Journal of Cleaner Production 461 (2024) 142636

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Revealing the ecological footprint of Argan (*Argania spinosa*) derivatives: A comprehensive analysis of the carbon impact of Argan oil

Oussama Bayssi [a,b,d,*], Mustapha Naimi [a], Mohamed Sabir [c], Mohamed Chikhaoui [a], Jamal Hallam [b]

[a] *Hassan II Institute of Agronomy and Veterinary Medicine, Rabat, Morocco*
[b] *Regional Center Agricultural Research of Agadir, National Institute of Agricultural Research, Avenue Ennasr, BP 415 Rabat Principale, 10090, Rabat, Morocco*
[c] *National Forestry Engineering School, Salé, Morocco*
[d] *IRESEN (L'Institut de Recherche en Energie Solaire et Energies Nouvelles), 16, Avenue S.A.R, 10090, Rabat, Morocco*

ARTICLE INFO

Handling Editor: Tomas B. Ramos

Keywords:
Carbon footprint
Argan industry
Emissions
Argan biosphere reserve

ABSTRACT

Argania spinosa, commonly known as the Argan tree, assumes a crucial role in bolstering environmental sustainability by augmenting carbon storage in both biomass and soil. Despite its significant environmental contributions, there exists a conspicuous gap in scientific research and data pertaining to the carbon dynamics associated with Moroccan Argan forest ecosystems and their prized products, particularly Argan oil. To address this research gap, our study meticulously investigates the intricate details of the carbon footprint linked to Argan oil production within the "Argan Biosphere Reserve" in southern Morocco.

This innovative research aims to deliver a comprehensive assessment of the carbon footprint within the Argan oil industry, conducting a thorough examination of 10 companies and 16 cooperatives actively involved in production. The foundation of this investigation rests on on-site interviews with leaders of production units, systematically gathering essential data for rigorous analysis.

Employing the "Bilan Carbone" tool, we intricately calculated emissions, categorizing them into three scopes. The resulting carbon footprint outcomes were meticulously delineated across three distinct scenarios, shedding light on the nuanced dynamics of greenhouse gas emissions.

In the first scenario, encompassing all scopes, including export-related emissions, companies displayed an average carbon footprint of approximately 10.17 kg CO_2 eq.l^{-1}, while cooperatives recorded 8.68 kg CO_2 eq.l^{-1}. The second scenario, excluding export-related emissions, unveiled companies with an average carbon footprint of 3.71 kg CO_2-eq.l^{-1} and cooperatives with 6.32 kg CO_2-eq.l^{-1}. The third Scenario, concentrating solely on scopes 1 and 2, indicated companies with an average estimated carbon footprint of 1.31 kg CO_2 eq.l^{-1}, and cooperatives with approximately 3.01 kg CO_2 eq.l^{-1}.

Delving deeper into the intricacies of emissions by scenario and oil-producing organizations, our findings underscore the substantial impact of electricity consumption on the overall carbon footprint of Argan oil. For companies, electricity consumption contributed between 10.84% (first scenario) and 66.97% (third scenario), while for cooperatives, the range was 26.97% (first scenario) to 75.57% (third scenario).

To optimize the carbon footprint, our study recommends strategic interventions such as reducing electricity and butane consumption. Moreover, adopting sustainable practices, including leveraging photovoltaic electricity and synthetic gas from the pyrolysis of Argan byproducts, can significantly curtail the average carbon footprint of companies and cooperatives, charting a trajectory toward environmental sustainability. Specifically, a reduction of 37.05% and 40.75% (second scenario) and an impressive 71.66% and 77.01% (third scenario) for companies and cooperatives, respectively, could be achieved after a 30-year amortization period of photovoltaic panels.

These findings not only contribute valuable insights into the environmental impact of Argan oil production but also pave the way for future in-depth studies and the formulation of sustainable pathways to optimize the carbon footprint of this critical industry.

* Corresponding author.
E-mail address: o.bayssi@iav.ac.ma (O. Bayssi).

https://doi.org/10.1016/j.jclepro.2024.142636
Received 26 October 2023; Received in revised form 8 April 2024; Accepted 19 May 2024
Available online 20 May 2024

1. Introduction

Climate change is a major environmental issue caused by human intervention (Lima et al., 2020). It significantly negatively affects natural resources, terrestrial and aquatic ecosystems, human health, and human systems (García-Leoz et al., 2018). Human activities through greenhouse gas emissions have unequivocally caused global warming, with worldwide surface temperatures reaching 1.1 °C above 1850–1900 in 2011–2020 (Pörtner et al., 2022). Worldwide greenhouse gas emissions increased from 2010 to 2019, with uneven authentic and current contributions from unsustainable energy use, land use and land-use change, lifestyles and consumption, and production patterns within and between regions, countries, and individuals. Human-induced climate change is currently influencing numerous extreme climate events worldwide. This has widespread negative impacts on food and water security, human well-being, economies, and society, as well as losses and damage to nature and individuals. Vulnerable communities that have historically contributed the least to the current climate change are excessively affected (IPCC, 2023).

Correct accounting of greenhouse gas (GHG) emissions limits global warming below 1.5 compared to the pre-industrial era (UNFCCC, 2015; UNFCCC, 2021). In this regard, several countries have introduced national mitigation targets (Faragò et al., 2022). For example, the European Union aims to reduce its emissions by at least 55% by 2030 compared to 1990 (European Commission, 2021). Morocco launched its latest National Determination in 2021, which revised the objectives of the first version of 2016 into a 45.5% reduction objective for emissions by 2030, including an unconditional target of 18.3% (MTEDD, 2021). Agriculture is a significant source of greenhouse gases (Liu et al., 2022). In particular, agri-food systems contribute significantly to the dynamics of climate change. In 2008, food systems contributed 19% and 29% of global anthropogenic greenhouse gas emissions, releasing 9800 and 16 900 megatons of carbon dioxide equivalent ($MtCO_2eq$), respectively (Vermeulen et al., 2012). Rosenzweig et al. (2020) estimated that the food system accounts for 20–40% of human emissions from all different activities and Crippa et al. (2021) quantified food system contribution to approximately one-third of total human emissions. These important contributions further highlight the potential for food-related GHG mitigation, boosting innovative approaches in food supply chains and waste linked to mitigation at the level of agricultural operations and landscapes (Tubiello et al., 2021). More sustainable food production and consumption will require significant changes as national and international regulatory regimes are implemented to decrease greenhouse gas emissions (Rinaldi et al., 2014).

Argania spinosa (L.) is a tree endemic to southwestern Morocco that belongs to the family *Sapotaceae* (Ait Aabd et al., 2012). Over the years, the Amazigh population, an indigenous people of the North, inhabited the area of the Argan grove and developed a way of life dependent on it in the southwest of Morocco (Gharby and Charrouf, 2022). The production of argan oil, derived from the fruits of the *Argania spinosa* (L.) The skeels tree carries significant socioeconomic significance in Morocco, especially highlighting the pivotal contribution of Amazigh women. Each argan fruit contains a seed with up to five almonds from which argan oil is derived (Ait Aabd et al., 2012). Unroasted kernels yield cosmetic oils and roasted kernels yield edible oils (El Oumari et al., 2022; Mouahid et al., 2022). Regarding the bioactive components of the *Argania spinosa (L.) Skeels* tree, an oil cake, is a diverse source of bioactive phytochemicals (phenolic compounds) that remain after Argan oil extraction. It is suitable for consumption and boasts a mild yet distinctive flavor profile, making it a well-deserved reputation as one of the most nutritionally rich oils globally. This exceptional nutritional quality fuels its popularity among consumers and drives its incorporation into culinary applications. Traditionally, argan oil has been a customary ingredient for bread. Furthermore, it imparts exceptional flavor enhancement when drizzled over grilled salads, fish, tajin, and couscous. Argan oil serves as the primary ingredient in the preparation of “Amlou”, a peanut butter-like spread created by grinding toasted almonds with honey and argan oil (Guillaume and Charrouf, 2013). Argan oil is recognized as a globally traded commodity originating in Morocco, with various European and North American companies distributing it to markets worldwide (Gharby and Charrouf, 2022). The production of Argan oil is aimed at both local markets and international exports. As a result of the contract program developed under the agricultural strategy of the Green Morocco Plan (2008–2020), Argan oil exports reached 1348 tons, generating revenue of 273 billion Moroccan dirhams (MAPMDREF, 2023). Similarly, in a global context, where both production and consumption methods operate on a worldwide scale, the networks responsible for supplying raw materials and their distribution frequently span multiple national and regional boundaries (Yeung and Coe, 2015). The need for sustainability in the transformation of the agri-food and fruit industry has been demonstrated and has become imperative (O`Rourke, 2014).

Carbon footprint is an effective indicator for assessing the environmental aspects of agricultural activities (Weinheimer, 2010). It is defined as the sum of GHG's emitted by a service or product during the entire production process (Luo et al., 2021). Numerous studies have aimed to determine the carbon footprint of agricultural products, particularly vegetable oils (Rinaldi et al., 2014; Pattara et al., 2016; Proietti et al., 2017; Fernández-Lobato et al., 2021a,b; Lam et al., 2019). However, there appears to be a distinct lack of comparable research on Argan oil. The carbon offset mechanism will be fully implemented at the borders of the European Union from January 1, 2026, with a transition period from October 1, 2023, to December 31, 2025. As a partner of the European Union, Morocco is also affected by this process (ERTL et al., 2023). Exporters of oils from Morocco must calculate their carbon footprint to avoid the consequences of the carbon offset mechanism. Currently, there is a scarcity of data and scientific research that evaluates the estimated carbon sequestration and carbon emissions linked to the Moroccan Argan forest ecosystem and its products, such as the production of Argan oil. Given this lack, coupled with the importance of shaping the dynamics of combating climate change in Morocco, it is crucial to consider various aspects connected to carbon emissions within the Argan value chain. This involves exploring aspects such as carbon sequestration and evaluating the carbon footprint of the Argan oil produced. The investigation of these elements was the primary objective of this study. In this study, we conducted surveys of cooperatives and companies engaged in the production of Argan oil and its derived products. The main goal of this research was to evaluate the carbon emissions associated with the Argan value chain and identify ways to reduce its carbon footprint. Specifically, this study aims to pinpoint the sources that contribute the most to carbon emissions by analyzing the relationship between emissions from each source and the total emissions. This analysis was conducted by comparing the findings with those of other studies to determine the carbon footprint of Argan oil and to develop measures for optimization and reduction.

2. Materials and methods

2.1. Study area

The Argan Biosphere Reserve (ABR) is a unique and original feature of Morocco. It was the first biosphere reserve created in Morocco and was recognized by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) in 1988. The reserve spans an area of over 2.4 million hectares, as per UNESCO records in 2018. Revolved around the Argan tree, an indigenous forest species exclusive to Morocco, the reserve significantly holds the Argan tree as a biogeographical value asset and has become a major characteristic of the Macaronesian region. Forest ecosystems based on Argan trees are predominantly located in the southwestern region of Morocco. The Argan strata constitute the final barrier against the encroaching Sahara, exhibiting a remarkable adaptation as a result, Argan forests have become a shield against direct desertification, offering a wide range of products and applications that hold vital significance for individuals whose socio-economic activities are intricately tied to the various offerings of the Argan tree.

2.2. Surveys and data collection

Our study focused on the stakeholders involved in the Argan value chain, particularly targeting cooperatives and businesses (companies) within the Argan Biosphere Reserve zone (Fig. 1) to calculate their footprint. Given the extensive span of the Argan area, we categorized it into three agroecologically homogeneous regions, referred to as eco-regions: north, central, and south.

We utilized a stratified sampling approach to conduct surveys within the industrial entities operating in the argan sector. The database on the number and locations of cooperatives and companies within the Argan Biosphere Reserve was provided by the Moroccan Argan Federation (FIFARGANE) and the National Agency for the Development of Oasis and Argan Areas (ANDZOA), which are key players in the development of the Argan sector. For logistical reasons, we initially decided to survey 10% of the facilities in each category of each eco-region.

