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Sustainability assessment of a valorization model of urban Used Cooking Oils (UCOs) in the City of Bogota

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To Virginia Mateus, an extraordinary, loving, and generous soul.

To Clara Mateus, the strongest and most tenacious woman I know.

Statement of originality

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Abstract

Sustainability assessment of a valorization model of urban Used Cooking Oils (UCOs) in the City of Bogota

This work assessed the sustainability of one of the current Used Cooking Oil (UCO) valorization models in Bogota from a holistic perspective and under a life cycle approach. The valorization model of interest consists of the collection, pretreatment, and exportation of UCO to produce UCO-based biodiesel. A set of sustainability assessment criteria was defined, and suitable indicators were assigned and evaluated through proper assessment tools. The selected criteria include human health, labor conditions, work safety, water use, demand for fossil resources, climate change, water quality, soil quality, waste management, economic performance, social acceptance, governmental framework, and land-use change. Results were interpreted within the conceptual framework of the Integrative Concept of Sustainability (ICoS) and compared with production of palm oil-based biodiesel as the reference system. In general terms, UCO-based biodiesel represents a significant improvement towards sustainability, considering a lower magnitude of the life cycle impacts or a better overall performance in most of the criteria except for climate change, demand for fossil resources, and governmental framework. This panorama can be improved if local production and consumption of biodiesel are fostered, since the exportation of UCO is a major contributor to the life cycle impacts, specifically, GHG emissions, use of fossil resources, noxious emissions to air, and acidification potential.

Keywords: Used Cooking Oil (UCO), sustainability assessment, Integrative Concept of Sustainability (ICoS), Life Cycle Assessment (LCA), UCO-based biodiesel, palm oil-based biodiesel.

Resumen

Análisis de sostenibilidad de un modelo de valorización de Aceites de Cocina Usados (ACUs) urbanos en la ciudad de Bogotá

Este trabajo evaluó la sostenibilidad de uno de los modelos de valorización de Aceite de Cocina Usado (ACU) en la ciudad de Bogotá, bajo una perspectiva holística y con un enfoque de ciclo de vida. El modelo de valorización consiste en la recolección, el pretratamiento y la exportación de ACU para producir biodiesel. Un conjunto de criterios de sostenibilidad fue definido, e indicadores apropiados fueron asignados y evaluados a través de las herramientas de análisis adecuadas. Los criterios seleccionados incluyen salud humana, condiciones laborales, seguridad en el trabajo, uso del agua, demanda de recursos fósiles, cambio climático, calidad del agua, calidad del suelo, gestión de residuos, desempeño económico, aceptación social, marco gubernamental, y cambio en el uso del suelo. Los resultados fueron interpretados en el marco del Concepto Integrado de la Sostenibilidad (ICoS por sus siglas en inglés), y comparados con la producción de biodiésel de palma como sistema de referencia. En términos generales, el biodiésel de ACU representa un avance significativo hacia la sostenibilidad, considerando una menor magnitud de los impactos de ciclo de vida o un mejor despeño en la mayoría de los criterios, excepto en los de cambio climático, demanda de recursos fósiles, y marco gubernamental. Este panorama puede mejorar si se promueve la producción y el consumo local de biodiésel, ya que la exportación del ACU presenta uno de los mayores porcentajes de contribución a los impactos de ciclo de vida, específicamente, emisiones de GEI, uso de recursos fósiles, emisiones nocivas al aire, y potencial de acidificación del suelo.

Palabras clave: Aceite de Cocina Usado (ACU), análisis de sostenibilidad, Concepto Integrado de la Sostenibilidad, Análisis de Ciclo de Vida (ACV), biodiésel de ACU, biodiésel de palma

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Introduction

Management of Used Cooking Oil (UCO) is one of the major challenges faced by densely populated cities around the world [1], and the capital of Colombia is not the exception. In Bogota, mismanagement of UCO is characterized by three situations that imply the development of severe ecological and social impacts [2]: first, UCO is illegally collected, rudimentarily treated, and redistributed as new oil among low-income populations; second, UCO is poured through sinks and siphons, generating a series of cascading problems that range from blockage of sewage pipes to pollution of soil and freshwater bodies; and third, UCO is sent as solid waste to sanitary landfills, increasing lixiviates generation and methane emissions.

Within this context, different UCO management strategies have been proposed and implemented to exploit UCO as feedstock for the oleochemical industry, particularly, to produce soaps and biodiesel [3]. Even though these strategies have certainly contributed to preventing the ecological and social impacts that arise from UCO mismanagement, these have been laid out under a merely disciplinary approach. Therefore, the generated impacts within the life cycle of the proposed schemes have been usually overlooked or underestimated.

This work assessed, in terms of sustainability, one of the current UCO valorization models in the city of Bogota, which consists of its collection and exportation to produce UCO-based biodiesel. To achieve this goal, it was necessary to characterize the current harnessing model and to identify the environmental effects associated with its life cycle. Beyond analyzing the ecological performance or the economic viability of the scheme of interest, this work sought to investigate the sustainability of the modeñ from a broad and holistic perspective. In this sense, instead of using the traditional Triple Bottom-Line theory to address three dimensions of sustainability as independent spheres, this assessment was performed within a comprehensive conceptual framework, namely, the Integrative Concept of Sustainability (ICoS). This framework proposes a set of sustainability goals and principles that allow analyzing if a technology, a system, an organization, or even a policy, effectively contributes to sustainability. Based on this, relevant assessment criteria were defined and evaluated for the system of interest through suitable indicators. Results led to identifying strengths and weaknesses of the system and proposing strategies for its improvement towards sustainability.

This dissertation consists of five chapters. Chapter 1 provides an overview of UCO management and valorization, in order to understand the problems associated with its generation and the current ways of approaching such problems. Chapter 2 introduces the fundamentals of sustainability assessment, which comprise the conceptual and methodological developments on this subject, and it presents the selected assessment framework (ICoS). Chapter 3 describes the proposed sustainability assessment methodology for the UCO valorization model of interest, and it indicates the most relevant aspects of the respective project background. Chapter 4 presents the overall sustainability assessment results, followed by an analysis in the framework of circular economy. Finally, conclusions are stated in Chapter 5.

The performance of this sustainability assessment highlights the need for a transdisciplinary approach when designing and implementing initiatives that seek to contribute to the solution of environmental problems. Above all, this work acknowledges the complexity of the environment beyond its biophysical dimension and attempts to understand the existing relationships between ecosystems and social structures.

1. Context of Used Cooking Oil (UCO)

Used Cooking Oils (UCOs) correspond to oils or fats of vegetable or animal origin that have been used for cooking or frying purposes in the food industry, in restaurants, or -at consumer level- in households. Because of the degradation process that occurs during cooking, UCOs are no longer fit for such purposes [4], [5].

UCO is considered non-hazardous waste and it has the potential to become a suitable second-generation feedstock for the oleochemical industry, taking into account the following aspects: the food value of the oil has already been exploited; UCOs generate major ecological and social impacts when mismanaged; there is a large, global, and evenly distributed supply of UCO; and UCO is generally available at lower costs than traditional vegetable refined oils [2]. Each of these aspects will be explained in detail in the following sections.

1.1 Generation of UCO

There are two main sources of UCO: commercial UCO from hotels, restaurants, casinos, and caterers (commonly known as HORECA sites), and domestic UCO from households [4]. Although it is difficult to determine the exact amount of the global UCO supply, some appraisals have been recently reported. It is estimated, that the current global production of UCO ranges between 41 and 67 million tons per year, which corresponds to 20 – 32% of the total vegetable oil consumption [3].

Production of UCO per capita varies drastically among countries, mainly due to the diverse gastronomic customs in the different regions [1]; for instance, whereas in the USA the annual average production of UCO per capita is about 5.74 kg, in India this value is just 0.86 kg [2]. Further data is shown in Appendix A. It is important to consider that, according to FAO and OECD, worldwide consumption of these products for edible purposes is projected to increase by 25% from 2015 to 2025 [6]. Thus, a proportional increase in the production of UCO should be expected.

Regarding the Colombian panorama, consumption of refined vegetable oils has had an upward trend during the last decades, with a consequent increase in the generation of UCO. According to recent estimates, about 704,000 tons of cooking oils and fats are consumed every year, of which almost 90% are for domestic use, 7% for HORECA sites, and 3% for industrial frying [1]. Now, considering that between 20 to 32% of the cooking oils and fats are discarded as UCO, the potential generation in Colombia is estimated at 225,000 tons per year, which corresponds to an annual production of 4.1 – 5.0 kg per capita [1], [2]. These estimates are in the middle-high range compared with worldwide reports [7].

In highly populated areas, such as in the capital city Bogota, generation of UCO is certainly larger, because of the higher presence of HORECA sites in metropolitan areas. Besides, the characteristic food habits in urban centers are different than those in the countryside, and these include greater consumption of fast food. A recent study calculates that UCO generation in the metropolitan area of Bogota is at least 45,000 tons per year [1].

1.2 Waste management of UCO

As stated before, the foreseen increase in vegetable oil consumption implies an expected increase in the generation of UCO. This type of waste requires proper management to prevent the ecological and social impacts that result from inadequate disposal [6]. Within this context, management of UCO calls for the implementation of strategies for waste collection at a local level, which shall be supported by policies and governmental actions, along with the participation of the different stakeholders within the life cycle of the edible oils [8].

1.2.1 Current disposal practices of UCO and associated impacts

Frying as a cooking technique takes place under high temperatures (175 – 185 ˚C), which brings about a complex set of physicochemical interactions that include oxidation, hydrolysis, and thermal degradation of the cooking oil; with time, further chemical reactions occur producing noxious and even carcinogenic components that affect the oil's edible character [1], [2]. For this reason, cooking oils become unsuitable for edible purposes, cannot be reused indefinitely, and should be disposed of after a certain time, turning thereby harmful to the biophysical environment [9].

Currently, most generated UCOs are disposed of inadequately. Mismanagement practices include pouring through sinks and siphons and mixing with the solid waste that is sent to landfills. These practices are a result of unconscious behaviors, absence of regulations, and lack of law enforcement.

Generally, UCOs are drained as waste, which generates a variety of cascading problems: blockage of domestic and urban sewage pipes, sanitary sewer overflows, flooding during rainy seasons, damage of private/public infrastructure, proliferation of vectors (rats, cockroaches, mosquitos), bad odors, and increase in the operating costs of sewage and wastewater treatment plants [2], [6], [9]–[11]. Clogs of pipes from solidified fats and oils are quite expensive to clear, and separation of oil from water is 700 times more expensive than regular water purification [4]. In the case of Bogota, the Water and Sewerage Company has had to invest at least 1.5 million USD every year to eliminate grease blockages [12].

Due to the low solubility and low degradation rate of UCO, it can easily escape from conventional wastewater treatment facilities [11], so once it reaches surface or underground waters, a supernatant lipid layer avoids water oxygenation, increasing the Chemical Oxygen Demand (COD), and boosting eutrophication [2]. Freshwater bodies and basins are thereby contaminated with organic matter and noxious chemicals, causing detrimental effects to organisms [4]. As for the disposal in landfills, leaching of UCO affects the normal biodegrading processes and can contribute to the increase of lixiviates and methane emissions [2].

Sometimes, a more dramatic public health issue occurs, mainly in not well-regulated areas of developing countries such as Colombia: UCO is illegally collected, filtered, bleached, and redistributed as new oil among low-income populations [2]. The existence of such an illegal market is a crucial public health problem, because such rudimentary treatment is not enough to remove the toxic compounds that are produced during the use of the oil in cooking and frying [13].

1.2.2 Worldwide landscape

Management of UCOs is still a challenge in most regions of the world, particularly in urban areas, considering the continuous population growth and the consequent increase in the consumption of cooking oils and fats [2]. While management of UCO from HORECA sites and industrial facilities has been widely regulated and promoted in many countries, management of domestic UCO has been harder to approach.

