 kg CO_2eq, upon the underlying assumptions (Espadas-Aldana et al., 2019). The breakdown provides insight into the major sources of carbon emissions within the conventional VOO production process. Our results are aligned with previous LCA studies. The primary driver of CF in the S1 scenario is the cultivation phase of olive trees (Fernández-Lobato et al., 2021; Proietti et al., 2017), accounting for a substantial +84.50 % of emissions. Following this, bottling and packaging is identified as the second driver (Ferrara and De Feo, 2023) contributing +9.11 %, while the other operations at the olive mill make up the remainder.

The S2 OIL-BECCS scenario exemplifies the considerable advantages of integrating BECCS technology into the olive mill. This scenario only exploits a fraction of the available pruning residues to meet the energy needs of the olive mill operations and concurrently capture CO_2 emissions. In particular, 0.37 kg of prunings would be exploited out of the 1.40 kg that corresponds to the FU of a 1-l bottle of VOO (assuming conservatively that, per hectare of olive grove, 5.00 t of olives and 1.40 t of prunings would be available). Notably, the S2 OIL-BECCS scenario exhibits a reduction of 35.74 % in CF when compared to the baseline scenario (+1.25 kg CO_2eq vs. +1.93 kg CO_2eq). In this particular scenario, the electricity generated from BECCS, derived from olive tree prunings, carries a negative carbon intensity (−1.53 kg CO_2eq kWh^{-1}, see breakdown in Fig. 4, subplot B). This carbon-negative electricity, used to power various olive mill operations, would offset the positive direct and indirect GHG emissions throughout the value chain. This S2 OIL-BECCS necessitates the combustion of 0.37 kg of pruning material per 1-l bottle of VOO to meet electricity and heat demands (0.84 kg pruning per kWh produced and 1.03 kg per kWh delivered). As a result, approximately 0.61 kg of CO_2 released from this combustion process (considering a conservative 90 % capture efficiency) would be captured and subsequently separated using amines and transported 200 km to secure geological formations situated deep underground, ensuring its isolation and permanence out of the atmosphere. This strategic step serves to prevent the release of CO_2, thus contributing significantly to reducing the overall CF associated with VOO production.

The S3 OIL-BECCS scenario embodies a strategy that maximizes the utilization of all available olive tree prunings, resulting in a remarkable reduction in CF. Notably, this scenario attains carbon negativity, achieving −0.32 kg CO_2eq per 1-l bottle of VOO. In this scenario, all the pruning biomass associated with the FU, totaling a conservative value of 1.40 kg of prunings would be fully exploited via BECCS (assuming that in one hectare of olive grove, 1.40 t of prunings and 5.00 t of olives can be exploited annually). This comprehensive approach leads to the capture, transportation, and secure underground storage of a total of 2.81 kg of captured CO_2 emissions per 1-l bottle of VOO. This strategic utilization of prunings and carbon capture technologies results in not only a substantial reduction in carbon emissions but also a net removal of carbon dioxide from the atmosphere, making it a highly sustainable and environmentally beneficial approach. Note that our finding is conservative as the prunings availability could be increased to 4.00 t per hectare, which would result in a higher surplus of energy and, consequently, higher CO_2 removal and more carbon-negative CF of the VOO.

Concluding our CF analysis, our analysis underscores the significance of including and accounting accurately for the biogenic CO_2 in BECCS systems. For scenarios S2 and S3 w/o CCS (excluding the CCS system and the biogenic carbon) the results reveal notable differences. In S2 w/o CCS the CF stands at 1.84 kg CO_2 per 1-l bottle of VOO, a 47.52 % increase compared to S2 OIL-BECCS and slightly lower than S1 OIL-BAU (−5.20 %). This marginal improvement in CF compared with conventional olive oil production (S1 OIL-BAU) is attributed to a decreased carbon intensity in electricity powering the processes, sourced either from the grid (0.35 kg CO_2eq kWh^{-1}) or a biomass power plant (0.06 kg CO_2eq kWh^{-1}). On the other hand, in scenario S3 w/o CCS, the CF is 1.92 kg CO_2eq per 1-l bottle of VOO, aligning with the S1 OIL-BAU. However, S3 w/o CCS scenario generates an excess of 1.31 kWh of renewable electricity from biomass that can be delivered to the grid (assuming 0.84 kg of pruning per kWh generated and subtracting the self-consumption). Notably, the electricity output surpasses that of the S3 OIL-BECCS due to the energy penalty of the CCS system, which consumes part of the generated electricity, necessitating more pruning