Our initial attempts to survey randomly selected cooperatives have been unsuccessful. The combination of consecutive years of drought and the conditions imposed by the coronavirus disease (COVID-19) pandemic significantly affected Argan oil production and distribution, rendering many cooperatives non-operational. In addition, functional actors displayed reservations in providing information, particularly for companies that increasingly guarded data sensitivity and trade secrets. Considering these circumstances - functional limitations and business skepticism - in relation to the substantial effort and logistics required, fewer actors were surveyed compared to the original plan. To facilitate thorough calculations, we developed detailed questionnaires that encompass the entire argan oil production value chain—from fruit harvest to oil distribution. These questionnaires are crafted to gather specific information, including quantities of processed fruits, transportation distances to processing facilities, consumption of electricity and butane gas during processing, details about personnel transportation, procurement of packaging materials, and organizational equipment such as computers, printers, air conditioners, building

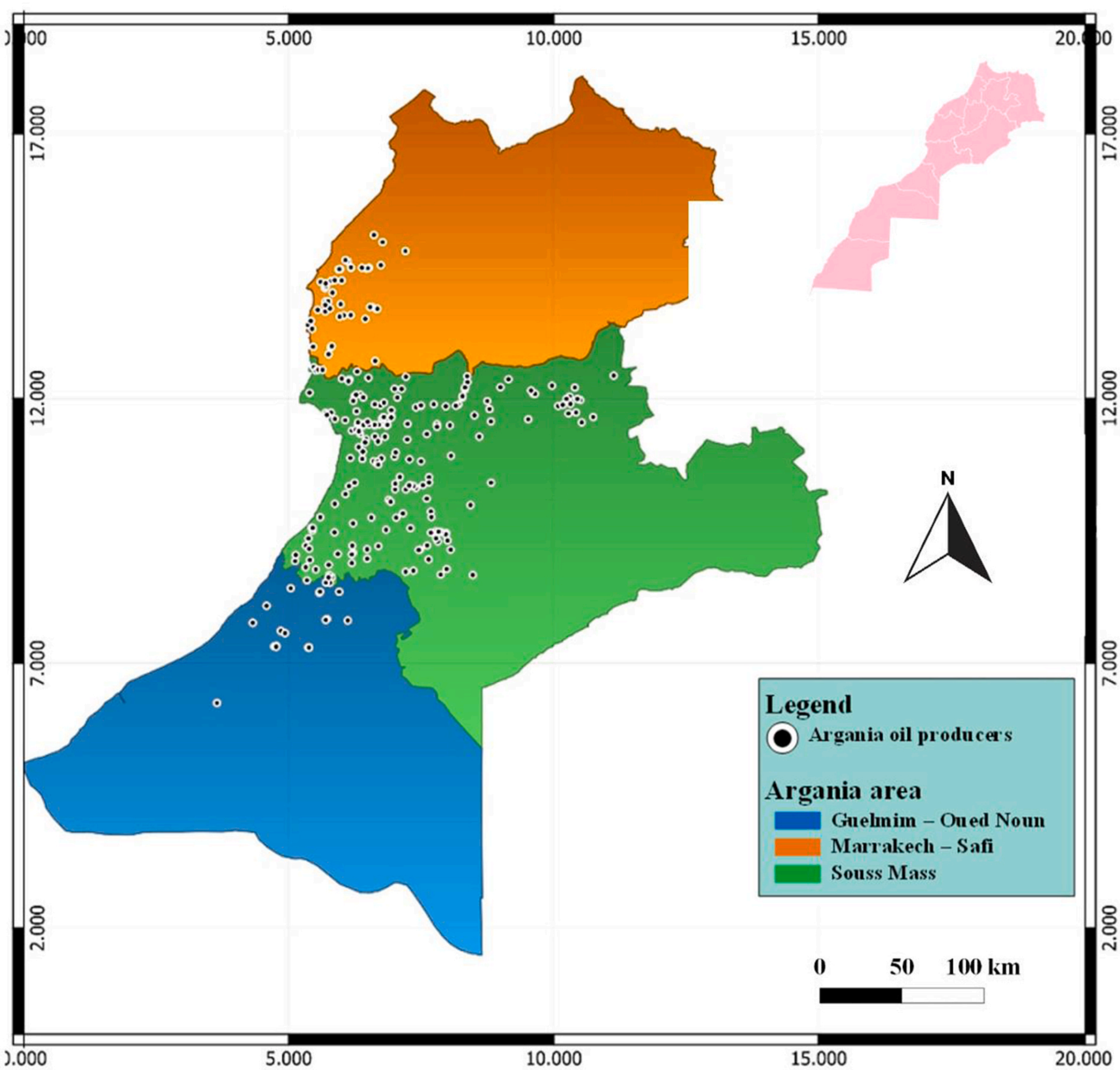


Fig. 1. Geographical dispersion of cooperatives within the Argan Biosphere Reserve. The Arganeraie Biosphere Reserve spans across three regions in Morocco: Guelmim-Oued Noun, Marrakech-Safi, and Souss-Massa. The production units under investigation in the present study are located within these specified regions (ANDZOA/FIFARGAN, 2019).

depreciation, etc. Additionally, the flow of oil distribution is also documented. The administration of these questionnaires took place on-site in collaboration with representatives from the organizations under study. Surveys were carried out from late 2021 to early 2023, involving a total of 16 cooperatives and 10 companies (Supplementary Table 1). Nevertheless, we believe that the collected and analyzed data from this sample would offer an overarching perspective of the value chain for the studied region and a more detailed insight into the entire Argan sector. Notably, owing to the unavailability of certain key managers and the seasonal closure of some entities, a few surveys were conducted through telephone calls or emails. Our surveys covered the entirety of the Argan oil extraction process and its derivatives, ranging from fruit collection to packaging and export. To mitigate the potential bias caused by the COVID-19 lockdown in oil production, we used 2019 as the reference year for the collected production data.

2.3. Theory/calculation

This tool was developed by Mohammed VI Environmental Protection Foundation (FM6E). Aligned with ISO 14069 and greenhouse gas protocols, this tool was built on a database comprising 300 emission factors derived from international publications and databases (IPCC AR6, Base Carbone®), with 100 being specific to Morocco. Emission factors are employed to transform activity or source information into the quantity of gas emitted. By multiplying this amount by the characterization factor, the climate impact is quantified, which is expressed in tons of carbon dioxide equivalent (tCO_2eq). In numerous situations, emission factors consider the Global Warming Potential and convert activity data directly into tCO_2eq (IPCC, 2023).

The tool's development builds upon an initial 2013 study focused on establishing a Greenhouse Gases accounting tool. The current approach involves updating prior work by collecting recent data after 2013 and refining emission factors to suit the Moroccan context. Extensive research has been conducted to enhance was carried out, enhancing the accuracy of results for the development developing of a credible carbon accounting tool tailored to the Moroccan context. The Mohamed VI Foundation for the Protection of the Environment led the update of the existing Greenhouse Gases accounting tool through a participatory approach involving stakeholders related to sectors or activities emitting greenhouse gases. Most of these stakeholders actively contribute to the study's oversight committee. Additionally, the "Association pour la Transition Bas Carbone Française (ABC)" aids project owners and ensures compliance with the Bilan Carbone® methodology (FM6E, 2023).

Housed within the spreadsheet calculator, it encompasses both an overarching summary result sheet and individual sheets dedicated to each emission component. The tool addresses emissions across three distinct categories (Table 1). Scope 1 emissions, also known as direct emissions, are generated from activities owned or controlled by the organization. Examples of these emissions include combustion from boilers, furnaces, and vehicles that are owned or controlled as well as emissions from chemical production in process plants that are owned or controlled. On the other hand, Scope 2 emissions, or indirect emissions, are associated with the consumption of purchased electricity, heat, steam, and cooling, and they are released into the atmosphere. These emissions are the result of an organization's energy consumption, but they arise from sources that the organization does not own or control. Finally, Scope 3 emissions, or other indirect emissions, are a result of an organization's actions that occur at sources that are not owned or controlled and are not classified as Scope 2 emissions. Examples of Scope 3 emissions include business travel that is not owned or controlled by the organization, waste disposal, purchased materials, or fuels that are not owned or controlled by the organization (Hill et al., 2021). This tool is based on the use of emission factors and activity data. The French Environment and Energy Management Agency (ADEME) defines activity data as quantities specific to a given service or activity. For example, the activity data for "heating a building" could be the energy consumption required for this service, or, if the data are not available, the heated surface area of this building. Emission factors provide an idea of the quantity of greenhouse gases, expressed in tons of CO_2 equivalent (tons or tCO_2 eq), resulting from the "mobilization" of a given unit of service (ADEME, 2014). Table 2 summarizes the equations employed to calculate the emissions for each emission area and source.

Table 1
Comprehensive assessment of carbon emission scopes and their associated components in the development of a calculation tool, featuring detailed emission subcategories.

Emissions scope	Content of the scope of the emissions	Emission sources
Scope 1	Direct Greenhouse Gas emissions from Greenhouse gas sources owned or directly controlled by the organization	- Combustion stationary sources - Combustion mobile sources - Wastewater treatment - Climatization - Agriculture - Land Use, Land Use Change and Forestry
Scope 2	Greenhouse Gas emissions from the generation of purchased electricity, heat, cooling, or steam consumed by the organization	- Electricity
Scope 3	Greenhouse Gas emission that is a consequence of the organization's activities but arises from greenhouse as sources that are not owned or directly controlled by the organization	- Purchase - Fixed Assets - Waste - Freight-Merchandise - Mobility-people - Vehicle Manufacturing

2.4. Functional unit and emission sources

We selected 1 L of Argan oil as the functional unit for our study. The decision to adopt 1 L as the functional unit stems from its widespread use as a standard measure for argan oil in production, trade, and consumption contexts in Morocco. While some professionals, particularly companies, may utilize the ton unit (that considers oil density), the liter unit is more commonly employed by cooperatives. Packaging units smaller than 1 L are typically utilized due to the expensive nature of the oil, but selecting 1 L as the standard unit is more conceivable. Concentrating on 1 L enables a more accessible and comprehensible analysis of the carbon footprint linked to the production process, especially for the general public and decision-makers. This facilitates comparisons with other oils, enhancing accessibility for stakeholders. A functional unit is a quantitative description of a product's functionality and serves as the reference standard for all impact-assessment calculations. Functionality can be determined on the basis of the diverse attributes of the products examined. Examples include performance, aesthetics, technical quality, supplementary services, and cost (Arzoumanidis et al., 2020). The measurement of CO_2 emissions was confined to the timeframe from fruit harvesting and transportation to distribution of the produced oil. This rationale is called "Cradle to grave" principle within of lifecycle analysis philosophy. It includes all stages, from the extraction of materials and fuels from the environment to the point where all materials are returned to the environment (Nieuwlaar, 2013).

Argan fruits can undergo two distinct processing methods (Fig. 2) as outlined by Gharby and Charrouf (2022). The first, referred to as the traditional route, is predominantly employed by most cooperatives and encompasses seven stages. In the first stage, ripe fruits are manually gathered from the argan forest between May and August, then sun-dried for a few weeks. Following the drying period, the dried peel is manually removed, resulting in "argan nuts." The argan nuts are cracked open, and the kernels are meticulously selected and collected. The kernels then undergo gentle roasting in clay plates for several minutes, with the duration determined by individual judgment based on color and smell.

Table 2
Tabulated overview of emission calculation formulas organized by emission scope and source.

Emission scope	Emission Source	Emission calculation (Kg eq $CO_2.l^{-1)}$	Uncertainty (%)	Source
Scope 1	Diesel	Diesel consumption (liter) x Diesel emission factor (Kg eq $CO_2.liter^{-1}$)	10	Mohammed VI Foundation for Environmental Protection
	Butane	Butane consumption (Ton) x Butane emission factor (Kg eq $CO_2.Ton^{-1}$)	10	
	Harvesting via donkeys and mules	Animal number x emission factor (Kg eq CO_2)	73	
Scope 2	Electricity[a]	Electricity consumption (KWh) x (1+ online loss) x Electricity emission factor (Kg eq $CO_2.KWh^{-1}$)	10	
Scope 3	Cardboard waste	Cardboard waste (Ton) x emission factor (Kg eq $CO_2.Ton^{-1}$)	50	
	Plastic waste	Plastic waste (Ton) x emission factor (Kg eq $CO_2.Ton^{-1}$)	50	
	Animal food	Animal number x emission factor (Kg eq CO_2)	74	
	Purchase & materials[b]	Σ raw material purchased quantity (Ton) x raw material emission factor (Kg eq $CO_2.Ton^{-1}$)	10–20	
	Fixed assets[c]	(Σ number of items (unity) x raw material emission factor (Kg eq $CO_2.unity^{-1}$))/ payback time (years)	Depends on the item	
	Transportation & exportation[d]	Σ Distance covered (Km) x emission factor (Kg eq $CO_2.Km^{-1}$)	10	

[a] Line losses were considered when calculating emissions associated with electricity consumption, a natural phenomenon. During transmission between the place of generation and delivery, electricity is subject to losses, the amount of which depends on the current strength, the transmission distance, and the characteristics of the network.