In the case of the European Union, it is estimated that the collected amount of UCO is only a seventh part of the overall potential collectible amount [5]. Commercial UCO has been actively collected in many EU countries for the past 30 years, initially to be used as animal feed, and later -after being banned for this purpose in 2002- to become a feedstock for the biofuel industry [4]. In alignment with the Waste Framework Directive, HORECA sites have already implemented highly effective selective collection systems through authorized collectors, which is easy to control from the perspective of the waste authority [14]. In most EU countries, it is a legal requirement that commercial UCO is collected by an authorized agent, which is usually a specialized waste collection company that aids the recovery or disposal of the waste oil [15].

However, collection of domestic UCO has not been that successful, mainly due to the logistics involved in collecting small amounts of UCO from a very large number of individual households [4], and apparently, only 6% of domestic UCO in Europe is collected [2]. Existing collection systems are generally encouraged by regional or local governments or stem from private initiatives [14]. In countries where there is already a relatively developed system and there are more coordinated initiatives, from 30 to 64% of the generated domestic UCO is collected and valorized [16]. Outstanding countries are Belgium, Austria, and the Netherlands, which have managed to collect a significant percentage of their domestic UCO through well-established countrywide collection systems [4]. More detailed statistics are presented in Appendix A.

1.2.3 Colombian landscape

In Colombia, undertaken efforts to promote adequate management of UCOs are recent. Concerns about this matter emerged due to the existence of a UCO illegal market and the consequent impacts on public health. In the legal framework, the first measure was

Resolution Nr. 2154 of 2012, ruled by the Ministry of Health and Social Protection, which defined the sanitary requirements of oils and fats of vegetable and animal origin for human consumption. However, it was only in 2015, when the first regulations on the generation, collection, treatment, and proper recycling of UCO were established, through the Agreement Nr. 634 of Bogota's City Council. Since the impacts of UCO mismanagement are much more serious in big urban areas, Bogota was urged to take the lead in this topic, even despite the lack of a nationwide public policy.

Subsequently, the Ministry of Environment and Sustainable Development ruled the Resolution 316 in 2018, which dictates regulations related to the management of UCOs that apply to producers, distributors, and traders of edible vegetable oils, as well as to producers and recycling agents of UCO that undertake activities of collection, treatment and/or recycling of this residue. This resolution provides a legal framework, not only for the proper waste management of UCO, but also for integrated management of the edible vegetable oils' value chain, in agreement with the National Public Policy on Sustainable Production and Consumption [17].

Since then, in the main cities of the country and particularly in Bogota, management of UCO from HORECA sites is now regulated, and it is attempted to integrate the work of the different actors along the value chain of UCO: producers, collectors, transporters, and recycling agents. Although household producers are not explicitly involved, some recycling agents -in cooperation with the communities and environmental organizations- have initiated awareness campaigns, so that citizens dispose properly of UCO in different collection centers.

Currently, schemes under which registered recycling agents in Bogota operate consist of the exploitation of UCO as feedstock for biodiesel [12]. Companies such as Bioils, Biogras, and Greenfuels focus on the collection, pretreatment, and export of UCO for biodiesel production; in 2017, the exported amount of UCO from these companies reached a total of 9,320 tons [5]. Other companies such as Biominerales and Bio D, which produce biodiesel from palm oil, explore the use of UCOs as feedstock. It is worth mentioning that first attempts to develop high value-added alternatives from UCO, such as epoxidized oils, have already begun and are under preliminary research [13].

1.3 Valorization of UCO

Valorization alternatives of waste depend largely on the composition of the residues. Despite the large content of impurities, UCO is mainly composed of triglycerides, partial glycerides, and fatty acids, having so the potential to become a second-generation feedstock for the oleochemical industry [1].

Figure 1-1 displays the main stages of the vegetable oil value chain without UCO valorization, where vegetable oil is not only used for cooking and frying purposes, but also as an oleochemical feedstock. It has been appraised that the potential global supply of UCO is almost equivalent to the global amount of vegetable oils that are currently consumed by the oleochemical industry for biofuels and chemicals manufacturing [2]; thus, different circular economy strategies for the exploitation and valorization of UCO as oleochemical feedstock have been proposed. By exploiting and valorizing UCO, as represented in Figure 1-2, ecological and social impacts generated by UCO mismanagement can be prevented; furthermore, if UCO exploitation effectively reduces the demand for virgin vegetable oil, the associated impacts to both its production and the production of oleochemicals could be mitigated.

Figure 1-1: Main stages of the vegetable oil value chain without UCO valorization

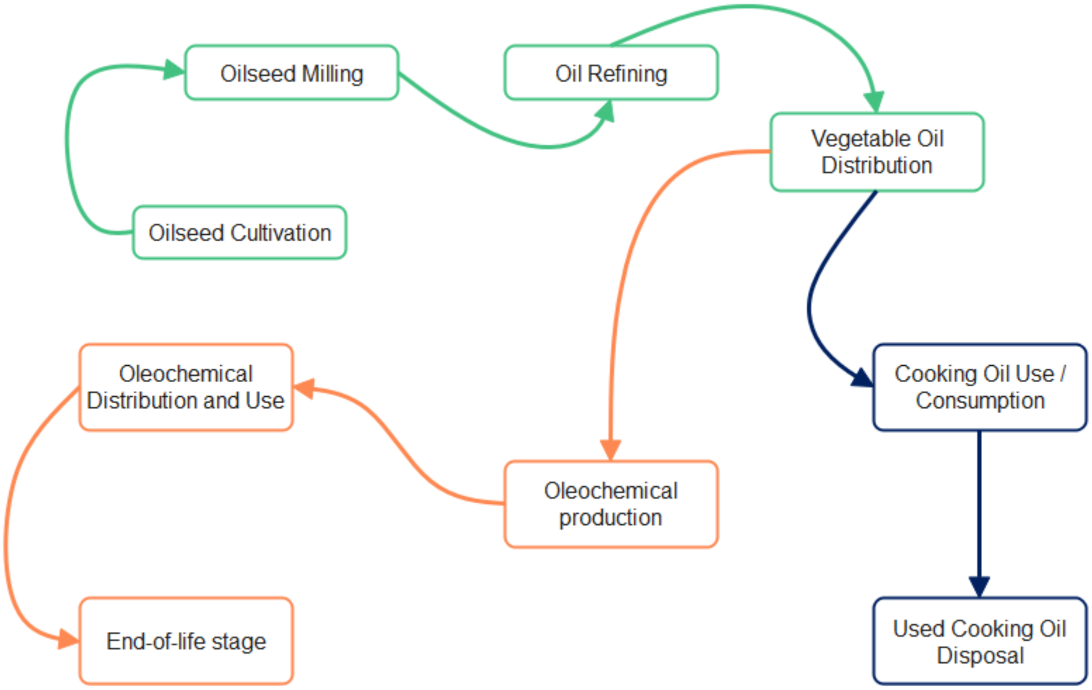
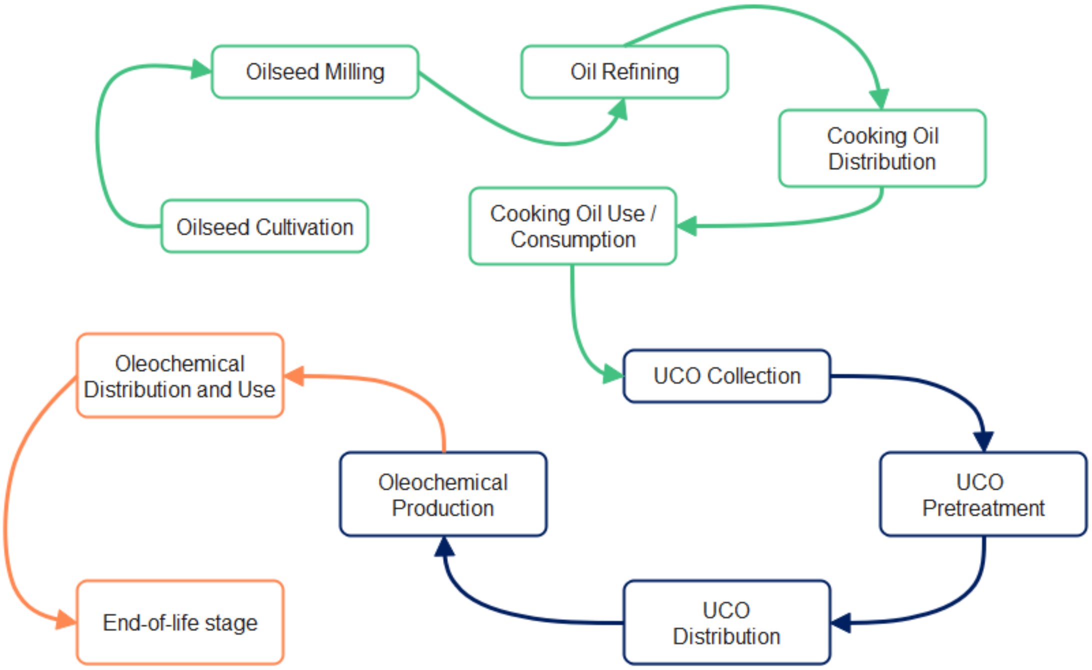


Figure 1-2: Main stages of the vegetable oil value chain with UCO valorization



This section briefly describes the different stages of the UCO valorization processes that are already available or currently under development.

1.3.1 UCO collection

Collection of commercial UCO is done by an authorized agent for waste management, and the following strategies have been identified [5]:

- Processor decentralized collection: The authorized agent sets up a door-to-door system to collect UCO directly from the HORECA sites.
- Processor centralized collection: HORECA sites deliver UCO at centralized points and the authorized agent collects it directly from these locations.
- Combined supplied collection: The authorized agent supplies HORECA sites with virgin vegetable oil and at the same time collects UCO.

Even though the collection of domestic UCO is not as developed as that of commercial UCO, analog strategies have also been proposed and implemented in a few cities of the world:

- Door-to-door collection [17], [18]: Citizens collect UCO at home and store it in small containers. Periodically (usually once a month), a special service collects the container.
- Urban distributed collection [14], [17], [18]: Citizens dispose of their collected UCO in large containers that are placed in specific points of the city. These containers can be adapted to receive UCO in bottles or have a hole through which the oil can be poured. Collection frequency is scheduled by an authorized agent according to the specificity of each location. This system is similar to the established for post-consumer waste (batteries, electronic devices, expired medicines, etc.).

As can be presumed, door-to-door collection systems are usually less efficient than distributed collection systems, since a greater distance must be covered to collect the same amount of UCO [18].

1.3.2 UCO pretreatment

As mentioned in section 1.2., a wide variety of chemicals are generated during frying, altering thereby the quality of the oil. For instance, water and free fatty acids (FFA) are detrimental for UCO-based biodiesel production, particularly under base-catalyzed conditions. The presence of water in a concentration higher than 0.06% in weight can lead to hydrolysis [9], while the presence of FFA in a concentration higher than 3% in weight favors saponification (production of soaps) [5]. These parallel reactions reduce the yield of biodiesel and hinder further purification and separation from glycerol [5], [9], [11], [15], [19]. For this reason, when reclaimed to be used as feedstock in the oleochemical industry, UCO must undergo a set of physical and/or chemical operations to reduce the content of impurities, mainly solids, water, and FFA [5], [15]. Such pretreatment operations include sieving, decantation, filtration, centrifugation, and sometimes esterification [9].

In general, the acid and saponification values determine both the quality and the price of UCO [5]. While refined virgin oils have an FFA content below 0.5% in weight, the FFA content of UCOs ranges between 0.5 and 15% in weight, depending on the source [15].