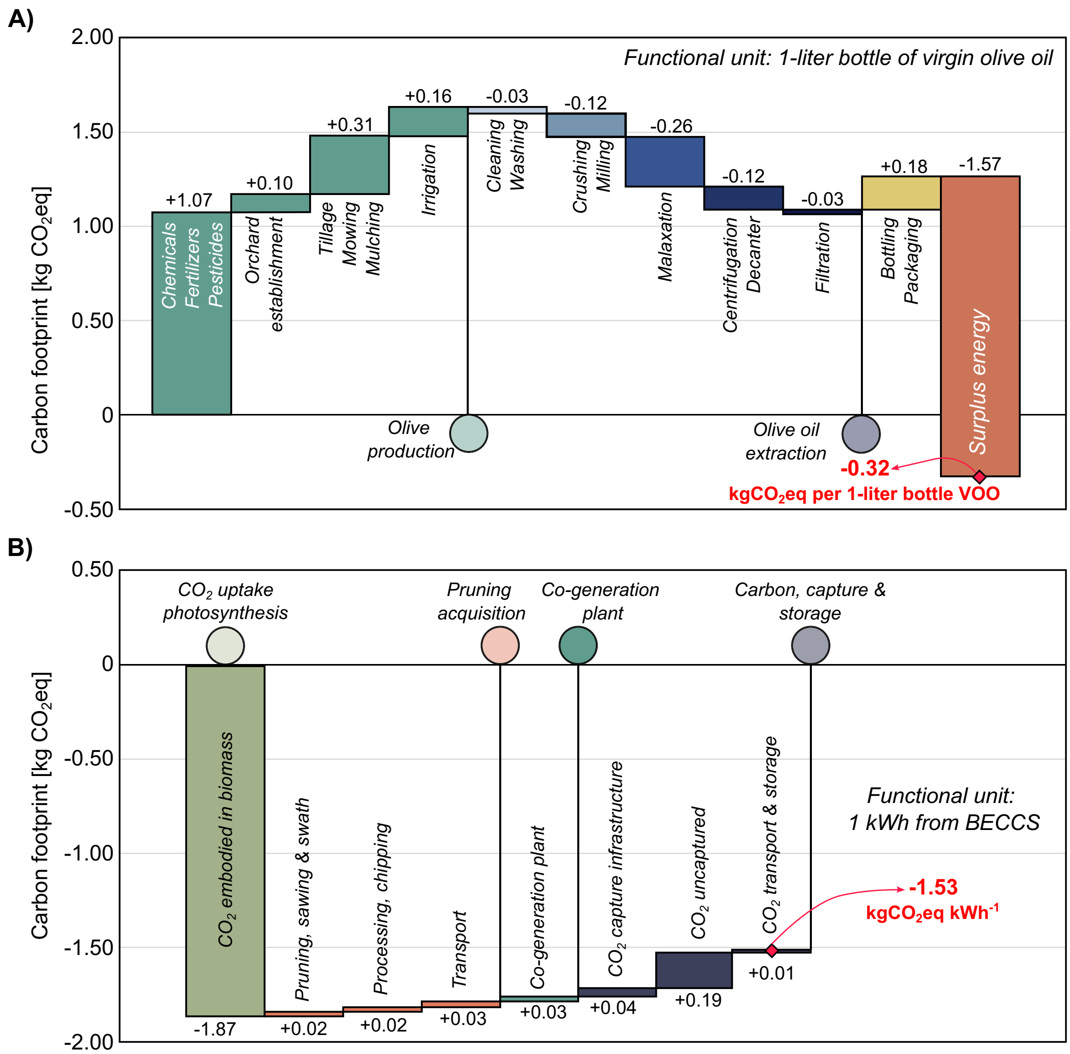

Fig. 4. Waterfall plot showing the breakdown of greenhouse gas emissions by activity and stage of virgin olive oil production for the S3 OIL-BECCS scenario (Subplot A) and the breakdown for the electricity generated with the bioenergy with carbon capture and storage (BECCS) system based on olive pruning (Subplot B).

to generate the same amount of net electricity.