[b] For purchases and equipment, there are several items (purchases: plastic, glass, etc., and equipment: computers, printers, etc.). Emissions are the sum of each item's emissions.

[c] Purchases, materials, buildings, and other items are depreciated. Emissions from depreciation are the total emissions from the depreciation of each item.

[d] Transports and exports are carried out using different types of vehicles. Emissions are the total emissions for each vehicle type.

The roasted kernels are crushed using a millstone, involving two stones—a foundation stone and a cone-shaped rotating piece. This artisanal process ensures the kernels are finely ground. The resulting oily dough undergoes manual malaxing for several minutes with the addition of small amounts of water. As the dough sets, it releases an emulsion from which argan oil is decanted. The final stage involves traditional oil production, a complex process requiring 24 hoursof work for a single person to extract about 1 L of oil from 50 kg of fruit. The solid residue may still contain up to 25%, and conventional extraction raises concerns about hygienic conditions, bacteriological safety, traceability, and oxidative stability (Charrouf and Guillaume, 2013). To address these issues, modifications were made to enhance quality and traceability by improving extraction technology (Gharby and Charrouf, 2022).

The second production route is mechanical, primarily adopted by companies. This method, as highlighted by Hilali et al. (2005), not only enhances the certified quality of the oil but also improves its yield. The process involves mechanical peeling of the fruits, and oil extraction is achieved through pressing. Advancements in this process have eliminated the use of water for extraction, and the roasting step has been refined. This approach offers two advantages: it allows the classification of argan oil as "extra virgin argan oil," comparable to olive oil, and it retains all the known benefits of argan oil with the added efficiency of the new technology (Gharby and Charrouf, 2022).Argan oil producers use butane gas (especially traditional cooperatives) and electricity to meet the needs of various processing machinery (pulping, roasting, etc.). The diesel consumption of mobile company vehicles is also considered. Petroleum production generates waste that requires the use of packaging materials and equipment. The by-product of Argan fruit processing serves as feed for goats. In Supplementary Fig. 1, different emission positions and their corresponding ranges can be observed. Supplementary Table 1 shows the emission sources used in our case study.

2.5. *Statistical analysis*

We assessed relationships between emissions from the various sources and total emissions from the oil production activity, using correlation analysis. Regression analysis was utilized to predict the changes in the carbon footprint of argan oil as a function of variations in emissions from different sources. Also, a principal component analysis (PCA) was performed. Our analyzes were conducted using Microsoft Excel.

3. Results and discussion

The data gathered from all surveys was utilized to derive diverse results and subsequently advance the discussions. The carbon footprint of Argan oil produced by companies and cooperatives was assessed across three distinct scenarios. The first scenario comprised three emission areas caused by export activities. The second scenario maintained the three scopes but eliminated the export share, while the third scenario only included Scope 1 and Scope 2. As outlined in the methodology section, emissions were categorized into direct (Scope 1) and indirect energy emissions (Scope 2). By examining the carbon footprint of Argan oil in these three different situations, we aimed to understand its environmental impact at various levels.

3.1. *Argan oil carbon footprint: role of export*

Including exports, the carbon footprint of oil produced by companies (10.17 ± 4.67 kg CO_2 eq.l^{-1}) is higher than that of oil produced by cooperatives (8.68 ± 4.26 kg CO_2 eq. l^{-1}). However, when excluding

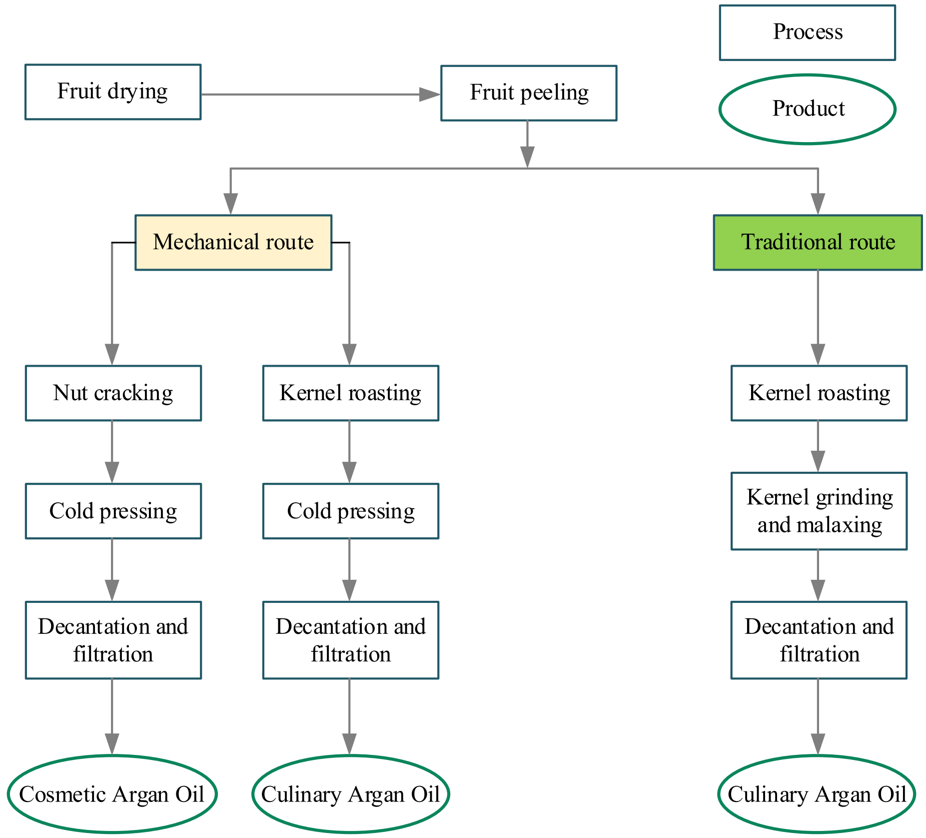


Fig. 2. Different Argan oil extracting techniques. Cooperatives typically follow traditional methods, while companies follow mechanical extraction processes (Gharby and Charrouf, 2022).

exports, the most noteworthy aspect is the higher CO_2 footprint of oil from cooperatives compared to companies (6.32 ± 4.65 kg CO_2 eq.l^{-1} vs. 3.71 ± 2.92 kg CO_2 eq.l^{-1} respectively). In contrast to cooperatives, companies exhibit greater reliance on global markets for product distribution. Most cooperative markets are local, and identifying company content with the local market is a rare occurrence. Rethinking Argan oil

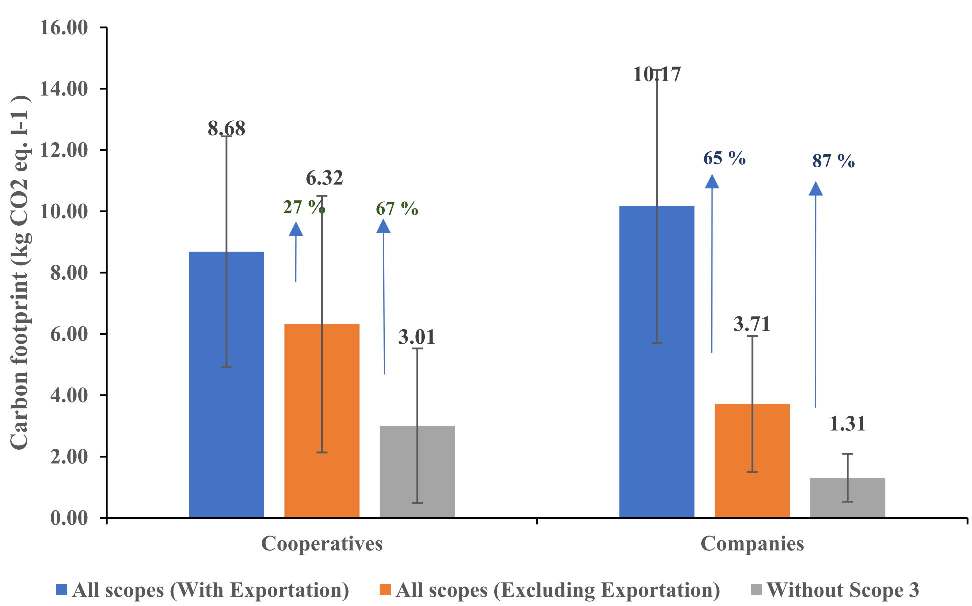


Fig. 3. Average carbon footprint values (kg CO_2 eq.l^{-1}) for Argan oil produced by cooperatives and companies. This study assessed the carbon footprint of cooperatives and companies producing argan oil using three different scenarios. Scenario 1: Greenhouse gas emissions from scopes 1, 2, and 3 are considered, including emissions associated with exports. Scenario 2: This includes emissions from scopes 1, 2, and 3, excluding those associated with exports. Scenario 3: Focuses specifically on Scope 1 and 2 emissions, the latter being the direct emissions generated by production units (Scope 1) or over which these units have partial control through their energy-related decisions (Scope 2). Error bars refer to standard deviation, n = 16 for cooperatives and 10 for companies).

production processes by implementing greener export methods or focusing on local consumption has the potential to curtail carbon footprints by approximately 65% for companies and 27% for cooperatives (Fig. 3).

3.2. Argan oil carbon footprint: scope 3 impact

The 15 categories of Scope 3 emissions, which include both upstream and downstream activities, vary in relevance, depending on the organization's industry and type. Although Scope 3 emissions are typically the largest source of emissions for most companies, significant differences exist between the sectors. However, because of their extraneous nature, calculating Scope 3 emissions is complex. Companies face distinct challenges in measuring and reporting Scope 3 emissions based on their maturity levels. Lower-maturity companies may grapple with data access and limited awareness, while higher-maturity companies may encounter challenges associated with supply chain intricacy. However, the most advanced companies face additional challenges such as stakeholder engagement, data accuracy, global regulations, and intricate, interconnected operations (Deloitte, 2023).

The third scenario examined in our analysis of the carbon footprint results was the exclusion of Scope 3 emissions. Under this scenario, the carbon footprint decreased significantly (Fig. 3). At the company level, the average carbon footprint dropped to 1.31 ± 0.84 kg CO_2 eq.l^{-1}, assuming that oil producers are exporters. This represents a reduction of 87% compared with the first scenario and 65% compared with the second scenario. For cooperatives, the average carbon footprint increased to 3.01 ± 2.65 kg CO_2 eq.l^{-1}, which is 67% lower than in the first scenario and 54% lower than in the second scenario.

3.3. Emissions scopes and emission sources

The largest contributor to the company's carbon emissions from oil extraction was identified within scope 3 of the emissions category. This category, encompassing exports, generated 85.70% of total carbon dioxide emissions. Even with exports excluded, Scope 3 remained the prevailing category, constituting 60.72 % of the CO_2 emissions. A similar pattern emerges for cooperatives, albeit with distinctions in Scope 3 of merely 8.13 %, between including and excluding exports. This is attributed to the prevalent practice of non-exportation among most of the cooperatives. The CO_2 emissions arising from Scope 2, linked to electricity consumption, are significant for cooperatives when considering both export scenarios (Fig. 4). Scope 1 primarily stems from the consumption of butane gas during retrofitting and the fuel consumption in company vehicles. However, its relative contribution is minor. When exports were excluded, several emission sources had a notable impact on companies' carbon footprint (Fig. 4). These included electricity consumption, purchases, animal feed-related emissions, and diesel consumption. However, for cooperatives, regardless of their export status, significant shares were attributed to electricity consumption, fixed assets, and purchases (Fig. 5). When Scope 3 is disregarded, electricity consumption (Scope 2) emerges as the most significant contributor, accounting for 26.37% (Scenario 2), 66.97% (Scenario 3) of the companies oil carbon footprint and 33.43% (Scenario 2) and 75.57% (Scenario 3) of the cooperatives oil carbon footprint.