When this value is low, UCO pretreatment consists only of filtering and heating above 100 °C for water removal. On the other hand, when the FFA content is high, further pretreatment of UCO is required [20]. The following are some of the techniques that are performed to reduce the FFA content of UCO [21]:

- Acid esterification with methanol and sulfuric acid
- Esterification with ion exchange resins
- Neutralization with alkalis followed by soap separation by a decanter
- Extraction with polar liquids along with acid esterification and distillation of FFA

1.3.3 Use of UCO as oleochemical feedstock

UCOs have been typically recovered to produce commodities such as biofuels -especially biodiesel and hydrogenated vegetable oil (HVO)-, soaps, and animal feed, thus creating a small but solid market of nearly 600 million USD/year [3]. In the case of biofuels, UCOs are attractive for not competing with food and avoiding potential land-use changes [22], [23]; hence, promotion measures such as favorable prices, capital investment subsidies, and tax reduction or exemptions have been implemented [2]. Nonetheless, UCO can be used as feedstock for a large variety of products beyond biofuels, which are high value-added chemicals, such as plasticizers, lubricants, polymers, resins, and biomaterials [3]. The following paragraphs delve into the current UCO valorization possibilities.

- **Production of biofuels**

It is estimated that the transportation sector accounts for nearly 22% of the global greenhouse gases (GHG) emissions [24]. In the search for strategies to reduce the carbon footprint of this sector, biofuels have attracted great attention during the last decades [15], [25], and governments around the world set in previous years short- and long-term goals to increase the share of biofuels in the transportation energy matrix.

The United States, for example, took the lead with the US Renewable Fuels Standard of 2007, which established a target of renewable fuels production (136 hm^3 annually) [10]. The European Union followed by ruling the Renewable Energy Directive (RED) in 2009, which was later updated in 2018 (RED II). The RED established a 10% of biofuel share in the motor fuel market by 2020 [26], and a 50% GHG savings threshold for biofuels -later increased to 60% with the RED II- [15]. This directive seeks to contribute to the security of the energy supply, technological development at a regional scale, and job creation [27].

In the particular case of biodiesel, this can be produced from edible and non-edible vegetable oils and animal fats, or from waste lipids (e.g. UCOs), which can be either blended with petroleum diesel and used in diesel engines or used directly as a fuel with certain engine modifications [28]. Typical vegetable oils that are used as feedstock include those from soybean, sunflower, rapeseed, and palm fruit (edible), as well as from jatropha, jojoba, rubber seed, polanga, tobacco, karanja, and maua (non-edible) [29]. The choice of feedstock is crucial to estimate the comparative advantage to fossil diesel, but considering only the combustion stage, biodiesel performs adequately and produces lower emissions of CO, hydrocarbons, and particulate matter [25].

The biodiesel production process consists of a batch or continuous transesterification of the triglycerides contained in the previous feedstocks, using a short-chain alcohol, in the presence of a catalyst or under supercritical conditions [6], [9], [19]. The catalyst can be homogeneous (acid or basic), heterogeneous, or enzymatic [30]. The most common conditions at industrial scale involve the use of a molar excess of methanol and dissolved basic catalyst such as sodium hydroxide or sodium methoxide [27]. The use of UCOs to produce biodiesel has significantly increased in the last decade. In Europe, for instance, where biodiesel is mainly produced from rapeseed oil [6], [9], consumption of waste-based biofuels has tripled in the last 8 years [31]. In Spain, UCO became the second most used feedstock for biodiesel production since 2011, exploiting more than 114,000 tons and accounting for almost 25% of the total domestic production [26]. In the UK, the contribution of UCOs to total biodiesel production reached 66% in 2012-2013 [25], and 86% in 2019 [32].

Besides biodiesel, UCO conversion into Hydrotreated Vegetable Oil (HVO), also referred to as Green Diesel, has gained greater attention in the last years. Recent reports indicate that the supply capacity of HVO in the EU is expected to increase by 2.3 times from 2018 to 2025 [31]. Additionally, there are available studies on the use of UCOs to produce

Hydroprocessed Esters and Fatty Acids (HEFA) fuels, which are approved for use in aircraft if blended up to 50% with conventional jet fuel [10].

- **Future opportunities**

Biofuels, the current valorization alternative of UCO, are low added-value commodities, which makes the UCO market highly vulnerable to changes in the economic and political environment. By exploiting the vast oleochemical potential of these substances, the portfolio of products could be diversified, improving the long-term stability of the supply chain [3]. A detailed record of possible high value-added alternatives from UCOs is shown in Appendix A, including plasticizers, binders, polyols, polymers, lubricants, surfactants, structured materials, resins, adsorbents, among others. UCO has the potential to reduce the carbon footprint of all these products, taking into consideration the growing demand in the respective application fields [33].

Epoxidized oils are one of the most interesting alternatives, since they are used as plasticizers and stabilizers in the processing of many polymers (such as PVC)., and also as additives in lubricant base oils to increase the viscosity and lubricity index [34]. Furthermore, epoxidized oils are required as feedstock in the production of alcohols, glycols, alkanolamines, olefins, and polymers such as polyurethanes, polyesters, and epoxy resins [13]. Biobased polymers can also be obtained from UCOs; polypropylene, for example, can be produced through a process equivalent to petrochemical steam cracking of a “bio naphtha” stream that is obtained from the hydrotreatment of UCO-based HVO [33].

It is expected that in the coming years, research and development on UCOs harnessing will be mostly focused on dealing with UCOs heterogeneity and impurities content, upgrading processes, enhancing household collection, and implementing resilient and intensified processes capable of incorporating different types of waste lipids to obtain high value-added products [3]. In any case, the definition of a suitable portfolio of UCOs derived products will require a sustainability assessment to identify the valorization routes that ensure socially responsible practices, environmentally conscious transformations, and highly profitable processes. Such assessment must be carried out within a life cycle framework.

2. Context of Sustainability Assessment

There is a high diversity of understandings concerning the concept of sustainability, which makes it a complex field of study and a subject of ongoing debate. This chapter seeks to delve into the different perspectives around sustainability and to explore the methodologies that have been proposed to assess sustainability.

2.1 Concept of sustainability

Sustainability has been a fundamental topic during the last decades, and different approaches to define it have been developed. It is possible to state that concerns about this subject arose in the 1960s, particularly with the publication of “The Silent Spring” by Rachel Carson in 1962. This work promoted the emergence of a collective awareness about the ecological crisis, which was further spread thanks to the United Nations Conference on the Human Environment in Stockholm 1972 [35]. In the same year, the role of the economic system was put into question with the issuance of the report “Limits to Growth” by the Club of Rome, which addressed the problems associated with population growth regarding the depletion of natural resources [36].

One of the most important milestones within this context was the publication of “Our Common Future” or Brundtland Report by the United Nations World Commission on Environment and Development in 1987. This document used the term “sustainable development” and defined it as the development “that meets the needs of present generations without compromising the ability of future generations to meet their needs” [37]. This concept was the pillar of the Earth Summit in Rio de Janeiro 1992, and it was set as the goal and guideline of the global political agenda. Since then, different positions concerning this term have emerged, assuming thereby a specific concept of sustainability from a certain perspective. When talking about sustainable development, the following questions have been discussed: What is to be sustained? What is to be developed? What is the relation between what is to be sustained and what is to be developed? [38].

Although the idea of sustainable development was quite successful in the political arena [39], many of the critics refer to the question “what is to be developed?”, and argue that it turns contradictory to maintain the structure and functioning of the ecosystems under the model of development that currently prevails, since it is based on the idea of unlimited economic growth, and it is measured by macroeconomic indicators such as the GDP [36].

As for the question of what is to be sustained, the term sustainability is often preceded by one of the following adjectives: weak or strong [40]: weak sustainability, on one hand, focuses on sustaining human welfare under the premise that natural capital is perfectly substitutable by manmade capital [41]; on the other hand, strong sustainability recognizes that natural capital is not substitutable and must therefore be maintained, acknowledging that ecosystems have a finite capacity to provide resources and absorb waste [42]. Recently, a third conception of sustainability has been proposed, namely critical sustainability: this notion calls for the identification of the ecological processes that are critical for human life, so that boundaries for trade-offs are established [43], and the substitution of non-critical capital is allowed [44].

However, in most of the proposed concepts, sustainability is recognized as a multidimensional concept. This feature is often described by the three pillars model that includes the following dimensions of sustainability: ecological (mostly referred to as environmental), social and economic. This model became prevalent when, in 1994, John Elkington applied it to the field of business administration under the term Triple Bottom-Line (TBL) [45], motivating thereby the development of a theory that seeks to integrate more aspects of sustainability beyond the ecological one. Nonetheless, the use of this theory has been often characterized by segmented management of the proposed dimensions [46], as four main interpretations of the concept of sustainability have resulted [38], [47]:

- Ecological sustainability: This interpretation focuses on a vision of the socio-economic system embedded in the global biophysical system and tends to emphasize the ideas of the ecological thresholds, carrying capacity of the earth, and the interdependence between ecological processes.

- Economic sustainability: This interpretation emphasizes the idea of social welfare, as well as the principle of intergenerational equity using capital theory, and seeks to internalize the external environmental costs associated with economic activity.
- Thermodynamic and ecological-economic sustainability: This interpretation accepts the essence of the ecological interpretation but goes further by posing ecological sustainability in the context of the entropic nature of the economic and environmental systems.
- Public policy and planning theory: This interpretation approaches the social, institutional, economic, and environmental dimensions of sustainability, within a framework that seeks to achieve a balance or integration of the different aforementioned factors.

While some insist that sustainability applies to the natural resource base itself, others focus on the wellbeing of people and their livelihoods deriving from the resource base. It is even accepted, in some cases, that there are paradoxes between the dimensions of sustainability that are inherent to the theory [48]. These differences may create biases of scientific or ideological character, that are usually adopted when assessing sustainability [38]. Therefore, instead of dealing with the dimensions of sustainability as if these were independent subjects, an integrative perspective should be adopted, so that the complex interactions that configure the environment are properly analyzed. Here, it is necessary to clarify, that the understanding of the environment in this work is not limited to the biophysical components of the planet, but it is conceived as a “field of interdisciplinary analysis that studies the relationships between social systems and ecosystems” [49].

In any case, a key fact to bear in mind is that concepts are discursive, so the use or application of a concept, such as sustainability, can be justified in different contexts; there is no scientific discourse that brings a general theory of sustainability, i.e., a theory accepted by all, but rather different competing theories that might have different structures or features, but that could agree on the foundation and practical consequences [39].

2.2 Sustainability assessment

One of the main consequences of having such different understandings of sustainability is the difference in the definition and the assessment of different capitals [38]. So, in the same way that the concept of sustainability has evolved, the process of assessing sustainability is dynamic and can be done from different perspectives. Each of these implies a different scientific domain, with some knowledge areas overlapping and others diverging or being overlooked. The following sections describe how the sustainability assessment has emerged and evolved to become a highly complex but still systemic tool nowadays.

Firstly, it is important to conceptualize the term sustainability assessment. This has been defined as a tool for decision-makers and policy-makers, to provide them with “an evaluation of global to local integrated nature-society systems in short and long term perspectives, to assist them to determine which actions should or should not be taken in an attempt to make society sustainable” [50]. In this sense, sustainability assessment transcends a purely technical or scientific evaluation, and it is based on a deep understanding of the interactions between the different components of a system [45].

Sustainability assessment has also been defined as a structured procedure that encompasses different field-specific analytical methods and models for specific decision contexts, which are generally addressed as the environmental (ecologic), economic and social contexts [47], being thus fundamental to assess from a holistic approach [45].

2.2.1 Early stages of sustainability assessment

The different analyses that have been developed to evaluate sustainability have been addressed in many ways: integrated assessment, triple-bottom-line assessment, extended impact assessment, 3-E impact assessment (i.e., environmental, economic, and equity), among others. The first attempts to carry out a thorough analysis around the concept of sustainability go back to 1996, when an international group of experts developed the Bellagio STAMP methodology (Sustainability Assessment and Measurement Principles), to “measure” the degree of contribution of a project to sustainable development [45].