Without CCS technologies, the biogenic CO_2 would be released back into the atmosphere when the biomass is burned for energy, potentially exacerbating GW if released faster than it was initially removed by the biomass during its growth. Integrating BECCS is valuable because it securely sequesters biogenic CO_2 underground guaranteeing the permanence of CO_2 removal over the long term and contributing to the CDR efforts. This permanence is crucial for maintaining public confidence and attracting investment in BECCS. Hence, the recently approved EU carbon removal certification framework includes definitions distinguishing between permanent carbon removal and temporary storage options, vital for building robust monitoring and standardization and verification environment to drive investment and maximize BECCS potential in addressing climate change.

Although our study does not delve into optimal planning and site selection, the incorporation of a BECCS-equipped olive mill should be ideally located close to both the olive grove (as biomass and fruit source) and geological storage sites. By locating the olive mill near the olive grove, the costs, energy expenditures, and environmental impacts associated with the transportation of large quantities of olives and biomass can be diminished. Similarly, co-locating the facility near suitable geological storage sites can substantially reduce the necessity for infrastructure, including extensive pipelines and networks (Negri et al., 2021). However, despite there will be obstacles to the deployment of BECCS systems, the geological storage capacity along with its varied sitting both at national and global levels will not pose impediments to the realization of this initiative (Bullock et al., 2023; Fuss et al., 2018b).

To provide a more comprehensive overview of the CF associated with the S3 OIL-BECCS scenario, we present a detailed breakdown of greenhouse gas emissions by activity and stage using a waterfall plot (Fig. 4, subplot A), along with a breakdown of the production of 1 kWh with the BECCS system (Fig. 4, subplot B).

The agricultural phase (represented by the green bars) stands out as the primary contributor to the life cycle GHG emissions (Fig. 4, subplot A). The agricultural phase encompasses various activities, including establishing the olive orchard (such as tree planting, tree nursery management, and irrigation), the productive phase of the orchard (involving machinery operations, fuel usage, storage facilities, fertilizer and pesticide application, harvesting, and irrigation), as well as emissions directly associated with field activities and land use changes. Notably, the use of chemicals in agriculture emerges as the leading emission source, amounting to +1.07 kg CO_2eq per FU. This category encompasses fertilizers such as urea, nitrates, and phosphates, as well as pesticides, herbicides, and their packaging. During this phase, field operations, including tillage, mowing, and mulching performed with agricultural tractors and machinery, contribute an additional +0.31 kg CO_2eq per FU, while irrigation accounts for +0.16 kg CO_2eq per FU.

Moving to the olive mill (blue bars in Fig. 4, subplot A), all stages contribute to reducing the CF due to the carbon-negative nature of the electricity and heating used in the processes. The carbon intensity of electricity generated from BECCS is −1.53 kg CO_2eq per kWh delivered. Examining the breakdown (Fig. 4, subplot B), the initial segment reflects negative emissions attributed to the CO_2 embodied in the pruning biomass, i.e., −1.87 kg CO_2 absorbed during growth via photosynthesis which is estimated considering the carbon content of olive prunings at a ratio of 0.84 kg kWh^{-1} and the energy penalty of the CCS system. Subsequent segments represent GHG emissions related to the pruning acquisition. It includes the pruning, processing (windrowing and chipping), and transportation to the BECCS plant at the olive mill, collectively contributing 0.07 kg CO_2eq. The energy generation phase adds 0.03 kg CO_2eq to total emissions per kWh, including infrastructure, direct and indirect emissions to air, and disposal of ashes and substances needed for operation (lubricating oil, organic chemicals, etc). Lastly, the CCS system contributes 0.24 kg CO_2eq, encompassing 0.04 kg CO_2eq for the MEA unit infrastructure and operation, 0.19 kg CO_2eq due to the uncaptured biogenic CO_2 emissions (assuming 90 % capture efficiency), and 0.04 kg CO_2eq for transportation and storage of CO_2.