3.4. Comparing carbon footprints: companies vs. cooperatives

3.4.1. Cooperatives

Correlation and regression analyses were conducted for the two types of oil-producing organizations (companies and cooperatives) in three distinct scenarios (Tables 3 and 4). In the case of cooperatives, it was found that butane consumption, electricity consumption, and export activities played a significant role in controlling variations in carbon emissions. A strong positive relationship was identified between total emissions and butane consumption ($r = 0.78$ for the first and second scenarios; r=0.69 for the third scenario) and electricity consumption ($r = 0.89$, for the first scenario; $r = 0.66$, for the second scenario; $r =$

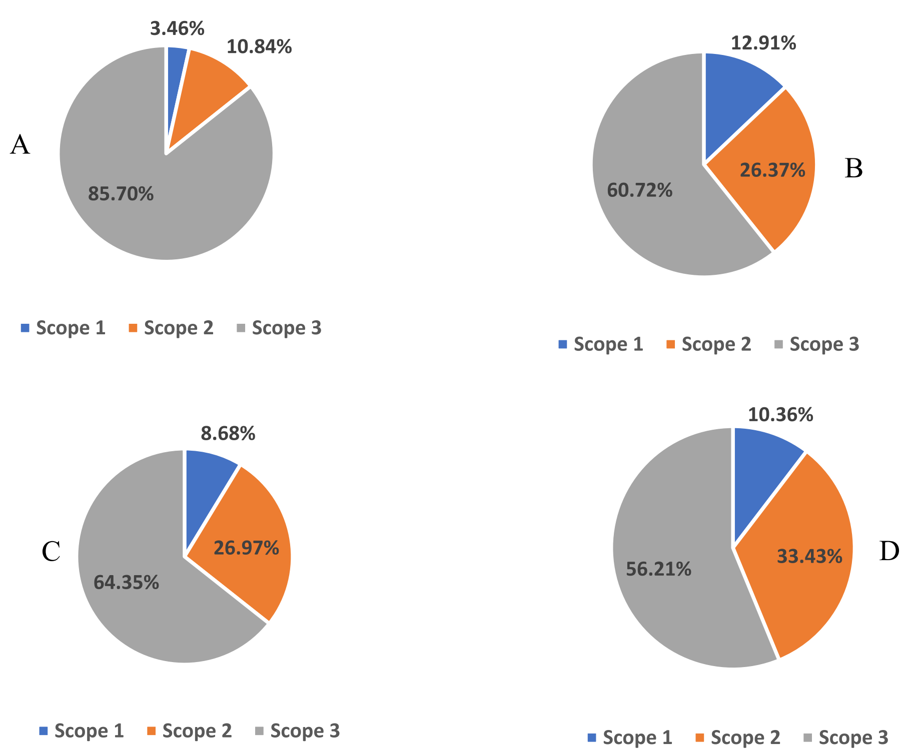
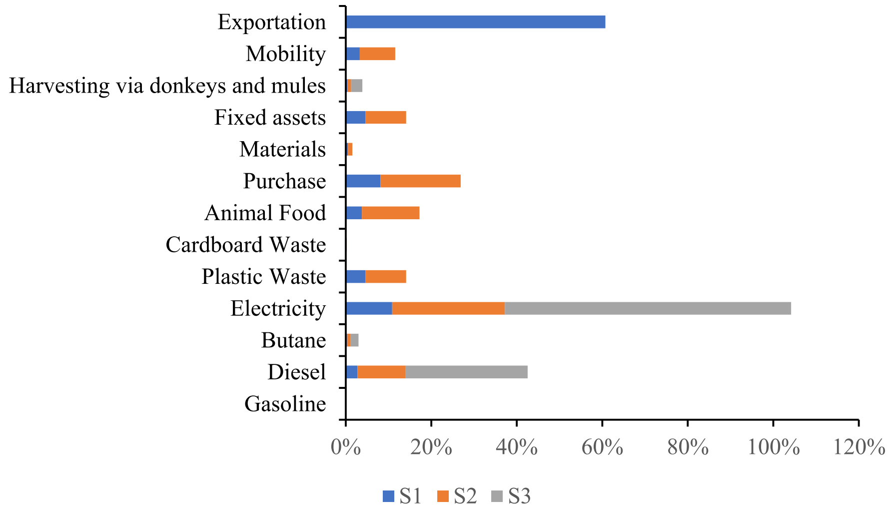
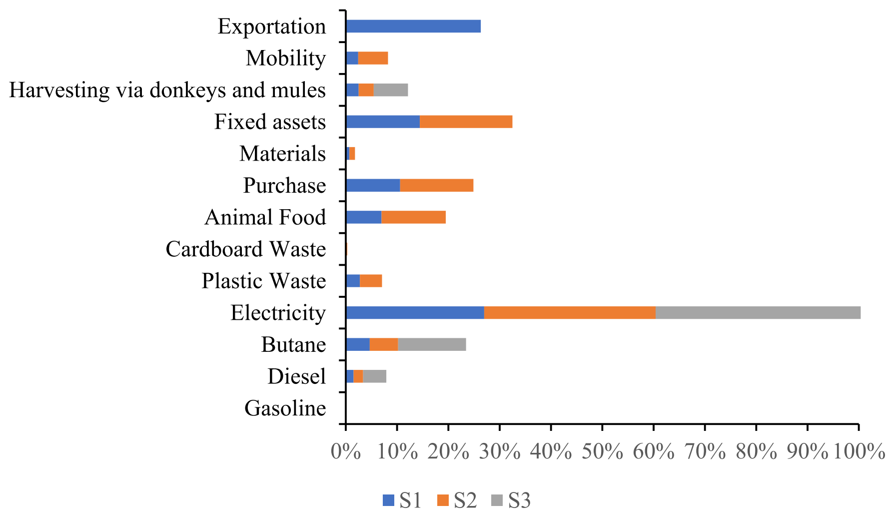


Fig. 4. Percentage breakdown of the three emission scopes contributing to the carbon footprint of companies and cooperatives across various export scenarios. Notations include A for companies with exports, B for companies without exports, C for cooperatives with exports, and D for cooperatives without exports. Scope 1 encompasses direct emissions linked to the production process (e.g., butane consumption), Scope 2 involves indirect emissions associated with electricity consumption, and Scope 3 covers all other indirect emissions (e.g., waste management, transport).



A



B

Fig. 5. Distribution of emission source contributions in percentage terms across different scenarios: S1 represents the first scenario (Scope 1, 2, and 3 with export), S2 represents the second scenario (Scope 1, 2, and 3 without export), and S3 represents the third scenario (area 1 and 2) (A: companies and B: cooperatives).

0.97, for the third scenario). It is also worth noting that the correlation between total emissions and emissions from harvesting via donkeys and mules is significant. The regression analysis provides insight into the relationship between total emissions and Scopes emission sources. If we take the example of cooperatives in the first scenario, an increase of 1 kg eq CO_2 from butane consumption results in a total emission increase of 111.09 kg eq CO_2 (as shown in Supplementary Fig. 2), while an increase of 1 kg eq CO_2 from electricity consumption leads to a total emission increase of 21.19 kg eq CO_2 (as depicted in Supplementary Fig. 3). The first scenario is characterized by export activities, which are closely related to total emissions ($r = 0.99$). An increase of 1 kg eq CO_2 from exports led to an increase in total emissions of 1.28 kg eq CO_2 (Supplementary Fig. 4). In the second scenario, a loss of exports causes the electricity consumption to retain its influence ($r = 0.66$). Based on 1 kg eq CO_2 from electricity consumption, there is a carbon emission of 5.09 kg CO_2 equivalent (Supplementary Fig. 5). In contrast, animal feed ($r =$ 0.91) and transport ($r = 0.78$) increased total emissions. Animal feed and transportation can increase emissions of 3.98 kg eq CO_2 and 7.93 kg eq CO_2, respectively (Supplementary Figs. 6 and 7). In the third scenario, an increase in butane consumption ($r = 0.69$) and electricity consumption ($r = 0.97$) leads to an increase of 4.6 kg eq CO_2 and 1.08 kg eq CO_2, respectively (Supplementary Figs. 8 and 9). In the third scenario, butane and electricity consumption contributed significantly to total emissions. An increase of 1 kg eq CO_2 from butane means 4.06 kg eq CO_2 more emissions. For the same reason, an increase of 1 kg eq CO_2 from butane means an increase in total emissions of 1.09 kg eq CO_2.

3.4.2. *Companies*

Exports have a significant impact on companies with a correlation coefficient of 0.95. For every 1 kg eq CO_2 emissions from exports, there are 1.06 kg eq CO_2 emissions in total (as shown in Supplementary Fig. 11). However, in contrast to cooperatives, 1 kg eq CO_2 emissions

Table 3
Tabulated overview of the outcomes of correlation analysis, including p-values of 0.1, between carbon emissions from individual sources and the overall carbon emissions in three distinct scenarios.

Emission scope	Emission source	Scenario					
		Scenario 1 (Scope 1, 2 & 3 + Exportation)		Scenario 2 (Scope 1, 2 & 3 – Exportation)		Scenario 3 (Scope 1 & 2)	
		Companies	Cooperatives	Companies	Cooperatives	Companies	Cooperatives
Scope 1	Diesel	0.76 (0.007)	−0.11	0.41	−0.005	0.37	0.1
	Butane	0.16	0.78 (7.12 E−05)	0.42	0.78 (0.03)	0.76 (0.005)	0.69 (0.002)
	Harvesting via donkeys and mules	0.54	0.71 (0.03)	0.91 (4.8 E−04)	0.64 (0.004)	0.58 (6.93 E−05)	0.73 (0.004)
Scope 2	Electricity	0.51	0.89 (0.04)	0.71 (0.01)	0.66 (0.004)	0.88 (2 E−04)	0.97 (0.03)
Scope 3	Cardboard waste	−0.28	0.29	−0.15	0.41	–	–
	Animal food	0.46	0.73 (6 E−04)	0.42	0.91 (1.1 E−07)	–	–
	Purchase	−0.02	0.69 (0.002)	0.71 (0.02)	0.84 (1.2 E−05)	–	–
	Fixed assets	0.22	0.53	0.35	0.68 (0.007)	–	–
	Transportation	0.16	0.64 (0.008)	0.73 (0.009)	0.78 (1 E−04)	–	–
	Materials	0.26	0.88 (3.1 E−07)	0.65 (0.03)	0.68 (0.02)		
	Plastic Waste	−0.01	0.49	0.35	0.73 (0.0004)	–	–
	Exportation	0.95 (6.6 E−06)	0.99 (3.7 E−03)	–	–	–	–

from diesel consumption can lead to 24.73 eq CO_2 equivalent emissions in total (as shown in Supplementary Fig. 10). In the second scenario, an increase in emissions related to electricity consumption ($r = 0.71$) could result in a 1.33 kg increase in total CO_2 equivalent emissions (as shown in Supplementary Fig. 12). Additionally, purchases ($r = 0.71$) and transportation ($r = 0.78$) can lead to an increase in total CO_2 equivalent emissions of approximately 3.06 kg and 4.75 kg, respectively (as shown in Supplementary Figs. 13 and 14). Also, the correlation between total emissions and emissions from harvesting via donkeys and mules is significant ($r = 0.91$ for the second scenario; r=0.58 for the third scenario). In the third scenario, an increase of 1 kg eq CO_2 of butane consumption ($r = 0.76$) and electricity consumption ($r = 0.88$) could increase total CO_2 equivalent emissions by 41.6 kg and 0.96 kg, respectively (as shown in Supplementary Figs. 15 and 16).

One of the benefits of differentiating between these three scenarios is the ability to examine the impact of each emission source. It can be observed that certain sources, such as cardboard, plastic waste, capital goods, and equipment, do not have a significant impact on total emissions. However, sources, such as animal feed, purchasing, and transportation, are not always important. Analysis of the different scenarios using regression and correlation techniques clearly indicated that butane consumption (Scope 1) and electricity consumption are typically the sources that have a significant impact on emissions. An increase in emissions from these sources directly leads to an increase in overall emissions. Considering these impacts and the fact that oil producers are primarily responsible for these sources (rather than Scope 3), measures can be taken to reduce CO_2 emissions in general, and specifically to optimize the carbon footprint.