During this stage of early development, sustainability assessment had two main focal points: on one hand, ecosystem goods and services, and on the other, the economic perspective about consumption, production, and welfare [45]. For this reason, sustainability assessment was first associated with the conventional methodologies of Environmental Assessment, Environmental Impact Assessment, and Strategic Environmental Assessment, which have always been tied to processes of decision making in the political and legal arena [51].

2.2.2 Features and challenges of sustainability assessment

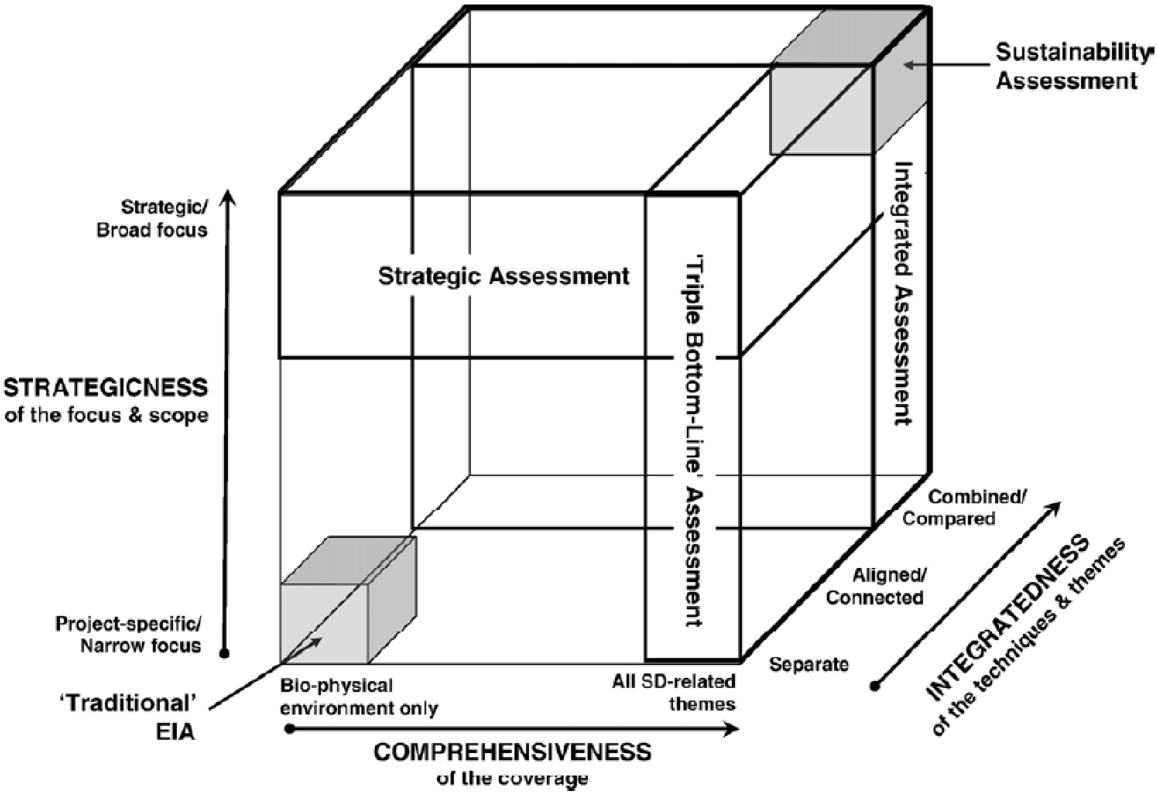
According to a recent literature review by Hacking and Guthrie [51], there are three key features associated with sustainability assessment, for the policy, plan, and program level, as well for the project level:

- Comprehensiveness: The themes associated with sustainability are covered.
- Integratedness: The themes that are covered and/or the techniques that are used are aligned, connected, compared, or combined.
- Strategicness: The focus or perspective is broad and forward-looking.

Figure 2-1 shows how these categories form a three-dimensional space within which various forms of assessment can be located. Now, according to a more recent study [47], besides the three previously described features of sustainability assessment, the following are also strongly related to this subject:

- Boundary orientation: This feature refers to the adopted reference in terms of thresholds, which can be based on scientific developments or oriented to policy-making.
- Stakeholders' involvement: This feature describes the level of communication and interaction of stakeholders in the phases of the assessment.
- Scale: An assessment can be based either on local, specific, and limited time frame approaches, or it can use methods that are capable to deal with multi-temporal and multiscale aspects.
- Transparency: An assessment should reflect transparently its guiding values.

Figure 2-1: Sustainability assessment features.



Reproduced from: Hacking and Guthrie [51]

Overall, Hacking and Guthrie identify that an almost universally promoted feature in the literature of sustainability assessment is the extended coverage beyond the purely biophysical. Even though the methodologies that are based on the TBL theory are widely used, these still lack integratedeness, because social and economic matters are managed independently [51]. In fact, many case studies that adopt the TBL theory still end up comparing different alternatives based on indicators in the three pillars of sustainability, without deepening the analysis of potential interconnections between them, and sometimes legitimate trade-offs between the pillars [47].

Therefore, many sustainability assessment studies reflect a reductionistic approach and the unification of segmented results from different themes [45]. In this sense, Sala et al. consider that the following are the most important challenges to achieve a coherent sustainability assessment [47]:

- Adoption of a holistic approach for understanding the dynamic interactions between nature and society.
- Consideration of the vulnerability and resilience of complex social-ecological systems.
- Shift from multidisciplinarity, via interdisciplinarity towards transdisciplinarity.
- Dealing with uncertainties and adoption of a probabilistic approach for the assessment of scenarios.
- Promotion of social learning and mutual feedback leading to co-production of knowledge with other stakeholder groups (business, politicians, and society).

2.2.3 Methodologies of sustainability assessment

There is not a single methodology and method, but several in continuous evolution, that can offer support in acquiring a better insight into complex problems of sustainability [38]. Hence, a difficulty when analyzing sustainability assessment methodologies is not the scarcity of literature, but rather the vast quantity. This diversity lies, on one hand, on the demand for approaches that have more specific assessment performance, and on the other hand, on the demand for tools that are accessible to a wider user group for differing case circumstances [50].

In general terms, the process of integrating and constructing knowledge from different disciplines and actors to assess sustainability requires specific frameworks, methodologies, methods, models, tools, and indicators, which can be defined in the following way [38]:

- Framework: The rationale and the structure for the integration of concepts, methodologies, methods, and tools.
- Methodologies: A collection of individual characterization methods, which together address the different ecological, economic, and social issues and the associated effect/impact.
- Methods: A set of models, tools, and indicators that enable the calculation of indicator values for a certain impact category.
  - Models: A model of the impact of ecological, social, or economic interventions adopted to calculate an indicator.
  - Tools: Software, applications, databases supporting the analysis done by adopting a specific method and its related models.

- Indicators: Indicator is a parameter, or a value derived from parameters, which points to, provides information about, or describes the state of a phenomenon, with a significance extending beyond that directly associated with its value. The parameter could be quantitative, semi-quantitative, or qualitative derived from a model, often through a tool.

In the context of sustainability assessment, it is possible to identify generic phases of integrative approaches, but it is not convenient to develop a universally applicable and detailed formulated procedure to assess sustainability, in the way that it is often done in many other disciplines [45]. A sustainability assessment is based on principles and criteria that are specific to a certain context, and it is not often achieved through a single form of assessment, but rather through a comprehensive combination of assessment techniques [51]. Still, this does not mean that standardization of tools is not imperative; on the contrary, standardization contributes to a better understanding and comparison of results [50].

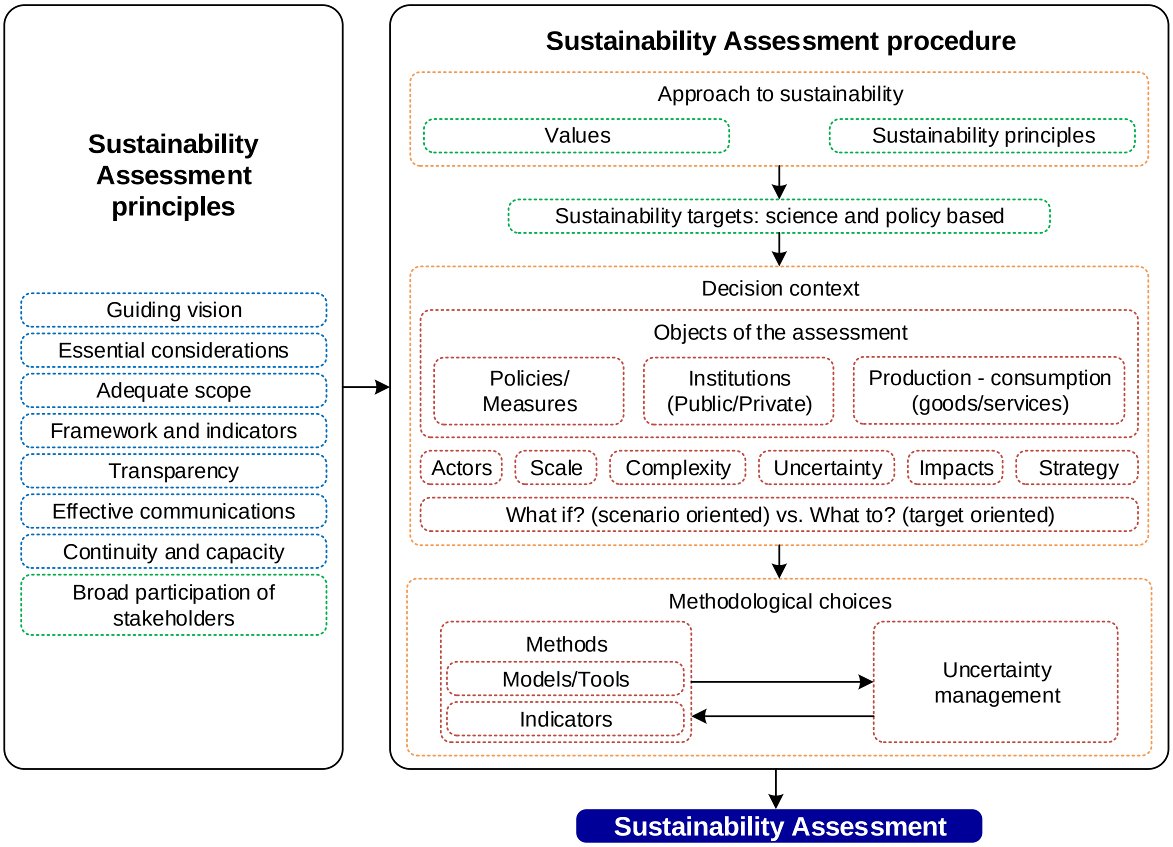
In order to develop a comprehensive sustainability assessment, Sala et al. [47] propose a systemic framework that applies to projects, products, policies, etc. The architecture of this framework is outlined in Figure 2-2, and it consists of two main parts: principles and procedural guidelines.

Principles are based on those proposed by the Bellagio STAMP methodology [40]:

- Guiding vision: The goal should deliver well-being within the carrying capacity of the biosphere and ensuring it for future generations.
- Essential considerations: These include system dynamics, uncertainties, and implications of decision-making, among others.
- Adequate scope: This refers mainly to the time horizon and geographical scale.
- Framework and indicators: The conceptual basis for identifying core indicators and related reliable data, projections, and models.
- Transparency: It is mandatory to clearly report and explain the data, sources, models, indicators, results, choices, assumptions, and uncertainties. Access to information should be public, and sources of funding and potential conflicts of interest should be disclosed.

- Effective communications: Information must be presented fairly and objectively.
- Continuity and capacity: This aspect calls for a monitoring phase, repeated measurement, and responsiveness to change.
- Broad participation: To reflect the views of the public while strengthening legitimacy and relevance, there should be engagement with the users of the assessment.