Among the stages at the olive mill powered with the BECCS, malaxation stands out as the main contributor to negative emissions (−0.26 kg CO_2eq per FU, Fig. 4 subplot A). This is primarily attributed to malaxation being the most energy-intensive step in VOO production, involving mechanical work, the need for precise temperature control of the paste, and a relatively long processing duration compared to other phases. Beyond the production stage, bottling and packaging also contribute with positive GHG emissions to overall CF with +0.18 kg CO_2eq per FU (yellow bar in Fig. 4). This is mainly associated with the production of polyethylene terephthalate (PET) granulate, a key raw material for bottle and film production. Finally, the electricity generated through the BECCS system that is delivered to the grid (after subtracting the electricity self-consumed) contributed with −1.57 kg CO_2eq, effectively offsetting the positive emissions and resulting in an overall net negative CF of −0.32 kg CO_2eq per FU.

4.2. Potential environmental consequences of carbon-negative products

Integrating BECCS within the olive mill has the potential to reduce the CF of the VOO, potentially reaching a state of carbon negativity by displacing the use of fossil fuels and actively removing CO_2 from the atmosphere (as shown in Figs. 3 and 4). Nevertheless, the overall environmental implications are contingent on several factors, and there may be an increase in the environmental footprint across other impact categories. To evaluate the possibility of burden-shifting (reduction of one environmental impact category at the expense of an increase in another one), we next examine the comparative performance of the S1 OIL-BAU and the two scenarios integrating BECCS (S2 OIL-BECCS and S3 OIL-BECCS) considering a set of midpoint and endpoint indicators of the ReCiPe 2016 (Huijbregts et al., 2016) (Fig. 5). The absolute values for each impact category are also presented in the heatmap of Fig. 6.

Our analysis reveals that unintended negative consequences would occur when compared to the baseline scenario (S1 OIL-BAU scenario). Specifically, in scenario S3 OIL-BECCS, which achieves a negative CF, there would be increased impacts on terrestrial acidification, freshwater eutrophication, and ecotoxicity (both terrestrial and freshwater). The primary drivers of acidification and eutrophication are emissions like nitrogen oxides and ammonia, stemming from fertilizer use during olive tree cultivation (which are allocated to the olive tree prunings). Additionally, the CCS system also contributes to these impacts due to its reliance on monoethanolamine solvent, an amine compound that can oversupply nutrients to the environment. The burden-shifting is particularly relevant in terrestrial ecotoxicity, which increases by 43.00 % in the S3-BECCS scenario compared to the S1 OIL-BAU scenario (7.68 vs 5.38 kg 1,4-DCB). This impact is associated with the increased utilization of pruning in this scenario. The combustion of pruning material releases various pollutants, including particulate matter, nitrogen oxides (NOx), and volatile organic compounds (VOCs), contributing to ecotoxicity. Moreover, the transportation and pretreatment of biomass with diesel-powered vehicles result in higher GHG and air pollutants that contribute to terrestrial ecotoxicity. Strategies like sourcing biomass locally to reduce transportation distances and using cleaner vehicles are