3.4.3. Companies vs cooperatives

In the first scenario, the average carbon footprint of companies surpasses that of cooperatives (Fig. 3). This disparity is predominantly attributed to Scope 3 emissions, particularly those associated with exports. Notably, companies exhibit substantially higher CO_2 emissions related to export activities, averaging 193.46 tons of CO_2 equivalent, in contrast to cooperatives emitting an average of 38.45 tons of CO_2 equivalent. The reason for this disparity is that all the companies in our study export their production and usually operate on a larger scale, whereas cooperatives do not consistently engage in exports.

Although cooperatives have a lower production capacity than companies, their average carbon footprint is higher in the second and third scenarios. To explain this observation, it is necessary to examine the efficiency of oil production. Cooperatives use more electricity per liter of oil produced than companies do, with an average electricity consumption of 3.59 $KWh.l^{-1}$ compared to companies' maximum of 1.48 $KWh.l^{-1}$. This results in a higher carbon footprint for cooperatives (2.31 kg eq $CO_2.l^{-1}$) than for companies (0.78 kg eq $CO_2.l^{-1}$). Similarly, cooperatives use more butane per liter of Argan oil produced than companies, with 34.91 L of butane used by cooperatives compared to 4.58 L used by companies. This difference in butane consumption per liter of oil produced also affects the butane carbon footprint, with cooperatives having a higher footprint (0.3 kg eq $CO_2.l^{-1}$) than companies (0.04 kg eq $CO_2.l^{-1}$).

3.4.4. Sensitivity analysis

Sensitivity analysis involves examining how uncertainty in a model's output can be apportioned among the various sources of uncertainty in its input. One approach to sensitivity analysis is the "one-at-a-time" method, which was used to investigate the sensitivity of electricity and butane consumption (in terms of activity data and emission factors) to carbon emissions. Table 5 summarizes the results of the sensitivity analysis of electricity and butane consumption for companies and cooperatives. Significant fluctuations in electricity consumption can affect the carbon footprint. For instance, when the average electricity consumption of companies reaches 60 000 kWh, the average carbon footprint of electricity can rise to 1.66 kg eq $CO_2.l^{-1}$ (compared to 0.83 kg eq $CO_2.l^{-1}$ under current conditions). The situation is similar for cooperatives, where the average carbon footprint from electricity can be approximately 2 kg eq $CO_2.l^{-1}$ (compared to 0.8 kg eq $CO_2.l^{-1}$ under current conditions). Reducing the emission factor of electricity consumption is a significant challenge, and primarily involves integrating renewable energy into electricity generation. If the emission factor is lowered to approximately 0.043 kg eq $CO_2.KWh^{-1}$, the average carbon footprint drops to 0.06 kg eq $CO_2.l^{-1}$ for companies and 0.53 kg eq $CO_2.l^{-1}$ for cooperatives. Crude oil production must be aligned with electricity consumption. A decrease in production can negatively affect carbon footprint. With an average crude oil production of 6000 L for companies and 1200 L for cooperatives, the average carbon footprint can reach 3.6 and 4.8 kg eq $CO_2.l^{-1}$, respectively.

The amount of butane consumed can have an impact on the average carbon footprint resulting from that consumption, particularly for companies. The footprint can range from 0.01 kg eq $CO_2.l^{-1}$ under

Table 4
Tabulated overview of the results of linear regression analysis, with a significance level set at a p-value of 0.1, depicting the relationship between carbon emissions from individual sources and the total carbon emissions in three different scenarios.

Emission scope	Emission source	Scenarios											
		Scenario 1 (Scope 1, 2 & 3 + Exportation)				Scenario 2 (Scope 1, 2 & 3 – Exportation)				Scenario 3 (Scope 1 & 2)			
		Companies		Cooperatives		Companies		Cooperatives		Companies		Cooperatives	
		Constant	Regression coefficient	Constant	Regression coefficient	Constant	Regression coefficient	Constant	Regression coefficient	Constant	Regression coefficient	Constant	Regression coefficient
Scope 1	Diesel	63 297.3	24.73	Insignificant		Insignificant		Insignificant		Insignificant		Insignificant	
	Butane	Insignificant		−25 203.26	111.09	insignificant		Insignificant		11 452.21	41.6	2994.24	4.6
	Harvesting via donkeys and mules	Insignificant		Insignificant		402.34	−106 703.3	160.6	−36 505.61	Insignificant		Insignificant	
Scope 2	Electricity	Insignificant		−54 627.95	21.19	40 864.17	1.33	−6903.64	5.1	9530.79	0.96	976.3	1.09
Scope 3	Cardboard waste	Insignificant		Insignificant		Insignificant		Insignificant		–	–	–	–
	Animal food	Insignificant		Insignificant		Insignificant		5895.12	3.99	–	–	–	–
	Purchase	Insignificant		Insignificant		28 478.02	3.04	Insignificant		–	–	–	–
	Fixed assets	Insignificant		Insignificant		Insignificant		Insignificant		–	–	–	–
	Transportation	Insignificant		Insignificant		37 054.98	4.76	10 048	7.93	–	–	–	–
	Materials	Insignificant		Insignificant		Insignificant		Insignificant		–	–	–	–
	Plastic Waste	Insignificant		Insignificant		Insignificant		Insignificant		–	–	–	–
	Exportation	52 677	1.06	9251.69	1.28	–	–	–	–	–	–	–	–

current conditions to 0.03 kg eq $CO_2.l^{-1}$ when average butane consumption reaches 0.3 tons and tends towards 0 when average butane consumption reaches 0.5 tons. Currently, cooperatives have an average carbon footprint of 0.02 kg eq $CO_2.l^{-1}$. However, if butane consumption increases to 0.6 tons, the average butane carbon footprint could rise to 0.07 kg eq $CO_2.l^{-1}$. On the other hand, if butane consumption decreases to 0.1 tons, the average butane carbon footprint could drop to 0.01 kg eq $CO_2.l^{-1}$. Replacing butane with less polluting gas can result in a significant reduction in the average butane carbon footprint. For example, if the gas used has an emission factor of 1428 kg eq.T^{-1} (compared to 3248 kg eq.T^{-1} for the current butane emission factor in Morocco), the average butane carbon footprint of companies and cooperatives would tend towards 0. It is important to ensure that the level of oil production is consistent with butane consumption and electricity. When average oil production drops to 10 000 L for companies and 1200 L for cooperatives, the average butane carbon footprint drops to 0.03 and 0.57 kg eq $CO_2.l^{-1}$, respectively.

3.4.5. *Principal component analysis*

Principal Component Analysis delving into the emissions profiles of both cooperatives and companies provides a nuanced understanding of the underlying factors shaping their environmental impact. The discerned inflection points on the scree plots guided the decision to retain three components for cooperatives and four for companies, underscoring the significance of the identified components in capturing the variance within the emission datasets.

Supplementary Fig. 17 and Table 6 summarize the principal component analysis results for companies. Three components emerge from this analysis, the first component (Process) is linked to elements in the production process, incorporating electricity, transportation, materials, butane, and purchase. The second component (Harvesting, Distribution & Energy) amalgamates harvesting, distribution, and energy-related elements, such as diesel and exportation. The third component (Others) encompasses various elements, including animal feed, plastic waste, and fixed assets. Supplementary Fig. 18 and Table 7 summarize the principal component analysis results for cooperatives. Three components emerge from this analysis, the first component (Process, Harvesting & Distribution) is marked by significant loadings for elements related to the production process and distribution, encompassing butane, electricity, animal feed, purchase, materials, transportation, and exportation. The second component (Waste management & energy) comprises elements associated with waste management and energy, including cardboard waste, plastic waste, and diesel. The third component (Fixed assets) is predominantly characterized by fixed assets.

In the case of companies, the existence of an additional fourth component, with an eigenvalue superior to 1, underscores the complexity of their emissions landscape, revealing diverse elements beyond the core operational triad of production, distribution, and energy. For cooperatives, the three components pinpoint critical aspects such as production processes, waste management and energy, and fixed assets that contribute significantly to their emissions. This breakdown facilitates a granular assessment, allowing cooperatives to tailor their strategies towards specific operational domains. The principal component analysis provides recommendations aiming to translate these insights into actionable strategies. For cooperatives, the emphasis is on enhancing efficiency in production processes, implementing effective waste management strategies, and optimizing energy usage. These targeted measures align with the identified influential components, promoting a focused and impactful approach to emission reduction. Meanwhile, companies are urged to adopt a holistic strategy that not only addresses production processes, distribution, and energy but also encompasses a broader consideration of diverse factors contributing to emissions. This holistic approach recognizes the multifaceted nature of emissions in companies, guiding them towards comprehensive and sustainable mitigation measures.

Table 5
Summary of results from sensitivity analysis using the one-at-a-time method for electricity and butane in the average carbon footprint. The analysis was conducted under three scenarios. Case 1: keeping the emission factor constant while varying oil production and consumption; Case 2: holding consumption and oil production constant and varying the emission factor; and Case 3: Maintaining consumption and emission factor constant, with variation in oil production.

Production factor	Case	Companies Carbon footprint (Kg eq CO2.l-1)								
Electricity	Case 1	0.28	0.55	0.83	1.11	1.38	1.66			
	Case 2	0.06	0.31	0.57	0.83	1.09	1.35			
	Case 3	3.6	1.35	0.83	0.6	0.47	0.39			
Butane	Case 1	0.01	0.01	0.02	0.02	0.03	0.03			
	Case 2	0	0.01	0.01	0.01	0.02	0.02			
	Case 3	0.03	0.02	0.01	0.01	0.01	0.01			
Production factor	Case	Cooperatives Carbon footprint (Kg eq CO2.l-1)								
Electricity	Case 1	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00
	Case 2	0.05	0.30	0.55	0.80	1.05	1.30			
	Case 3	4.80	1.37	0.80	0.56	0.44	0.36			
Butane	Case 1	0.01	0.02	0.03	0.05	0.06	0.07			
	Case 2	0.01	0.02	0.02	0.03	0.04	0.04			
	Case 3	0.57	0.16	0.10	0.07	0.05	0.04			

Table 6
Component matrix resulting from principal component analysis (case of companies emissions). The analysis retains three components. The first includes production process elements (C1). the second includes harvesting. distribution and energy (C2). and the third includes other elements (C3).

	C1: Process	C2: Harvesting. Distribution & Energy	C3: Others
Electricity	0.75		
Transportation	0.86		
Materials	0.81		
Butane	0.72		
Diesel		0.95	
Exportation		0.94	
Harvesting via donkeys and mules		0.87	
Animal feed			0.94
Cardboard Waste			0.61
Plastic Waste			0.96
Fixed Assets			0.89
Purchase	0.7		

Table 7
Component matrix resulting from principal component analysis (case of cooperatives emissions). The analysis retains three components. The first includes production process elements. harvesting and distribution (C1). the second includes waste management and energy (C2). and the third includes fixed assets (C3).

	C1: Process. Harvesting & Distribution	C2: Waste Management & Energy	C3: Fixed Assets
Diesel		0.79	
Butane	0.83		
Electricity	0.92		
Cardboard Waste		0.75	
Plastic Waste		0.92	
Animal Feed	0.89		
Harvesting via donkeys and mules	0.59		
Purchase	0.88		
Materials	0.83		
Fixed Assets			0.9
Transportation	0.94		
Exportation	0.97		

3.5. Comparing carbon footprints: Argan oil vs. vegetable oils

Owing to the limited existing research on the carbon footprint of Argan oil, and on essences typically found in forest environments with comparable boundaries and calculation assumptions, our comparison and deliberative examination will focus on other vegetable oils. The assessment of the carbon footprint of these oils considers both agricultural and industrial aspects for the vast majority of vegetable oils (such as olive oil, rapeseed oil, and sunflower oil), and fruit production follows a well-thought-out and controlled agrotechnical process: seed preparation, basic, top, and foliar fertilization, irrigation, phytosanitary treatments, and others (e.g., pruning of trees). These fruits are then destined for industrial processing into oil. In contrast, argan oil production takes a completely different approach. Argan fruits are not grown using an agricultural method. Argan fruits are collected in the forests of the Argan Biosphere Reserve and transported to the processing units. A comparison of the carbon footprints of Argan oil and vegetable oils, despite their distinct origins in forest and orchard environments, respectively, is indeed feasible and can provide valuable insights. While it is true that their growth environments differ, there are justifiable reasons for making this comparison, including a common analytical framework, the impact on climate change, policy and consumer awareness, supply chain similarities, and the applicability of findings. The comparative analysis is undertaken to assess their carbon footprints within their respective production and value chain frameworks, recognizing that the insights gained can contribute to a broader understanding of sustainable practices within the vegetable oil industry.