Figure 2-2: Schematic representation of the conceptual framework for sustainability assessment.



Source: Sala et al., 2015 [47]

Regarding the procedural guidelines, the sustainability assessment refers to the following components [40]:

- Approach to sustainability: As already mentioned, there have been different approaches to the concept of sustainability, so it is important to stand from a specific point of view to carry out the sustainability assessment. The analyst essentially “subscribes to” and ultimately “enforces” that specific point of view as legitimate to assess the sustainability performance of a project, plan, or product. Values and principles build the basis of an approach and are dependent on the context. Some examples of well-known sustainability principles are the precautionary principle, irreversibility, regeneration, substitutability, critical loads, the holistic approach, the polluter pays principle, intergenerational equity, good governance, planetary boundaries, among others. These have been proposed in different initiatives such as the Agenda 21, the Millennium Development Goals, the EU Sustainable Development Strategy, and recently, the Sustainable Development Goals.

- Targets: Regardless of the interpretation, sustainability as a concept is translated into targets, with which the results of the assessment will be compared. For the authors, there is no reason to talk about sustainability assessment if no sustainability targets are defined.
- Decision context: Some of the fundamental issues to take into consideration are the scale of the assessment, the complexity of the decision, the uncertainties, and the time horizon in which the impacts are foreseen.
- Methodological choices: This is the core of the sustainability assessment framework, and it consists of the following phases:
  - Identification of the most suitable methods, models, tools, and indicators
  - Sensitivity and uncertainty analysis of the assessment framework
  - Definition of monitoring strategies to track progress towards sustainability.

2.2.4 Indicators of sustainability

Because indicators create a connection between the conceptual and the operational level [45], these are considered the basis of every assessment and require therefore special attention. Indicators, when properly selected, contribute to building an image of the reality that is easier to understand and thereby fulfill the functions of informing, orienting, structuring, and communicating [52].

During the last 30 years, a significant amount of indicators has been developed to assess different aspects of sustainability [47]. Special emphasis has been laid on indicators that are designed to measure the state of the biophysical environment (widely known as environmental indicators). The European Environment Agency (EEA) proposed a framework for these types of indicators, according to which there is a need for clear and specific information about the **D**riving forces and the resulting ecological **P**ressures on the **S**tate of the ecosystems, that generate **I**mpacts and lead to societal **R**esponses [53]. This is referred to as the DPSIR framework, and it suggests four categories to classify indicators:

- Descriptive indicators: These describe the situation about main ecological issues, such as climate change, acidification, toxic contamination, and wastes, concerning the geographical scale at which these issues manifest themselves.
- Performance indicators: These compare actual conditions with a specific set of reference conditions, measuring thereby the distance between the current state and the target situation.
- Efficiency indicators: These provide an insight into the efficiency of products and processes.
- Total welfare indicators: These strive to “measure” sustainability and go beyond the ecological dimension.

In the international arena, the Organization for Economic Co-operation and Development (OECD), the United Nations Environmental Program (UNEP), the World Resources Institute (WRI), the World Bank, among many other institutions, have designed a set of indicator systems to assess different aspects of sustainability. The United Nations (UN), for instance, created a global indicator framework in alignment with the Sustainable Development Goals and the targets of the 2030 Agenda for Sustainable Development, which includes 231 indicators [54].

In sustainability assessments, it is often tried to aggregate indicators to give a single result, but such a process is performed under certain assumptions and these are based on specific values and attitudes [45]. In this sense, transparency is a fundamental principle when performing assessments, so that there is clarity about the conception of sustainability upon which an assessment is based, and no information is lost.

2.3 Integrative Concept of Sustainability (ICoS)

Given the high diversity of understandings that governs the concept of sustainability itself - as explained in Section 2.1.-, and the consequent relative validity of different approaches to the sustainability assessment, the Integrative Concept of Sustainability (ICoS) seeks to provide the missing framework to carry out a comprehensive sustainability assessment [55]. This is the conceptual framework upon which the results and the indicators of this work will be interpreted.

2.3.1 Structure

The ICoS framework recognizes that sustainability is a priority in the worldwide agenda, so it takes -in a critical way- elements from the milestones of the Brundtland's Report and the World Summit in Rio de Janeiro 1992, to formulate a set of integrated and comprehensive sustainability goals and rules. These elements are [56]:

1. The global perspective: The phenomenon of global environmental deterioration and the growing prosperity gap between regions of the world is an interrelated crisis of modern society.
2. The mutual interdependence of intra- and intergenerational justice: a fair present is a prerequisite for a just future. Justice is primarily understood as distributive justice, so the current inequalities in access to natural resources and the distribution of income are regarded to be the cause of global problems and conflicts. A re-distribution of rights, responsibilities, opportunities, and burdens is then required. ICoS is based on the postulate that every human being has a right of access to certain basic goods, as indispensable preconditions for an autonomous existence. Inter- and intra-generational justice are held to be related and equal in rank.
3. Anthropocentric point of departure: The satisfaction of human needs is, in this concept, the primary goal of sustainable development, today and in the future. The conservation of nature is not taken as an objective, but as a prerequisite for lasting societal progress. Even when nature is attributed an intrinsic value, this is done from the viewpoint of -and according to the standards of- human beings. Like other approaches to sustainability, ICoS is based on a position of "enlightened" anthropocentrism which justifies the responsibility for a cautious utilization of nature with mankind's well-understood self-interest.

2.3.2 Goals and principles

The three aforementioned constitutive elements are operationalized in two steps: first, they are "translated" into three general goals of sustainable development: securing human existence, maintaining society's productive potential (comprising natural, human-made, human, and knowledge capital), and preserving society's options for development and action. In a second step, these goals are concretized by sustainability principles, which apply to various societal areas or certain aspects of the relationship between society and nature. These principles, which are explained in Table 2-1, provide criteria to assess the sustainability performance of particular societal sectors, spatial entities, technologies, policies, etc.

Table 2-1: Substantial principles of ICoS

Label	Principle	Description
1	**Goal: Securing human existence**	
1.1	Protection of human health	Hazards and unacceptable risks to human health due to anthropogenic environmental burdening must be avoided
1.2	Ensuring basic needs	Every member of society must be assured a minimum of basic supplies (housing, food, clothing, health care) and protection against fundamental risks to life
1.3	Securing an autonomous existence	All members of society must be given the possibility of securing their existence by voluntarily undertaken activities
1.4	Fair sharing in the use of natural resources	The utilization of natural and environmental resources must be distributed according to the principles of justice and the fair participation of all people affected.
1.5	Balancing inequalities in income and wealth	Extreme inequalities in the distribution of income and wealth must be reduced
2	**Goal: Maintaining society's productive potential**	
2.1	Sustainable use of renewable resources	The rate of utilizing renewable resources is not to exceed the regeneration rate or endanger the ecosystems' capability to perform and function
2.2	Sustainable use of non-renewable resources	The range of proved non-renewable resources must be maintained
2.3	Sustainable use of the environment as a sink for waste and emissions	The release of substances is not to exceed the absorption capacity of the environmental media and ecosystems

2.4	Avoiding unacceptable technical risks	Technical risks with potentially catastrophic impacts on humanity and the environment must be avoided
2.5	Sustainable development of human-made, human and knowledge capital	Human-made, human and knowledge capital must be developed in order to maintain or improve the economy's performance
3	**Goal: Keeping options for development and action open**	
3.1	Equal opportunities	All members of society must have equal chances to access education, occupation, information, and public functions as well as social, political, and economic positions
3.2	Participation in societal decision-making processes	Every member of society should be allowed to participate in relevant decision-making processes
3.3	Conservation of cultural heritage and diversity	Human cultural heritage and cultural diversity must be preserved
3.4	Conservation of the cultural function of nature	Cultivated and natural landscapes or areas of special uniqueness and beauty must be preserved
3.5	Conservation of social resources	To ensure societal cohesion, the sense of legal rights and justice, solidarity, and perception of common welfare must be enhanced

Source: Grunwald [55]

Since it is not possible to provide a sort of "algorithm" for sustainability assessment, ICoS has not been specifically developed as an instrument, but rather a normative framework for technology assessment, bearing in mind that technology can only make (positive as well as negative) contributions to sustainability. ICoS upholds the notion of critical sustainability and does not conceive the conventional association of the concept of development with economic growth.

2.3.3 Critics

Critics around the ICoS framework are mainly related to the anthropocentric point of departure: when asking the question "what is to be sustained?" in the debate of sustainability, it could be pointed out that -according to ICoS- ecosystems are seen as a mean to secure services for humanity, so it could be argued that conservation of biodiversity per se should be a goal even if not directly linked with a human appropriation of goods and services [38], and that nature should not only be seen as a mean to mankind's ends [55].

The anthropocentric component of the concept says that sustainability is inherently inseparable from human needs and goals, and this statement can lead to two interpretations: (i) that sustainability supposes an intergenerational anthropocentric ethic, or (ii) that anyone, that accepts the principle of sustainability, cannot or may not necessarily confer a moral value to another living being aside from human beings [39]. The present work acknowledges these critics and decides to choose the first interpretation, by considering that, regardless of the role that humans are assigned in this debate (central or equal), human action is urgently needed and indispensable to generate change.

2.4 Life Cycle Thinking (LCT)

From a conceptual perspective, ICoS was chosen as the framework for this work. However, from a methodological perspective, the core of this sustainability assessment is the Life Cycle Thinking (LCT) approach.

LCT provides valuable support to integrate sustainability into the design and evaluation of products and services [38]. LCT emerged as a concept thanks to the development of the Life Cycle Assessment (LCA) tool, which is fundamental to carry out a comprehensive and global analysis of the environmental impacts that products and services generate. LCA is considered to be a milestone in the construction of what today is known as the ecological footprint [57], and it essentially aims at making better-informed decisions related to products and services in business and policy [38].

According to Sala et al. [38], two particular features of LCA make it a significant tool for environmental sustainability: (i) the life cycle perspective, through which all phases of the life cycle of a product or service are assessed; and (ii) the cross-media approach, in which relevant environmental impacts are taken into account, i.e. both on the input side (use of resources) and the output side (emissions to air, water, and soil, including waste and physical impacts).