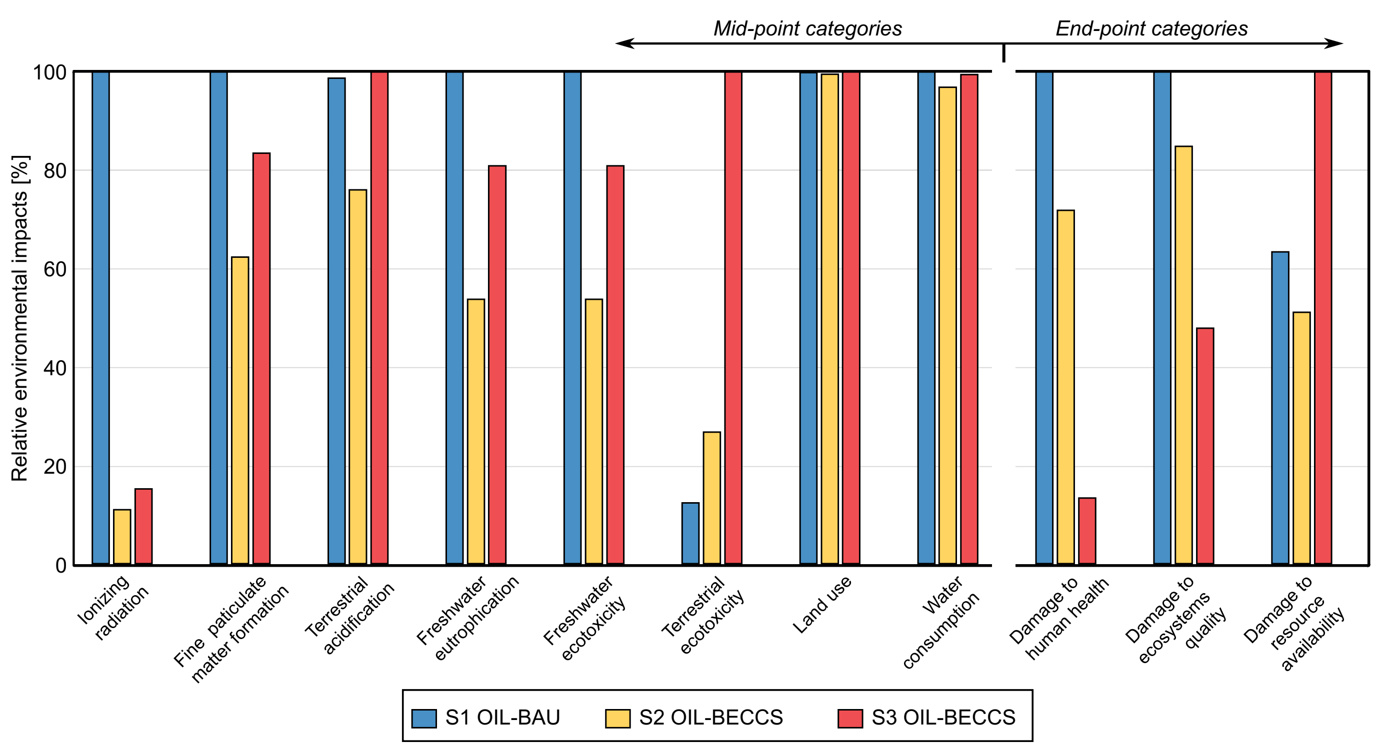

Fig. 5. Comparative environmental implications of conventional production of virgin olive oil (S1 OIL-BAU scenario) and the two scenarios integrating bioenergy with carbon capture and storage at the olive mill (S2 OIL-BECCS and S3 OIL-BECCS).