Upon closer examination of the various studies analyzed, it becomes evident that our chosen approach is distinct from the rest. One fundamental distinction arises from the origin of the fruit used in these processes: Argan fruit for oil production is sourced from natural forests, whereas most vegetable fruits are cultivated in agricultural farms. Argan fruits are harvested using donkeys and mules. In our case study, this process alone summarizes the agricultural phase.

Various studies have conducted life cycle analyses to assess carbon footprints. However, emission sources related to Scope 3 were not examined using the same approach. It should be noted that the agricultural aspect of Argan oil production is nonexistent. Thus, our comparison focuses on the process of converting fruits into oil. In other words, we compared the carbon footprints of the third scenario (Scope 1 and 2) with those of converting olive fruits into oil.

3.5.1. Olive oil

Pattara et al. (2016) conducted five case studies in Abruzzo, Italy to quantify greenhouse gas emissions related to olive cultivation and the production of olive oil, specifically focusing on the agricultural and milling phases. This study aims to identify the underlying factors contributing to these emissions, excluding the planting and distribution of olive trees. The average carbon footprint of the industrial transformation phase in the cases examined was approximately 0.47 kg eq CO_2 per liter of olive oil. This is lower than the average carbon footprint of companies (1.27 kg eq CO_2 per liter of olive oil) and may be due to the amount of fruit processed, which was approximately 1301.5 tons on average. However, cooperatives face production efficiency issues, leading to varying CO_2 footprints. Optimization efforts could significantly reduce the carbon footprint and potentially achieve lower values than those reported by Pattara et al. (2016).

The difference in the carbon footprint of olive oil processing reported by Fernández-Lobato et al. (2021a,b) and our results may be explained by the varying amounts of processed fruit. They conducted a life-cycle analysis of five crops covering an area of 4000 ha in Jaen, Spain, with an average carbon footprint of approximately 0.55 kg eq $CO_2.l^{-1}$ when processing olives. The quantity of olives used was approximately 4.81 kg per 1000 kg of virgin olive oil, which is significantly higher than the 66 kg of Argan fruit used per liter of oil produced by the two production organizations.

Proietti et al. (2017) conducted a research study to evaluate the carbon footprint of extra virgin olive oil (EVO) in Italy, intending to promote sustainable production processes through the implementation of environmentally friendly techniques and technologies. The study found that the average carbon footprint of converting olives into oil was 0.15 kg eq $CO_2.l^{-1}$ of oil produced. One of the companies examined by Proietti et al. processed 120 000 kg of olives to produce 23 152.17 L of oil, which corresponds to 5.18 kg of olives per liter.

Rinaldi et al. (2014) conducted a study on the life cycle carbon footprint and energy balance of Extra Virgin Olive Oil produced in the province of Perugia, Umbria region, and exported from Italy to major importing countries. Their research closely aligns with our approach. Fig. 6 illustrates the carbon footprint breakdown (agricultural, industrial, and export) in this study and Rinaldi's results. In terms of the industrial phase, Rinaldi's average carbon footprint is higher than that of Argan companies and lower than that of Argan cooperatives. However, it should be noted that Rinaldi et al.'s harvest data were presented uniformly (1548 kg per hectare), which makes it difficult to make the same comparisons as in other studies. Rinaldi et al. also included emissions linked to freezing, refrigerant leakage, coproduct spreading, and other factors in their study, which may explain the high carbon footprint of the industrial phase. Regarding exports, Rinaldi et al.'s impact on this activity is greater than that of companies and cooperatives. The olive oil examined in Rinaldi et al.'s study was exported to Japan and the United States, whereas the Argan oil examined in this study came from Morocco and was exported to Europe.

3.5.2. *Rapeseed oil*

Rapeseed oil is a significant and widely used cooking oil (Lin et al., 2013), and its carbon footprint has been the subject of numerous studies (Badey et al., 2013; Schmidt, 2015; Rustandi and Wu, 2010; Uusitalo et al., 2014; Bieńkowski et al., 2015). Badey et al. (2013) analyzed the entire life cycle of rapeseed oil, from agricultural production to end-of-life and packaging and found that the total carbon footprint for 1 kg of milled seeds is approximately 1.27 kg eq CO_2. However, these data do not provide information on the carbon footprint of converting seeds into oil. Schmidt (2015) evaluated the environmental performance of rapeseed oil and other oils, revealing that 0.39 kg eq CO_2.l-1 is generated during the seed processing phase. Unfortunately, the data are not presented in a way that allows for a comparison of the carbon footprint of rapeseed oil with that of other oils, such as Argan oil. Although several studies have focused on biofuels made from rapeseed oil (Rustandi and Wu, 2010; Uusitalo et al., 2014), others have only examined the agricultural seed production stage (Bieńkowski et al., 2015).

3.5.3. *Palm oil*

Schmidt (2015) also examined palm oil in his research on the environmental impact of various oils. He calculated the carbon footprint of the oil mill process for palm oil to be 914.4 T eq CO_2 per ton. Hashim et al. (2018) conducted three scenarios to determine the carbon footprint of palm oil in Malaysia, resulting in values of 871, 1311.5, and 1752 kg eq CO_2 per ton of palm oil. However, the presentation of the data and results in this study does not allow for comparison with Argan oil. Like rapeseed oil, the carbon footprint of palm oil is also influenced by its energy aspect, as reported by Uusitalo et al. (2014).

3.5.4. *Agricultural phase: Argania oil vs vegetable oils*

Harvesting using donkeys and mules is the only process that includes the agricultural phase, unlike other vegetable oils whose fruit lineage is an agricultural route that includes several carbon-emitting activities. Consequently, the carbon footprint of the agricultural phase of vegetable oils significantly exceeds that of argan oil (Table 8).

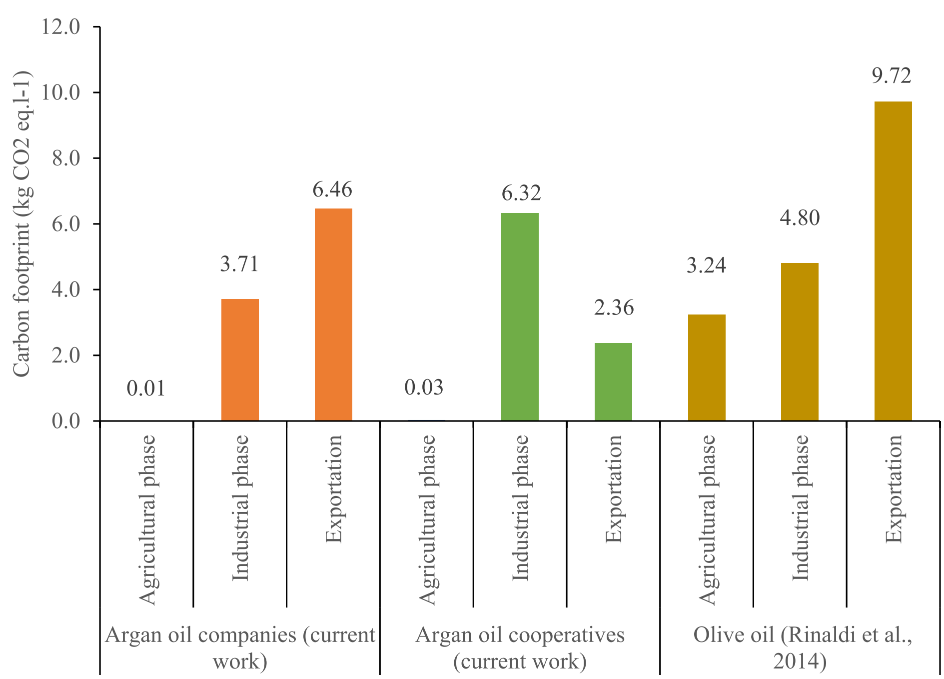


Fig. 6. Assessing the Carbon Footprint (CF) of Argan oil by comparing its average values with those reported by Rinaldi et al. (2014). The comparison focuses on three key aspects: upstream agriculture (fruit production), industrial processing, and oil exports.

Table 8
Comparison of the carbon footprint of the agricultural phase of argan oil found in our work with the carbon footprint of vegetable oils.

Oil type	Authors	Agricultural carbon footprint average value (Kg eq CO_2/FU)
Argan oil	Current work (companies)	0.01
	Current work (cooperatives)	0.03
Olive oil	Rinaldi et al. (2014)	3.24
	Pattara et al. (2016)	5.45
	Proietti et al. (2017)	0.91
	Fernández-Lobato et al. (2021a,b)	1.84
Rapeseed oil	Badey et al. (2013)	0.11
	Schmidt (2015)	0.73
	Rustandi and Wu (2010)	2.79
Palm Oil	Schmidt (2015)	0.67
	Hashim et al. (2018)	0.13

3.6. Carbon footprint mitigation pathways

Our analysis of carbon accounting for Argan oil revealed several observations. Independent of the influence of exports on the carbon footprint, it is evident that carbon emissions from oil produced by cooperatives remain notably high relative to existing production levels, indicating the need for improvement. In terms of production factors and emission contributors, electricity consumption has emerged as a crucial focal point warranting attention and mitigation endeavors. Electricity from photovoltaic panels could be an interesting alternative mitigation strategy. The Argan Biosphere Reserve area has substantial solar resources (Supplementary Figs. 18–20). Preliminary simulations, using data from the "Global Solar Atlas" reveal that an average photovoltaic system could yield 2.25 MWh/m^2 (Agadir) and 2.26 MWh/m^2 (Essaouira) making it well-suited for implementation by both Argan oil cooperatives and companies. This calculation tool enables the measurement of emissions resulting from the utilization of solar energy, specifically in terms of electricity consumption. Consideration of an "Off-Grid" photovoltaic system aligned with the electricity consumption data collected from the surveys, would lead to a significant reduction in emissions attributed to electricity consumption. If we examine the second scenario, electricity consumption emissions can become almost negligible over a 30-year immobilization period (as shown in Fig. 7). This holds the potential to substantially reduce the carbon footprint of Argan oil production, resulting in a reduction of 35.31% and 36.93% for companies and 40.35% and 40.66% for cooperatives after 5 and 30 days of immobilization, respectively (Fig. 7). The impact of electricity substitution is significant when examining the third scenario. Companies average carbon footprint from the oil can decrease to 0.87 kg eq $CO_2.l^{-1}$ after 5 years of immobilization, representing a reduction of 66.41%, and even lower to 0.94 kg eq $CO_2.l^{-1}$ after 30 years of immobilization, indicating a reduction of 71.76%. This effect seems particularly appealing for cooperatives, as there can be a 76.08% reduction (average reduction of 2.29 kg eq $CO_2.l^{-1}$) after 5 years of immobilization, and an even greater reduction of 77.07% (average reduction of 2.32 kg eq $CO_2.l^{-1}$) after 30 years of immobilization (as shown in Fig. 8).

An alternative strategy to reduce the carbon footprint involves the use of Argan by-products (e.g., oilseed cake) as goat feed. Pyrolysis, a process in which a solid (or liquid) undergoes thermal degradation into smaller volatile molecules without interacting with oxygen or other oxidants (Stauffer et al., 2008), offers potential environmental and socioeconomic benefits. Three products were obtained via high-temperature decomposition. Biochar, a carbon-enriched biomaterial generated via pyrolysis, has substantial and enduring benefits. carbon sequestration in soils and improved organic fertility (Santos et al., 2019). Incorporating biochar into soils increases the agricultural output by improving the physicochemical and biological properties of the soil, such as water retention, soil pH, and microbial activity (Ahmad et al., 2014). In addition, biochar has the potential to reduce agricultural emissions resulting from fertilizer use by reducing reliance on fertilizers (McGlashan et al., 2012).