3. Sustainability Assessment Framework for the UCO Valorization System

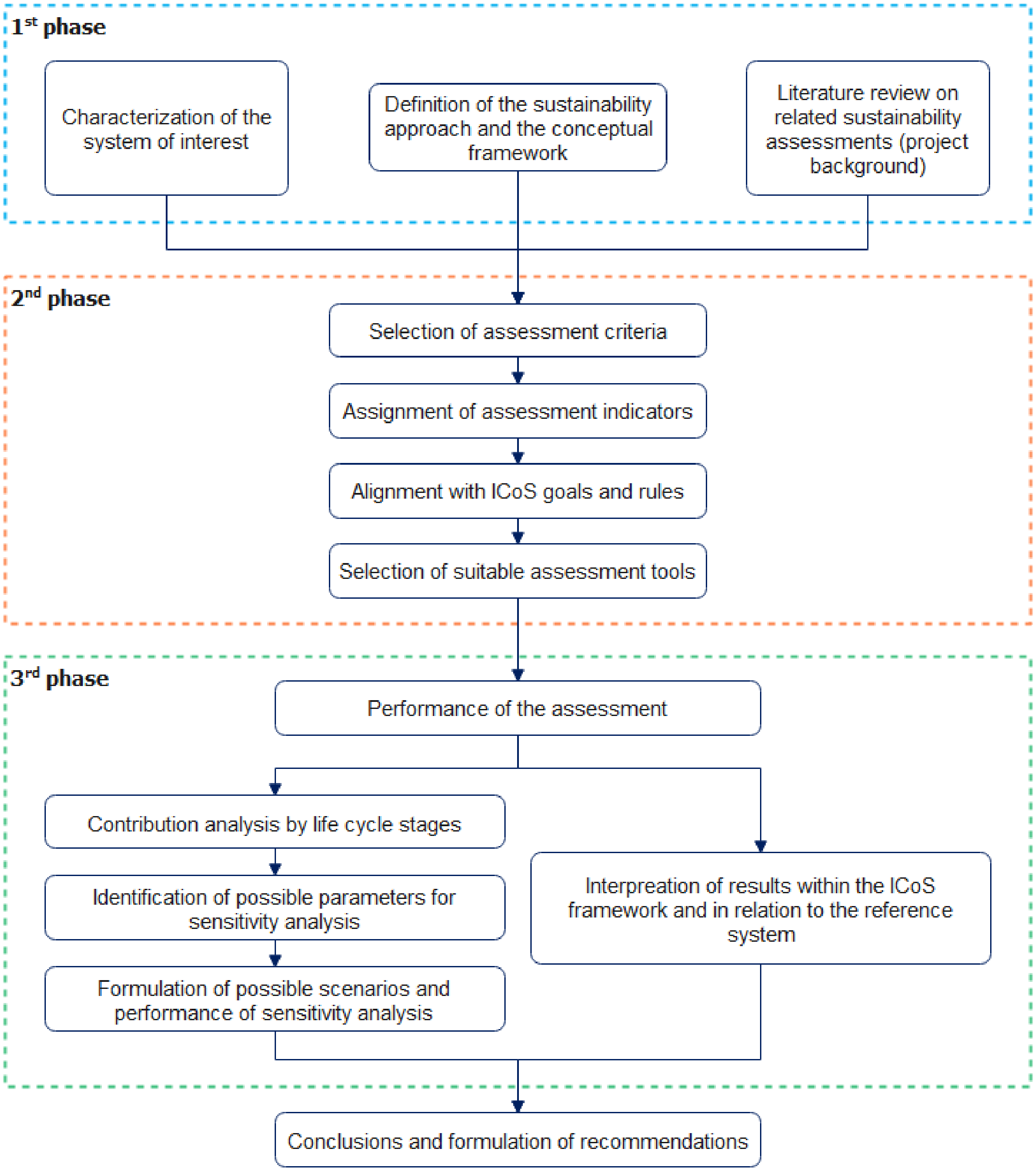
Although recycling of waste is in principle seen as a solution to environmental problems, there is the need to ensure that the developed strategies for the management and valorization of waste are in fact sustainable. Numerous UCO recycling projects have been implemented around the world, but many of them seem to have overlooked the whole life cycle of the valorization process; these have just focused on the prevention of the environmental impacts that are directly related to the disposal and the illegal commercialization of UCO.

In this regard, the identification of potential and suitable UCO-based products within the oleochemical industry requires a sustainability assessment, so it can be explicit that the associated impacts to its production and use, as well as to the sourcing of UCO, are lower than those generated by the current production practices. Also, it is important to understand under which conditions the collection and valorization of UCO can be sustainable.

This chapter presents the methodology that is proposed by the author of this work for the sustainability assessment of one of the current UCO valorization systems in the city of Bogota. The methodology, which follows the systemic framework proposed by Sala et al. [47], comprises three main phases (see Figure 3 1):

- First phase: It establishes the foundations of the sustainability assessment. This includes the characterization of the system of interest, the definition of the sustainability approach and conceptual framework, and a literature review on related sustainability assessments to define the project background.

Figure 3-1: Methodology outline



- Second phase: As it determines how to execute the assessment, this phase is the core of the methodological framework. Selected assessment criteria are assigned a respective assessment indicator and aligned with the corresponding ICoS goals and principles. Finally, suitable assessment tools are selected.

- Third phase: It consists of the performance of the assessment per se. Once the results are obtained, these are interpreted within the ICoS framework. Parallel to this interpretation, a contribution analysis by life cycle stage or hotspot analysis is carried out, in order to identify the key stages that generate the greatest impact on each of the sustainability criteria. This allows to select parameters for a sensitivity analysis, as well as to formulate possible improvement scenarios.

3.1 First phase

3.1.1 Characterization of the system of interest

The study system of this work is one of the current UCO valorization systems in Bogota, in which UCO is collected from HORECA sites, pretreated, and exported to Spain to be converted into biodiesel. This system corresponds to the operation of Greenfuel, one of the registered recycling agents in the city. At the time of this study, the company worked under cooperation with TEAM FOODS, the main local producer of edible vegetable oils that seeks to follow an Extended Producer Responsibility (ERP) policy by performing stewardship of its products until the end-of-life stage. A detailed description of this system can be found in Section 3.3.1.

The interpretation of the sustainability assessment results calls for the definition of a proper reference system. Conventional reference systems for biofuels and biomaterials are petrochemical, so the reference for biodiesel would be fossil diesel. However, since the aim of recycling UCO is to discourage the demand for virgin vegetable oil as oleochemical feedstock, virgin oil-based biodiesel is chosen as the reference system, specifically, palm oil-based biodiesel. The rationale for this choice, as well as a thorough description of this system, can be found in Section 3.3.2.

3.1.2 Sustainability approach and conceptual framework

Based on the systemic framework proposed by Sala et al. [47] (see Figure 2-2), the execution of this step led to the following statements:

- Since the conceptual framework for this assessment is the Integrated Concept of Sustainability, the notion of critical sustainability is implicit. In this sense, this work seeks to evaluate, for the study system, to what extent is natural capital being acknowledged as non-substitutable and effectively protected.
- The high complexity of the analyzed relationships and interactions between social systems and ecosystems is acknowledged; therefore, it is important to keep in mind that there is inherent uncertainty in the assessment of a system.
- Transparency is a fundamental value for this work. Complete description and reporting of the system features and assumptions for the assessment allow a clear understanding of the results and avoid inadequate extrapolation of conclusions to other study systems.
- This work highlights two main sustainability principles: the holistic approach and the planetary boundaries. The former principle is fundamental to avoid reductionism, and the latter recalls considering the capacity of the biosphere to tolerate anthropogenic action.
- The sustainability target underlying this assessment is to deliver well-being within the carrying capacity of the earth.

3.1.3 Project background

Since the target of this assessment is UCO-based biodiesel, the process of literature review focused on three main areas: sustainability of biofuels, sustainability of waste valorization systems, and sustainability of UCO valorization.

- **Assessment of biofuel systems**

Sustainability of biofuels compared to that of fossil fuels is a topic of continuous discussion. On the one hand, the potential of biofuels to reduce GHG emissions has been frequently highlighted, especially due to the need to mitigate climate change. On the other hand, direct and indirect effects of biofuel production, particularly related to land-use change and competition with production of food, have been subjects of controversy [22], [23], [58]–[60].

Within this context, many organizations around the world have outlined different sets of criteria and indicators to assess sustainability of bioenergy, biofuels, and bioproducts. An important milestone was the release of the Global Sustainability Standard for Biofuels in

2008 by the Roundtable on Sustainable Biofuels (now called Roundtable on Sustainable biomaterials) [61]. From then, numerous contributions to this subject have been done, being the following some of the most renowned: in 2011, the Global Bioenergy Partnership (GBEP) designed a set of sustainability indicators to assess bioenergy projects on the national scale [62]; a similar work was conducted in 2012 by the German Öko-Institut, to provide the European Union with the required input to improve the RED [63]; in 2015, the International Standards Organization published the ISO 13065 on Sustainability Criteria for Bioenergy, but it does not follow a life cycle approach for all of the criteria [60]. The main content of some of these contributions is presented in Appendix B.

These works have assisted governments in the making of public policies and the establishment of regulations for the biofuel sector. A decade ago, sustainability requirements would only address the minimum level of GHG savings and the direct effects of land-use change -such as the first version of the RED in 2009-; nowadays, these comprise a broader set of principles and criteria beyond climate change. Although the terms “principle”, “criterion” and “indicator” are confusedly used among the previously mentioned documents, it is possible to identify the following common criteria to guide sustainability assessment of biofuels [62]–[64]:

- Climate change mitigation (reduction of GHG emissions)
- Sustainable use of natural resources
- Protection of natural resources quality
- Avoidance of harmful direct and indirect land-use change
- Conservation and sustainable use of biodiversity
- Protection of food security
- Attention to competition with other local applications of biomass
- Respect for human and labor rights, and social welfare
- Economic viability
- Contribution to local and regional development
- Legal compliance
- Commitment to transparency

- **Assessment of waste-to-energy systems**

As identified in the literature review, sustainability assessment of waste valorization systems can disregard some of the previously stated considerations and must include additional factors, since the nature of the feedstock is significantly different. It is expected that the use of second-generation feedstock for bioenergy, biofuels, or bioproducts leads to a better environmental performance than the exploitation of first-generation feedstock, because the generated impacts by the cultivation stage of biomass and the effects of land-use change cannot be directly attributed to the recovered waste [65]. In particular, special attention is paid to the sourcing of the feedstock and the complexity of the supply chain, i.e. the degree of centralization of a waste valorization system [66].

- **Assessment of UCO valorization systems**

Appendix C shows a comprehensive summary of this literature review, in which it is evident that Life Cycle Assessment (LCA) studies on different UCO exploitation schemes prevail. Many LCA studies focus on the most common valorization practice nowadays: conversion of UCO into biodiesel. LCA studies on this matter have been performed worldwide: in Spain [14], [26], [67], Portugal [18], [19], [68], [69], Italy [6], [9], [70], the United Kingdom [22], Greece [11], Thailand [71]–[73], Japan [74], China [75], Malaysia [76], Vietnam [77], Singapore [72], [78], Cameroon [79], the United States [10], Brazil [24], [30], [80], [81], Argentina [81], and Colombia [82]. Most of the previous studies use the production of virgin vegetable oil-based biodiesel as a reference system [22], [26], [67], [71], [72]. In overall terms, these studies highlight that UCO-based biodiesel has a lower associated GHG intensity than the reference biodiesel (and fossil diesel), and that the environmental performance of the system strongly depends on the magnitude of the UCO supply chain.

LCA studies on UCO valorization have also focused on its use as drop-in fuel [6], [25], [83], as well as on its conversion into HVO [10], [74], [84], [85], pyrolyzed oil [71], biogas [86], and most recently polypropylene [33]. Although the use of UCO as second-generation does pose many advantages, these studies point out the influence of several factors on the magnitude of the impacts and the consequent deduction of conclusions.

Among the broad variety of LCA studies on UCO exploitation, an important degree of discrepancy is observed, particularly regarding the choice of the functional unit (mass of UCO, the mass of the final product, the energetic value of fuel, transport distance), the considered stages, as well the chosen allocation approach -if applicable-. In the case of UCO-based biodiesel, many studies include the stages of UCO collection, transportation, and pretreatment besides biodiesel production and distribution, but most of them focus on the stage of transesterification in order to evaluate and compare the different available technologies. Some studies take into account the combustion of the fuel, and some even consider the production of the virgin cooking oil, even though most LCA performers agree on the fact that UCO as a feedstock has a zero burden [9], [33], [68], [71], [77]. Ultimately, if UCOs are meant to be used as oleochemical feedstock, a comprehensive LCA would require the quantification of impacts along the whole valorization chain [4], [20], [68], [87].

Some LCA studies approach UCO recycling schemes at a local level and focus on the first stages of production of UCO-based biodiesel, pointing out the need for developing local valorization chains. These studies refer to cities of Spain (Barcelona [17]), Brazil (Campinas, São Paulo, and Rio de Janeiro: [8], [30], [88], Japan (Okayama and Kurume [89], [90]), and Colombia (Cali [91]).

From the reviewed studies, only a few include the assessment of criteria besides the impact categories of the LCA. Some include an economic analysis, mainly a cost evaluation [10], [14], [30], [89], and very few include the assessment of social aspects [30], [80]. Only two of the studies are based on a sustainability approach that goes beyond the traditional LCA approach. The first one, performed by Vinyes et al. in Spain, consists of an LCSA of different alternatives for domestic UCO collection [17]; the second one, performed by Mendecka et al., consists of a multicriteria analysis of a UCO valorization scheme to biodiesel [9].