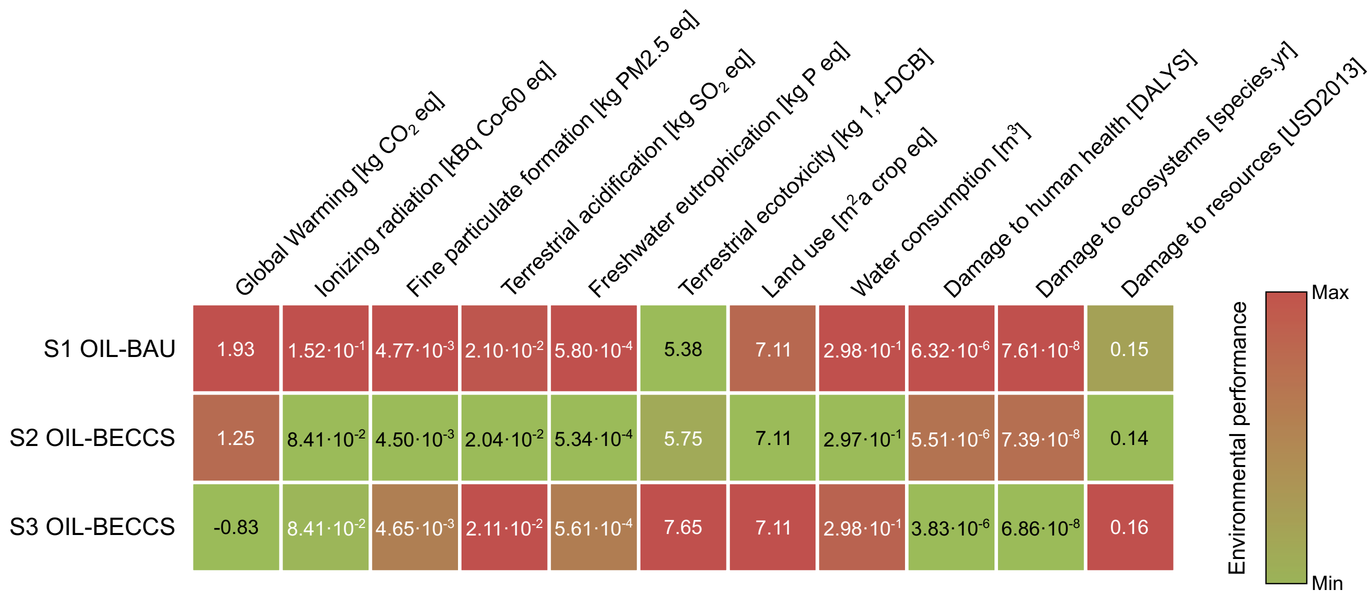

Fig. 6. Environmental performance of conventional production of virgin olive oil (S1 OIL-BAU scenario) and the two scenarios integrating bioenergy with carbon capture and storage (S2 OIL-BECCS and S3 OIL-BECCS) across the selected impact categories. Rows correspond to the scenarios, with each metric evaluated individually, using the color key corresponding to the bar. Absolute values are provided in each cell.

vital for mitigating terrestrial ecotoxicity. On the contrary, the retrofitting of BECCS reduces ionizing radiation and fine particulate matter formation due to the replacement of fossil and nuclear power with bio-based electricity.

Regarding end-point categories, integrating BECCS at the olive mill substantially reduces damage to human health and ecosystem quality. Pressure on human health and ecosystem quality decreases by 39.00 % and 10.00 %, respectively, in the S3-BECCS scenario compared to the baseline. In particular, the damage to human health reduces from 6.32 10^{-6} to 3.83 10^{-6} DALYS per FU and the damage to ecosystems from 7.61 10^{-8} to 6.68 10^{-8} species.yr per FU (Fig. 6). This reduction is attributed to the reduction of GHG and provision of CDR (CO_2 removal), thus reducing health and biodiversity risks associated with climate change and enhancing ecosystem resilience. However, the damage to resources increases with the S3-BECCS scenario compared to baseline VOO production (0.16 vs. 0.14 USD2013, Fig. 6), meaning that additional costs will be required to extract resources in the future due to depletion. These amplified impacts are primarily due to the complex BECCS technology, which increases damage to both mineral resource scarcity and fossil resource scarcity. The construction and operation of co-generation facilities, carbon capture, and transportation networks require significant quantities of minerals, metals, and fossil fuels across the entire value chain, contributing to resource scarcity.

When implementing BECCS technology in VOO production, there are trade-offs between different environmental aspects that offer valuable insights for informed decision-making and improvement opportunities. Particularly noteworthy is the S2-BECCS scenario, where only a portion of the available pruning is utilized, resulting in lower environmental impacts in most categories compared to the baseline scenario. The exception is terrestrial ecotoxicity, as shown in Fig. 5. Adopting sustainable and environmentally responsible practices throughout the entire lifecycle of olive tree prunings, from cultivation and harvesting to combustion and CO_2 capture and storage is crucial to reduce the undesired side effect of the BECCS system. Nevertheless, our findings highlight the potential for a win-win situation by making strategic choices and adopting holistic, integrated approaches to reduce environmental impacts across various categories while working towards carbon neutrality or even carbon negativity products.