Pyrolysis yields both pyrolysis oil and a gas mixture as its products, which can be harnessed using diverse methods, including electricity generation and heat transport (Pattiya, 2017). Similar analysis was conducted for butane, akin to the approach used for electricity. We assumed that the organisms consume the same amounts of electricity and butane gas, and in the calculation tool, we replaced conventional electricity with photovoltaics and butane with synthesis gas from pyrolysis. The amount of carbon emissions from the use of 1 kg of syngas ranges between 0.33 and 1.06 kg of carbon dioxide equivalent per liter of syngas, as reported by Zong et al. (2023). This metric helps understand the potential impact of replacing butane with another gas. For the second scenario, after five years of immobilization of photovoltaic modules, the average carbon footprint can decrease from 3.71 kg eq $CO_2.l^{-1}$ to 2.44 kg eq $CO_2.l^{-1}$ (average reduction of 34.23%) for companies and from 6.32 kg eq $CO_2.l^{-1}$ to 3.77 kg eq $CO_2.l^{-1}$ (a reduction of 40.35%) for cooperatives. In the long term, after 30 years of immobilization of the photovoltaic modules, the average carbon footprint can be

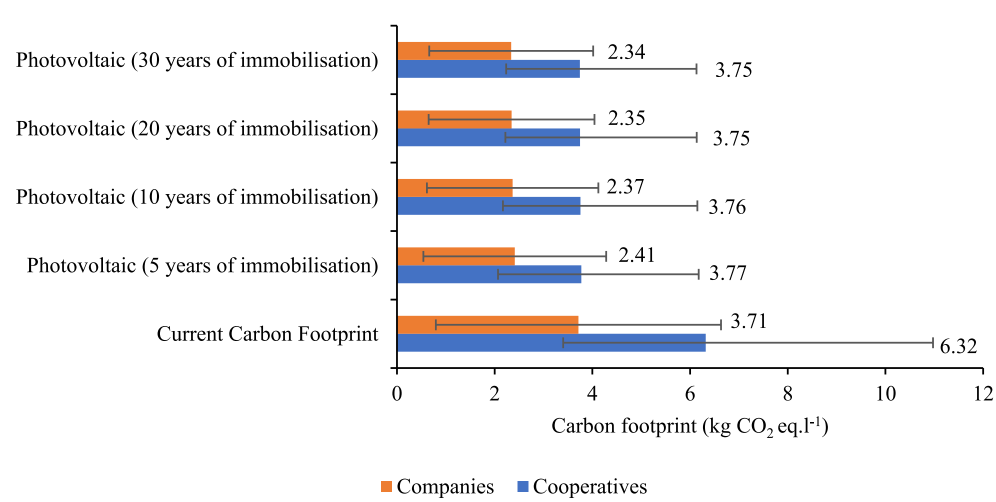


Fig. 7. Medium and long-term repercussions of replacing conventional electricity with photovoltaics on the average carbon footprint of companies and cooperatives, specifically in the second scenario, considering immobilization and payback periods.

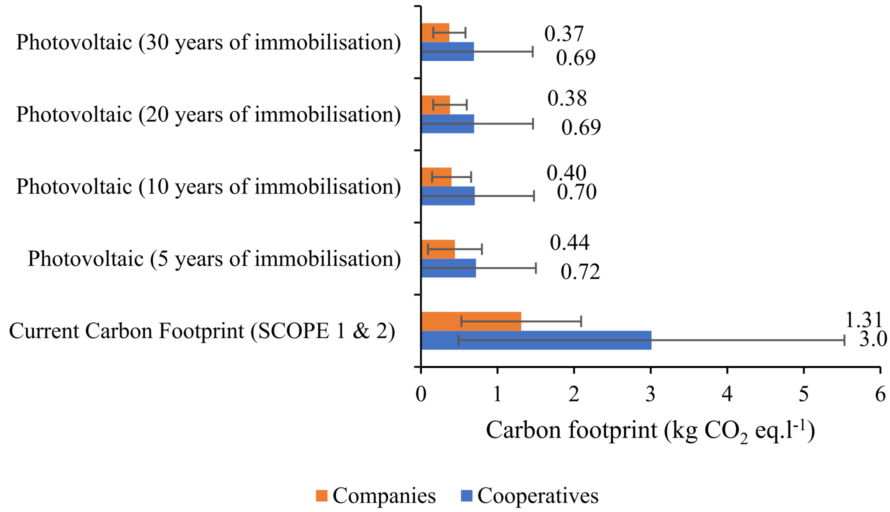


Fig. 8. Medium and long-term repercussions of replacing conventional electricity with photovoltaics on the average carbon footprint of companies and cooperatives, specifically in the third scenario.

reduced by 49.06% to 1.89 kg eq $CO_2.l^{-1}$ for companies and by 54.59% to 3.45 kg eq $CO_2.l^{-1}$ for cooperatives (Fig. 9). In the third scenario, companies are interested in reducing their average carbon footprints. After 5 years of immobilization, it can be amortized from 1.31 kg eq $CO_2.l^{-1}$ to 0.41 kg eq $CO_2.l^{-1}$ (an average reduction of 68.7%) and even to 0.33 kg eq $CO_2.l^{-1}$ (an average reduction of 74.81%) after 30 years of immobilization. For cooperatives, the situation is similar, with an interesting reduction of 85.38% (an average reduction of 2.57 kg eq $CO_2.l^{-1}$) after 5 years of immobilization and up to 86.38% after 30 years of immobilization (an average reduction of 2.6 kg eq $CO_2.l^{-1}$) (Fig. 10).

Other emission sources present challenges in their control and limitations. Purchases mainly involve raw materials used in packaging, which plays a crucial role in marketing and sales. Consequently, addressing emissions related to this area is challenging. Fixed assets related to buildings may be more important in terms of carbon emissions if Argan oil producers choose new buildings for various reasons. Thus, embracing ecologically sound and sustainable construction is a promising approach to emission mitigation. As sustainable transportation solutions are progressively evolving and require time to gain prominence, substantial action on emissions related to transportation and

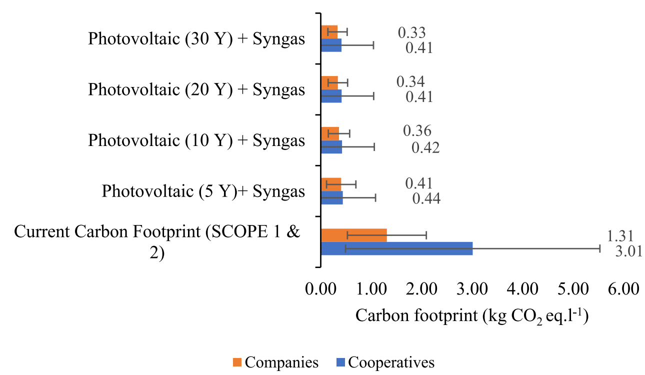


Fig. 10. Medium and long-term repercussions of replacing conventional electricity with photovoltaics and utilizing syngas from argan by-products on the average carbon footprint of companies and cooperatives, specifically in the third scenario, taking into account the years required for payback (Y).

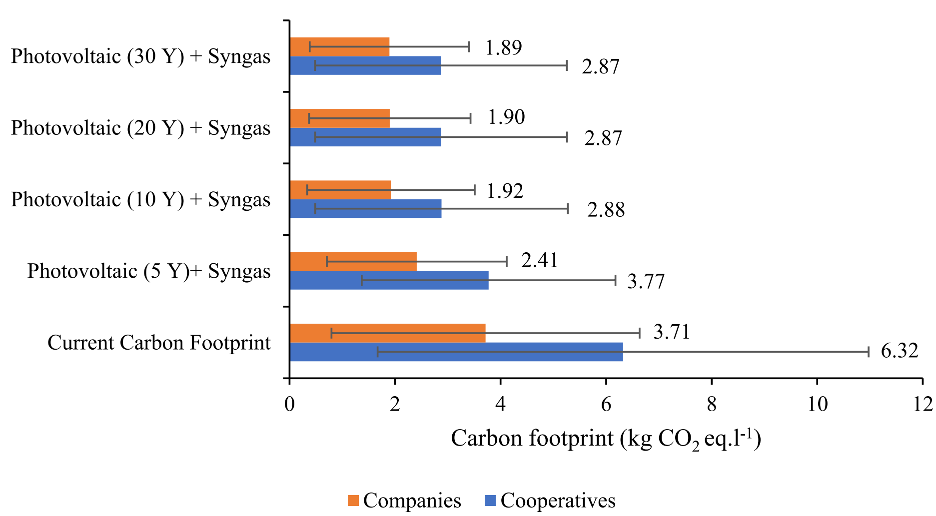


Fig. 9. Medium and long-term repercussions of replacing conventional electricity with photovoltaics and the use of syngas from argan by-products on the average carbon footprint of companies and cooperatives, specifically in the second scenario, taking into account the years required for payback (Y).

exports is likely to pose challenges.

4. Conclusion

This study measures the carbon emissions from Argan oil production in southern Morocco by cooperatives and businesses. Analyzing three scenarios for different carbon footprint levels, cooperatives can enhance production efficiency to lower their carbon footprint by producing more oil with reduced input consumption. Export inclusion significantly raises the carbon footprint, particularly from electricity and butane consumption. A sensitivity analysis indicates electricity and butane are key contributors to the carbon footprint. Mitigation strategies, such as using photovoltaic electricity and reusing byproducts, can reduce the carbon footprint. Future studies should explore these options further.

Argan oil's unique characteristic, requiring no agricultural intervention, aligns with ongoing efforts in Morocco to domesticate and cultivate Argan. A comprehensive carbon footprint study should consider the new operations of the agricultural phase in the coming years. Compared to other oils, Argan oil maintains a relatively low carbon footprint, with our research finding it lower than olive oil. However, varied results in other studies suggest the need for further comparative studies on the carbon footprints of different vegetable oils, including Argan oil.

Funding

This study was supported by the National Agency for the Development of Oasis and Argan Areas (ANDZOA), Project/Grant DARED 2021–23, funded by the Green Climate Fund (GCF).

Consent for publication

Not applicable.

Ethics approval and consent to participate

Not applicable.

CRediT authorship contribution statement

Oussama Bayssi: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mustapha Naimi:** Writing – review & editing, Writing – original draft, Validation, Supervision. **Mohamed Sabir:** Validation, Supervision. **Mohamed Chikhaoui:** Validation, Supervision. **Jamal Hallam:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition.

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.

Data availability

Data will be made available on request.

Acknowledgments

This research was conducted as a component of the Moroccan Implementation Project for Research on Argan Trees, which was carried out as part of the Arganiculture Development Project in Vulnerable Areas, known as "DARED," with funding provided by the Green Climate Fund (GCF). This study was also supported by the National Agency for the Development of Oasis Zones and Argan Trees (ANDZOA). Abderrahmane Ait Lhaj and Noureddine Ibnezzyn, along with their dedicated teams, are actively involved: the National Institute of Agricultural Research of Morocco and the Hassan II Institute of Agronomy and Veterinary Medicine of Morocco. We would like to acknowledge the support of the Interprofessional Federation of the Argan Sector (FIFARGANE) for help in accessing and using the database of stakeholders in the Argan sector and for facilitating initial contact. We would like to thank Ms. Nasma JRONDI, an expert at the Mohammed VI Foundation for Environmental Protection, Mr. Driss ZAKARYA, an expert in decarbonization, and Mr. Noureddine HAJJAJI, an expert in decarbonization and life cycle analysis, for their contributions. We gratefully acknowledge the helpful comments from the anonymous reviewers and the Editor-in-Chief, which helped us improve the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142636.

References

ADEME, 2014. Réalisation d'un bilan des émissions de gaz à effet de serre. https://presse.ademe.fr/wp-content/uploads/2014/12/guide-3-tomes.pdf.

Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y.S., 2014. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99, 19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071.

Ait Aabd, N., Msanda, F., El Mousadik, A., 2012. Univariate and multivariate analysis of agronomical traits of preselected argan trees. Not. Bot. Horti Agrobot. Cluj-Napoca 40 (2), 308–316. https://doi.org/10.15835/nbha4028209.

Arzoumanidis, I., D'Eusanio, M., Raggi, A., Petti, L., 2020. Functional Unit Definition Criteria in Life Cycle Assessment and Social Life Cycle Assessment: A Discussion, pp. 1–10. https://doi.org/10.1007/978-3-030-01508-4_1.