3.2 Second phase

Specific assessment criteria were selected upon relevance, regarding the features of the study system and the sustainability approach Subsequently, suitable indicators were assigned to each criterion upon representativeness and practicality, keeping in mind that a proper selection of indicators contributes to building an understandable representation of reality [52]. Finally, ICoS goals and rules were aligned to each pairing of criterion-indicator. The outcome of these steps is summarized in Table 3-3 at the end of Section 3.2.2.

3.2.1 Assessment criteria and indicators

In the framework of sustainability assessment, the selection of criteria should be made upon the nature and the context of the project. Since the present work focuses on a waste valorization system to produce biodiesel, assessment criteria must be suitable for both biofuel and waste valorization systems. From the wide set of suitable assessment criteria that were identified in the literature review, the following 13 criteria were chosen. Although the input from the first phase fairly backs up this selection step, the influence of value choices cannot be neglected.

- **Human health**

Health can be defined as a “state of complete physical, mental and social well-being and not merely the absence of disease or infirmity” [92]. Hence, several factors influence human health, and a vast quantity of indicators can be used to assess this criterion. Some Life Cycle Impact Assessment Methodologies (e.g. IMPACT 2002+ and Recipe 2016) consider human health as an endpoint impact category that is determined by human toxicity (carcinogenic and non-carcinogenic), ionizing radiation, particulate matter formation, stratospheric ozone depletion, photochemical ozone formation, and global warming included.

Any of the mentioned midpoint impact categories and their respective indicators would be then suitable to represent the criterion of human health, given the solid scientific basis behind each of these. However, emissions of fine particulate matter (kg PM2.5-eq) and photochemical oxidants (kg NOx-eq) were chosen as indicators, considering the increasing efforts to raise public awareness about the link between human health and air pollution [93].

- **Labor conditions**

Labor conditions comprise a wide range of topics and issues, such as wage and income, work time, work organization, employment security, among others [94]. For this work, this criterion was assessed by exploring the degree of formality displayed by the labor market of the study and reference systems. Formalization is important to guarantee decent work and equity in society, since it enables workers to pursue their livelihoods within the scope of occupational safety and health, and social protection [95].

- **Work safety**

Certain work sectors and occupations display more hazards than others, so the risk of suffering work-related accidents and diseases is higher and must be properly managed. In this study, work safety as a sustainability criterion was analyzed by delving into the risk of labor incidents that both the study and reference systems pose.

- **Water depletion**

Future availability of water is a matter of current concern and uncertainty, given the growing water demand from households, industry, and agriculture, as well as the social, political, and economic challenges linked to the integrated management of this resource [96]. This criterion was assessed by estimating the water stress index (WSI), which is based on the water-to-availability ratio and considers the quantity of used freshwater that is no longer available for downstream users [20].

- **Demand for fossil resources**

Modern societies around the globe depend on the use of fossil fuels for survival, specifically to supply energy needs and to provide the feedstock for the manufacture of countless goods, including the agrochemicals upon which food production relies [42]. The use of fossil resources has been one of the main drivers of economic growth since the industrial revolution, but also a key booster of climate change, accounting nowadays for about 75% of the global CO_2 emissions [97]. This criterion was assessed by estimating the life cycle consumption of coal, crude oil, and natural gas, expressed in equivalents of crude oil.

- **Climate change**

Because its impacts are global in scope and unprecedented in scale [98], climate change has been probably the most used criterion to assess sustainability. There is scientific consensus on the fact that trends of global warming over the past century are extremely likely due to human activities, particularly to the increasing release and consequent concentration of GHG in the atmosphere [99]; GHG emissions are strongly related to the burning of fossil fuels, but also deforestation, land use and land-use changes, fertilization, waste management and industrial processes [100]. Climate change was assessed in terms of GHG emissions, which are expressed in equivalents of CO_2 as the reference gas.

- **Water quality**

Pollutant loadings in water bodies due to human activities have contributed to the degradation of water quality and have therefore affected nature's capacity to provide water-related ecosystem services. Water quality can be described in terms of pH, turbidity, concentration of nutrients, organic matter, heavy metals, hydrocarbons, suspended and dissolved solids, toxic compounds, among other factors. In this study, the potential of freshwater eutrophication (kg P-eq) was chosen as a suitable indicator, considering the severity of the cascading impacts that are caused by an increase in the concentration of nutrients (expressed as equivalents of phosphorus compounds), namely oxygen depletion, changes in flora and fauna populations, and the appearance of risks for animal and human health [101].

- **Soil quality**

Healthy soils are fundamental to provide supporting ecosystem services, such as primary biomass production, nutrient cycling, and habitat for biodiversity [102]. An important element of soil quality is acidity: the availability of water and nutrients for plant growth is restricted in acid soils [103]. Since one of the causes of soil acidification lies in acidic precipitation and the deposition of acidifying gases from the atmosphere, this criterion was assessed by estimating the potential of terrestrial acidification, expressed as emissions to air of SO_2 equivalents [104].

- **Waste management**

Effects of non-hazardous waste, such as UCO, are usually overlooked because this type of waste does not exhibit features of ignitability, corrosivity, reactivity, or toxicity. However, when mismanaged, non-hazardous waste pollutes water, soil, and air, affecting thereby human and ecosystem health; furthermore, non-hazardous waste is responsible for a significant share of methane emissions, being therefore an important contributor to climate change [105]. Since this assessment addresses a waste valorization system, this criterion was evaluated by examining the avoided effects of UCO valorization, specifically, the emission of GHGs from UCO disposal.

- **Economic performance**

The economic performance of the product system is related to the economic feasibility of producing UCO-based biodiesel, which cannot be determined by one factor, but rather by a network of interacting factors, including investment and operating costs, political intervention (taxes, incentives, subsidies, import tariffs), and market dynamics (changes in prices and consequent changes in supply and demand) [32], [66]. This study acknowledges the high complexity of this network and points out the need for a detailed study on economic performance. However, an approximate assessment of this criterion was made upon the operating costs associated with the production of 1 ton of pretreated UCO and 1 ton of crude palm oil (i.e. the first two life cycle stages of each system), since these are proven to be a crucial factor of biofuels sustainability [32].

- **Social acceptance**

Like the concept of sustainability, social acceptance has been addressed from different perspectives and many definitions have been proposed. Broadly, social acceptance refers to the positive response of a specific social unit (household, community, organization, region, or country) towards a specific technology or socio-technical system [106]; this response cannot be taken for granted, since it can be a barrier for the implementation and sustainability of projects.

Social acceptance can be expressed in terms of attitudes, opinions, behaviors, or investments [107]. Public support, as a manifestation of social acceptance, was the selected aspect to assess this criterion; the analysis sought to explore attitudes of people towards the use of UCO or palm oil to produce biodiesel".

- **Governmental framework**

The governmental framework on the local, regional, or national scale is essential for the effective development of a product or the successful execution of a project. For this study, this criterion was assessed by screening the set of governmental policies and regulations that have been designed and implemented to support the sustainable development of the biofuel industry, both for UCO-based and palm oil-based biodiesel.

- **Land-use change**

Biofuels and bioproducts are by default linked to agricultural expansion, which is a major driver for land-use change (LUC). In this context, LUC can refer to the direct conversion of land to a bioenergy or bioproduct crop (direct LUC), as well as to the consequential shifts in other regions due to the influence of market dynamics (indirect LUC) [26], [65], [108]. LUC usually contributes significantly to the life cycle GHG emissions of a biofuel or bioproduct, given the changes in the carbon stocks of a specific land [108]; additionally, LUC can affect the social and cultural value of nature.

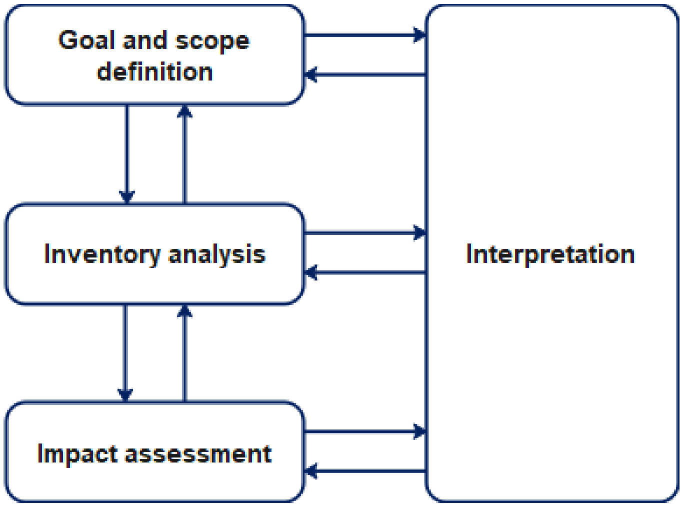
Even though LUC effects are not attributed to UCO valorization, this criterion was included in the assessment considering the potential avoided LUC effects compared to the reference system.

3.2.2 Assessment tools

- **Quantitative assessment**

Given the LCT approach that governs this work, LCA is the most suitable assessment tool for the environmental criteria. LCA can be defined as a technique that systematically assesses the environmental aspects and potential environmental impacts associated with a product or service throughout the entire life cycle, from raw material acquisition through production, use, end-of-life treatment and recycling, to final disposal [109]. The requirements for conducting an LCA are detailed in the ISO 14040 and 14044 standards. LCA broadly comprises four phases, which can be seen in Figure 3-2 and are briefly described according to the International Standard.

Figure 3-2: LCA Framework



Source: ISO [109]

The goal of an LCA states the intended application, the reasons that motivate the study, the intended audience, and whether the results are expected to be disclosed to the public or not. The scope specifies the functions of the product system or systems to be studied, the functional unit, the system boundaries, the allocation procedures (if these apply), the selected impact categories and impact assessment methodology, the assumptions and limitations, and the data quality requirements; these aspects can be modified along the way since LCA is an iterative technique.

As for the inventory analysis, this stage consists of data collection and calculation procedures to quantify the inputs and outputs of the product system. The magnitude and significance of the potential environmental impacts are evaluated in the impact assessment stage; this process associates inventory data with specific impact categories and category indicators, so environmental impacts can be better understood.

The LCA of this work was performed in the open-source software OpenLCA, version 1.10.2. The Ecoinvent 3.5 database was used for the background data of the study and reference systems, for the foreground data of the study system's fourth stage, and for the foreground data of the reference system's first, second, and fourth stages.

The functional unit was set to 1 ton of UCO-based biodiesel (or palm oil-based biodiesel), and the selected impact assessment methodology was ReCiPe 2016 (at midpoint level and from a hierarchist cultural perspective). The provided midpoint impact categories were coupled with the established criteria and respective indicators as presented in Table 3-1.

Table 3-1: Selected impact categories for each assessment criterion

Assessment criterion	Impact category	Unit
Human health	Fine particulate matter formation	kg PM2.5-eq
	Photochemical oxidant formation	kg NOx-eq
Demand for fossil resources	Fossil resource use	kg oil-eq
Climate change	Climate change	kg CO_2-eq
Water quality	Freshwater eutrophication	kg P-eq
Soil quality	Terrestrial acidification	kg SO_2-eq

According to the informative character of this LCA study, and following the recommendations of the International Reference Life Cycle Data System (ILCD) [110], attributional modeling was applied. In this type of modeling, recyclable materials are removed burden-free from the producing activity, which is valid considering that recycling of goods -that are often seen as waste- avoids the environmental impacts associated with the disposal of such goods. Therefore, and as accepted in similar studies [9], [33], [68], [71], [77], UCO is taken as a burden-free feedstock and UCO-based biodiesel only bears the burden of the valorization process.