4.3. Economic and policy dimensions

Besides the environmental implications, evaluating the economic viability of carbon-negative products is also paramount. Integrating BECCS into any production system entails higher upfront production costs related to the biomass logistics and processing and the carbon capture, and storage facilities. While initial investments in BECCS infrastructure and supply chain considerations may pose challenges, the long-term cost savings and potential revenue arisings from carbon offset markets or policy incentives can make this approach financially attractive.

The adoption of BECCS has several implications for both biomass producers and the industry. For biomass producers, it can provide additional income and diversification for farmers from selling olive prunings contributing to resource efficiency and circularity goals. For olive oil producers, it offers the opportunity to reduce emissions and align with sustainability goals and regulatory requirements, potentially enhancing corporate responsibility and competitiveness. The higher costs of their carbon offset projects can be passed on to consumers. The consumer acceptance and demand for such sustainable products reflect a growing trend in recent years which can drive the industry towards wider adoption of BECCS. Carbon-negative products may be considered premium by environmentally conscious consumers who are willing to pay extra for sustainability (Birkenberg et al., 2021). Hence, raising awareness about the benefits and importance of carbon-negative products is crucial. Over time, as technology advances and economies of scale are realized, the costs may decrease, making them more accessible to a broader range of consumers.

Moreover, government policies, incentives, and regulatory frameworks are emerging to promote sustainable food systems (Ammann et al., 2023) and carbon-negative practices (Schenuit et al., 2023). Despite several governments having committed to net-zero emissions targets, only a few have actual plans for supporting carbon capture initiatives (Honegger and Reiner, 2018; Smith et al., 2023). However, the upcoming regulatory environment can significantly impact the decision-making of industries. Hence, understanding the environmental and economic implications of BECCS adoption may create a market advantage for early adopters. Industries embracing BECCS may find opportunities for collaboration in research and development initiatives towards the effective implementation of BECCS. Nevertheless, industry-specific challenges will also emerge during the implementation of BECCS in VOO production or any other production system including technological barriers and regulatory hurdles. To succeed, further research and technology development is needed to optimize tailored approaches for the industries considering the unique characteristics of each project.

5. Conclusions

Our research presents promising findings with valuable implications for the broader integration of BECCS across diverse production systems. The adaptability of BECCS as a renewable energy source holds potential for widespread integration, transforming various industries into producers of carbon-neutral or even carbon-negative products to combat climate change.

Within the olive oil sector, our findings demonstrate the feasibility of producing carbon-negative VOO by utilizing the olive tree prunings as a biomass source to power milling processes via BECCS. By capturing and storing CO_2 emissions steaming from biomass combustion, the olive oil industry can play a pivotal role in reducing GHG concentrations in the atmosphere, thus contributing to global CDR efforts, maximizing resource efficiency, and creating innovative and circular carbon-negative food systems.

Our work also stresses the critical importance of the LCA methodology to certify and validate the net-negative footprint of products, emphasizing the need for comprehensive environmental impact assessments beyond climate change. While BECCS integration offers environmental benefits such as reducing the reliance on fossil fuels and the impact on human health and ecosystems, careful consideration is required to mitigate potential undesired collateral damages such as increased acidification and eutrophication or resource scarcity. Proper planning and operation, responsible resource management, and adherence to sustainability principles are essential to ensure that BECCS projects contribute to climate change mitigation while minimizing detrimental consequences on the environment.

In conclusion, the integration of BECCS into VOO production holds the potential for addressing climate change, fostering sustainable agriculture, and increasing the resiliency of the industry and the economy. With the right investments, policies, collaboration between public and private sectors, and consumer support, the olive oil industry can contribute to carbon-negative production and thus to a more sustainable and environmentally responsible future. Further research and collaboration among stakeholders are essential to unlock the full potential of BECCS in the context of the olive oil industry and beyond.

CRediT authorship contribution statement

Ángel Galán-Martín: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Supervision, Visualization, Writing – original draft, Writing – review & editing. **María del Mar Contreras:** Data curation, Funding acquisition, Investigation, Validation, Writing – review & editing. **Eulogio Castro:** Formal analysis, Supervision, Writing – review & editing.

Declaration of competing interest

The authors 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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