Badey, L., Lahitte, N., Flenet, F., Bosque, F., 2013. French environmental communication on sunflower and rapeseed oils based on life cycle assessment. OCL - Oilseeds and Fats, Crops and Lipids 20 (4). https://doi.org/10.1051/ocl/2013004.

Bieńkowski, J., Dąbrowicz, R., Holka, M., Jankowiak, J., 2015. Conventional farming: case study of large-sized farms in wielkopolska region (Poland). Asian J. Appl. Sci. Eng. 4 (3), 191–200.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food 2 (3), 198–209. https://doi.org/10.1038/s43016-021-00225-9.

Deloitte, 2023. Challenges and solutions in measuring and reporting Scope 3 emissions (Issue December). Available: https://www2.deloitte.com/nl/nl/pages/sustainability/articles/challenges-and-solutions-scope-3-emissions.html (Accessed 09 January 2024).

El Oumari, F.E., Bousta, D., Imtara, H., Lahrichi, A., Elhabbani, R., El, G., Al, O., Saleh, A., Parvez, M.K., Grafov, A., Houssaini, T.S., 2022. Chemical Composition and Anti-urolithiatic Activity of, 1–13.

Ertl, V., Haddad, L., Touati, A., 2023. Le mécanisme d'ajustement carbone aux frontières: Vol. REMENA Pol (Issue 1). https://www.kas.de/documents/264147/264196/CBAM+Morocco_REMENA+Policy+Paper+Series+1_FR.pdf/6991ed2c-210e-3c62-2832-51d691fd57f8?version=1.0&t=1682425686902#:~:text=Le. Mécanisme d'ajustement carbone aux frontières (CBAM) de neutralité carbone d'ici 2050.

European Commission, 2021. European climate Law (Vol. 2021, issue June. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119.

Faragò, M., Damgaard, A., Rebsdorf, M., Nielsen, P.H., Rygaard, M., 2022. Challenges in carbon footprint evaluations of state-of-the-art municipal wastewater resource recovery facilities. J. Environ. Manag. 320 (October) https://doi.org/10.1016/j.jenvman.2022.115715.

Fernández-Lobato, L., García-Ruiz, R., Jurado, F., Vera, D., 2021a. Life cycle assessment, C footprint and carbon balance of virgin olive oils production from traditional and intensive olive groves in southern Spain. J. Environ. Manag. 293 https://doi.org/10.1016/j.jenvman.2021.112951 (February).

Fernández-Lobato, L., López-Sánchez, Y., Blejman, G., Jurado, F., Moyano-Fuentes, J., Vera, D., 2021b. Life cycle assessment of the Spanish virgin olive oil production: A case study for Andalusian region. J. Clean. Prod. 290 https://doi.org/10.1016/j.jclepro.2020.125677.

García-Leoz, V., Villegas, J.C., Suescún, D., Flórez, C.P., Merino-Martín, L., Betancur, T., León, J.D., 2018. Land cover effects on water balance partitioning in the Colombian Andes: improved water availability in early stages of natural vegetation recovery. Reg. Environ. Change 18 (4), 1117–1129. https://doi.org/10.1007/s10113-017-1249-7.

Gharby, S., Charrouf, Z., 2022. Argan oil: chemical composition, extraction process, and quality control. Front. Nutr. 8 (February), 1–10. https://doi.org/10.3389/fnut.2021.804587.

Guillaume, D., Charrouf, Z., 2013. Argan oil for nutritional and skin care applications. Agro Food Ind. Hi-Tech 24, 28–30.

Hashim, Z., Subramaniam, V., Harun, M.H., Kamarudin, N., 2018. Carbon footprint of oil palm planted on peat in Malaysia. Int. J. Life Cycle Assessm. 23 (6), 1201–1217. https://doi.org/10.1007/s11367-017-1367-y.

Hilali, M., Charrouf, Z., Soulhi, A.E.A., Hachimi, L., Guillaume, D., 2005. Influence of origin and extraction method on argan oil physico-chemical characteristics and composition. J. Agric. Food Chem. 53 (6), 2081–2087. https://doi.org/10.1021/jf040290t.

Hill, N., Thistlethwaite, G., Bates, J., Karagianni, E., MacCarthy, J., Mullen, P., Kelsall, A., Hinton, S., Walker, C., Harris, B., 2021. Government greenhouse gas conversion factors for company reporting: Methodology paper. Department for Business Energy & Industrial Strategy (BEIS). July, 128. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/904215/2019-ghg-conversion-factors-methodology-v01-02.pdf.

IPCC, 2023. Synthesis Report of the IPCC Sixth Assessment Report (Ar6) 2, 2–5. https://eur-lex.europa.eu/legal-content/PT/TXT/PDF/?uri=CELEX:32016R0679&from=PT%0A. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52012PC0011:pt:NOT.

Lam, W.Y., Kulak, M., Sim, S., King, H., Huijbregts, M.A.J., Chaplin-Kramer, R., 2019. Greenhouse gas footprints of palm oil production in Indonesia over space and time. Sci. Total Environ. 688, 827–837. https://doi.org/10.1016/j.scitotenv.2019.06.377.

Lima, M.A., Mendes, L.F.R., Mothé, G.A., Linhares, F.G., de Castro, M.P.P., da Silva, M.G., Sthel, M.S., 2020. Renewable energy in reducing greenhouse gas emissions: reaching the goals of the Paris agreement in Brazil. Environmental Development 33 (December 2019), 100504. https://doi.org/10.1016/j.envdev.2020.100504.

Lin, J., Liu, Y., Meng, F., Cui, S., Xu, L., 2013. Using hybrid method to evaluate carbon footprint of Xiamen City, China. Energy Pol. 58, 220–227. https://doi.org/10.1016/j.enpol.2013.03.007.

Liu, D., Zhang, W., Wang, X., Guo, Y., Chen, X., 2022. Greenhouse gas emissions and mitigation potential of hybrid maize seed production in northwestern China. Environ. Sci. Pollut. Control Ser. 29 (12), 17787–17798. https://doi.org/10.1007/s11356-021-16990-w.

Luo, X., Guo, Y., Wang, R., Wang, N., Li, C., Chu, X., Feng, H., Chen, H., 2021. Carbon footprint of a winter wheat-summer maize cropping system under straw and plastic film mulching in the Loess Plateau of China. Sci. Total Environ. 794, 148590 https://doi.org/10.1016/j.scitotenv.2021.148590.

McGlashan, N., Shah, N., Caldecott, B., Workman, M., 2012. High-level techno-economic assessment of negative emissions technologies. Process Saf. Environ. Protect. 90 (6), 501–510. https://doi.org/10.1016/j.psep.2012.10.004.

Moroccan Ministry of Agriculture, Fisheries, Rural Development, Water and Forests "MAPMDREF", 2023. Filière arganier | Ministère de l'agriculture. https://www.agriculture.gov.ma/fr/filiere/arganier.

Moroccan Ministry of Energy Transition and Sustainable Development "MTEDD" (Sustainable Development Department), 2021. National determined contribution - updated. https://unfccc.int/sites/default/files/NDC/2022-06/MoroccanupdatedNDC2021_Fr.pdf.

Mouahid, A., Claeys-Bruno, M., Bombarda, I., Amat, S., Ciavarella, A., Myotte, E., Nisteron, J.-P., Crampon, C., Badens, E., 2022. Supercritical CO2 extraction of oil from Moroccan unroasted Argan Kernels: effects of process parameters to produce cosmetic oil. J. CO2 Util. 59, 101952 https://doi.org/10.1016/j.jcou.2022.101952.

Nieuwlaar, E., 2013. Life cycle assessment and energy systems. In: Reference Module in Earth Systems and Environmental Sciences (Issue March). Elsevier Inc. https://doi.org/10.1016/b978-0-12-409548-9.01334-8.

O'Rourke, D., 2014. The science of sustainable supply chains. Sciencemag.Org. https://doi.org/10.4337/9781781007235.00016.

Pattara, C., Salomone, R., Cichelli, A., 2016. Carbon footprint of extra virgin olive oil: a comparative and driver analysis of different production processes in Centre Italy. J. Clean. Prod. 127, 533–547. https://doi.org/10.1016/j.jclepro.2016.03.152.

Pattiya, A., 2017. Fast pyrolysis. In: Direct Thermochemical Liquefaction for Energy Applications. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-101029-7.00001-1.

Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegria, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B., 2022. Climate change 2022: impacts, adaptation and vulnerability. In: IPCC. https://www.ipcc.ch/report/ar6/wg2/about/factsheets/%0A. https://www.ipcc.ch/report/ar6/wg2/about/factsheets.

Proietti, S., Sdringola, P., Regni, L., Evangelisti, N., Brunori, A., Ilarioni, L., Nasini, L., Proietti, P., 2017. Extra Virgin Olive oil as carbon negative product: Experimental analysis and validation of results. J. Clean. Prod. 166, 550–562. https://doi.org/10.1016/j.jclepro.2017.07.230.

Rinaldi, S., Barbanera, M., Lascaro, E., 2014. Assessment of carbon footprint and energy performance of the extra virgin olive oil chain in Umbria, Italy. Sci. Total Environ. 482–483 (1), 71–79. https://doi.org/10.1016/j.scitotenv.2014.02.104.

Rosenzweig, C., Mbow, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M., Liwenga, E.T., Pradhan, P., Rivera-Ferre, M.G., Sapkota, T., Tubiello, F.N., Xu, Y., Mencos Contreras, E., Portugal-Pereira, J., 2020. Climate change responses benefit from a global food system approach. Nature Food 1 (2), 94–97. https://doi.org/10.1038/s43016-020-0031-z.

Rustandi, F., Wu, H., 2010. Biodiesel production from canola in western Australia: energy and carbon footprints and land, water, and labour requirements. Ind. Eng. Chem. Res. 49 (22), 11785–11796. https://doi.org/10.1021/ie1013162.

Santos, F.M., Gonçalves, A.L., Pires, J.C.M., 2019. Negative emission technologies. Bioenergy with Carbon Capture and Storage: Using Natural Resources for Sustainable Development 1–13. https://doi.org/10.1016/B978-0-12-816229-3.00001-6.

Schmidt, J.H., 2015. Life cycle assessment of five vegetable oils. J. Clean. Prod. 87 (C), 130–138. https://doi.org/10.1016/j.jclepro.2014.10.011.

Stauffer, Eric, Dolan, Julia A., Reta, Newman, 2008. Chemistry and physics of fire and liquid fuels. In: Fire Debris Analysis, pp. 85–129. https://doi.org/10.1016/B978-0-12-663971-1.X5001-5.

Tubiello, F.N., Rosenzweig, C., Conchedda, G., Karl, K., Gütschow, J., Xueyao, P., Obli-Laryea, G., Wanner, N., Qiu, S.Y., Barros, J. De, Flammini, A., Mencos-Contreras, E., Souza, L., Quadrelli, R., Heioarsdóttir, H.H., Benoit, P., Hayek, M., Sandalow, D., 2021. Greenhouse gas emissions from food systems: building the evidence base. Environ. Res. Lett. 16 (6) https://doi.org/10.1088/1748-9326/ac018e.

UNFCCC, 2015. Paris agreement. https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

UNFCCC, 2021. COP 26 glasgow climate pact A. In: Cop26. https://unfccc.int/sites/default/files/resource/cop26_auv_2f_cover_decision.pdf.

Uusitalo, V., Väisänen, S., Havukainen, J., Havukainen, M., Soukka, R., Luoranen, M., 2014. Carbon footprint of renewable diesel from palm oil, jatropha oil and rapeseed oil. Renew. Energy 69, 103–113. https://doi.org/10.1016/j.renene.2014.03.020.

Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37, 195–222. https://doi.org/10.1146/annurev-environ-020411-130608.

Weinheimer, J., 2010. Carbon Footprint: A New Farm Management Consideration in the Southern High Plains.

Yeung, H. W. Chung, Coe, N.M., 2015. Toward a dynamic theory of global production networks. Econ. Geogr. 91 (1), 29–58. https://doi.org/10.1111/ecge.12063.

Zong, Z., Cai, G., Tabbara, M., Chester Upham, D., 2023. CO2-negative fuel production using low-CO2 electricity: Syngas from a combination of methane pyrolysis and dry reforming with techno-economic analysis. Energy Convers. Manag. 277 https://doi.org/10.1016/j.enconman.2022.116624.