Appendix D contains the full description of choices, assumptions, and limitations for the LCA study of this work, according to the ISO 14040 and 14044 guidelines.

- **Qualitative assessment**

Some of the criteria were qualitatively assessed due to the qualitative nature of the assigned indicator, and some due to limitations to reach a quantitative result. Either way, a thorough qualitative assessment requires the application of proper research techniques, such as interviews and participatory observation. Since time constraints did not allow for the application of such techniques, the assessment was based on the available collected information and analogous studies found in the literature.

Only to provide a general comparison graph, results of the qualitative assessment were categorized, and a number (or grade) was assigned to each category, in the same way that it is done in different impact assessment methodologies, such as the Risk Assessment Matrix (RAM), the Rapid Impact Assessment Matrix (RIAM) [111], the Leopold Matrix [112], among others. When categorizing qualitative data, however, the risk of decontextualization due to value choices has to be acknowledged [113]. In this sense, it is important to underline that this categorization aimed at a visual comparison of the assessment and that it was not intended to reduce the whole analysis to a number.

Table 3-2 indicates how grades were assigned according to the overall performance, or the magnitude of the negative impact, depending on the criterion.

Table 3-2: Categorization for qualitatively assessed criteria

Overall performance	Negative impact	Assigned number
Excellent	None	0
Very good	Very low	1
Good	Low	2
Acceptable	Acceptable	3
Insufficient	High	4
Deficient	Very high	5

Table 3-3: Selected assessment criteria and indicators, and alignment with the ICoS goals and rules for interpretation

Assessment criterion	**Indicator**	**Unit**	**Assessment tool**	**ICoS Sustainability Principle**	**Understanding for this work**	**ICoS Sustainability Goal**
Human health	Fine particulate matter formation	kg PM2.5-eq	LCA	Protection of human health	The magnitude of direct and indirect impacts on human health generated by all of the activities related to the production of UCO-based biodiesel must be minimized.	Securing human existence
	Photochemical oxidant formation	kg NOx-eq	LCA			
Labor conditions	Level of labor formality	Qualitative assessment	Literature review	Securing an autonomous existence	Like any other productive project, valorization of UCO should create a job market where labor conditions are fair and safe, contributing thereby to society's welfare	
Work safety	Risk of labor incidents	Qualitative assessment	Literature review			
Water use	Water stress index (WSI)	m^3 water	LCA	Sustainable use of renewable resources	Required use of renewable resources for UCO valorization should not endanger long-term availability of these resources	Maintaining society's productive potential
Demand for fossil resources	Fossil resource use	kg oil-eq	LCA	Sustainable use of non-renewable resources	Use of non-renewable resources for UCO valorization should be minimized	

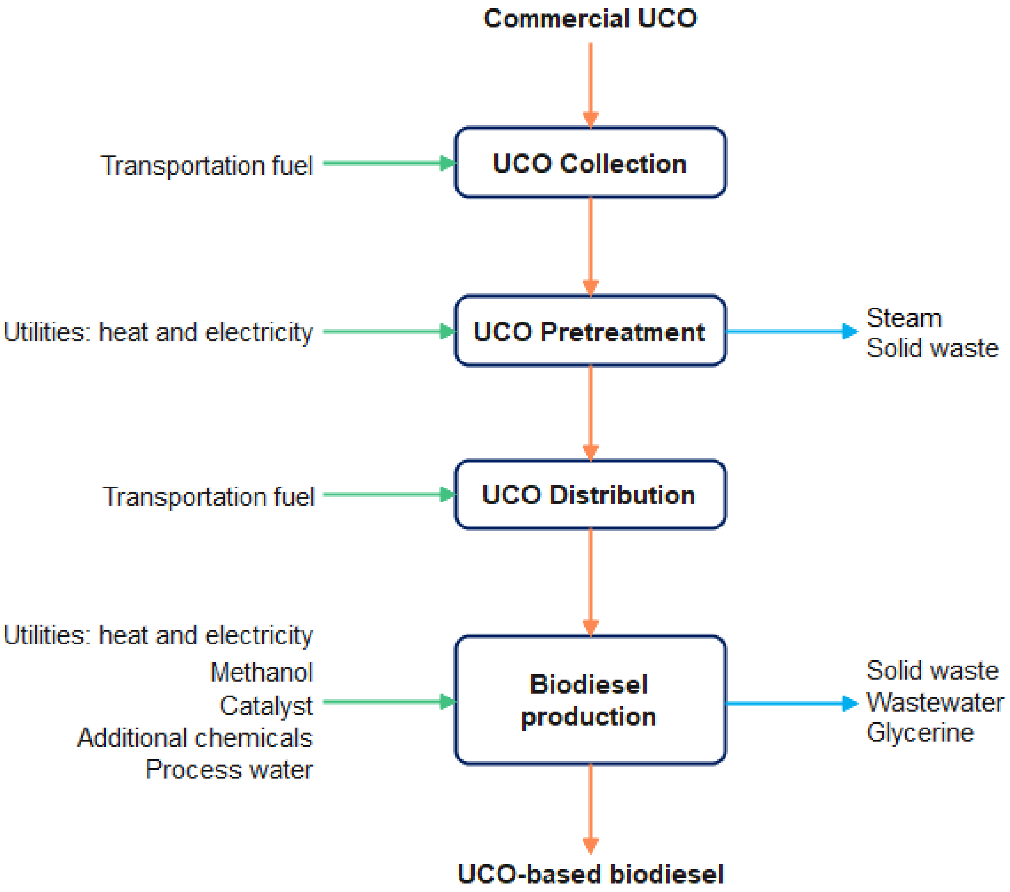
Assessment criterion	**Indicator**	**Unit**	**Assessment tool**	**ICoS Sustainability Principle**	**Understanding for this work**	**ICoS Sustainability Goal**
Climate change	GHG emissions	kg CO_2-eq	LCA	Sustainable use of the environment as a sink for waste and emissions	Waste and emissions produced by the UCO valorization system should be minimized so pollution levels do not surpass the earth's absorption capacity	
Water quality	Freshwater eutrophication	kg P-eq to freshwater	LCA			
Soil quality	Terrestrial acidification	kg SO_2-eq	LCA			
Waste management	Avoided GHG emissions	kg CO_2-eq	LCA			
Economic performance	Operating production costs before exportation of the feedstock	COP (Colombian pesos) and USD	OpEx estimation	Sustainable development of man-made, human and knowledge capital	In order to effectively reduce waste generation and maintain the UCO valorization system for the long run, total costs should be less than the benefits.	
Social acceptance	Degree of public support	Qualitative assessment	Literature review	Participation in societal decision-making processes	Involvement of society contributes to better sustainability of productive projects, such as UCO valorization	Keeping options for development and action open
Governmental framework	Robustness of related policy and regulations	Qualitative assessment	Literature review			
Land-use change	Cultural effects of direct land-use change	Qualitative assessment	Literature review	Conservation of the cultural function of nature	The UCO valorization system should contribute to the preservation of the social and cultural value of nature	

3.3 Description of the case study

3.3.1 Study system

As described in Section 1.3 and shown in Figure 1-2, a UCO valorization system consists of the following stages: UCO collection, UCO pretreatment, UCO distribution, and oleochemical production. The following paragraphs describe each of these stages for the study system, which is schematically displayed in Figure 3-3. Reported information for the first two stages is primary data collected through a visit to the facilities of the company; as for the third and four stages, information is taken from the literature.

Figure 3-3: Life cycle stages of the study system with respective inputs and outputs of materials and energy



- **UCO collection**

For this stage, Greenfuel operates under a Processor Decentralized Collection system. After having established a collection agreement with different HORECA sites -and thereby estimated the potential collectible volume-, the company can define a logistic scheme for UCO collection. The scheme divides the metropolitan area of Bogota into four main areas; each of these has a different number of collection routes, and each route consists of a specific set of HORECA sites to visit. Relevant information is shown in Table 3-4.

Table 3-4: Relevant data of the collection network in Bogota [114]

Area	Collection routes	Assigned HORECA sites	Monthly collectible amount (kg)
1	10	144	7,621
2	6	148	9,448
3	5	145	7,501
4	11	148	7,847

Source Rodríguez [114]

Light commercial vehicles with a capacity of 1.0 or 4.2 tons are used for UCO collection. Daily, drivers are assigned an area and a number of locations to visit per day, so they decide which route to take and which order to follow, based on their previous experience. Once the driver arrives at each HORECA site, he or she receives the UCO in plastic 20 L-drums, weighs each drum, issues a collection certificate following local regulations, and hands over an empty drum for further oil collection. After having completed the number of locations to visit, collected UCO is transported to the pretreatment facilities.

For the modeling of this stage, the average transportation distance for the collection of 1 ton of UCO was set to 50 km. This value was calculated upon the work of Rodríguez [114], who characterized the whole logistic scheme involved in this stage of the study system. It was assumed that all collection vehicles are light commercial vehicles. Also, the washing of the plastic containers was neglected for this study, since drums are reused multiple times without being washed, and when no longer suitable for UCO storage, these are handed to another recycling company that processes and transforms the plastic into building materials.

- **UCO pretreatment**

Collection vehicles are weighed on a certified scale once they arrive at the pretreatment facilities and after UCO has been unloaded. For quality control of the incoming UCO, operators take samples from randomly chosen drums and cover about 20% of the received load. Physicochemical properties of interest include color, pH, water content, acid value, and impurities content. It is expected that the received UCO has a maximum of 4% in mass of water content and impurities. If this value is exceeded, the situation is reported to the logistic team, so that the issue is discussed in terms of the trade agreement conditions established with the HORECA site that delivered the oil.

Plastic drums containing the collected UCO are stored in a closed and ventilated room, with optimal air humidity levels and safety measures, such as fire extinguishers and spills equipment. UCO is manually discharged from the plastic drums into an open vessel, where it is heated means a steam coil and decanted in order to reduce the content of water and suspended solids; this operation also favors the reduction of viscosity and density of the oil, as well as the melting and recovery of solid lipids. Afterward, the oil undergoes a mechanical filtration process, where the quality of the UCO is enhanced by the removal of smaller size particles that form during frying. Further treatment to reduce the content of FFA is not performed. Treated UCOs are stored in 20 to 30-ton silos that have a heating system to allow pumping to distribution trucks. Specifications of humidity, acid content, and impurities are analyzed for a random sample of the stored UCO.

For the modeling of this stage, the recycling agent provided the following data:

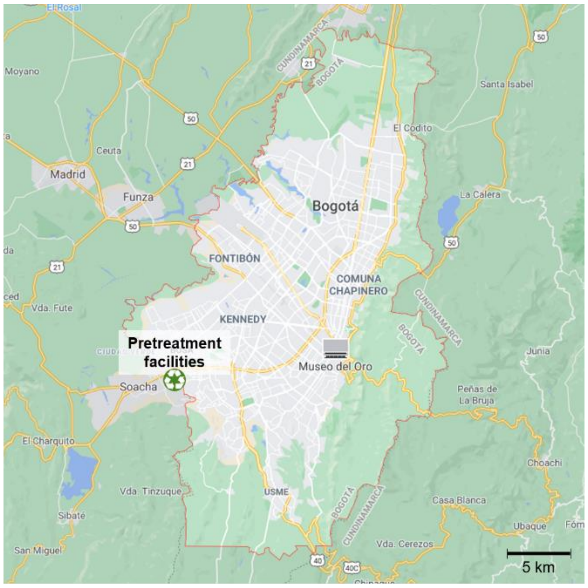
Table 3-5: Inventory data for the UCO pretreatment stage

Inputs		**Outputs**	
Collected UCO	1.03 t	Pretreated UCO	1 t
Electricity	8 kWh	Water vapor	0.0214 t
Heat	800 MJ	Biowaste	0.0086 t

- **UCO distribution and biodiesel production**

Pretreated UCO is transported about 1,000 km in heavy trucks from the pretreatment facilities in Soacha -a municipality that borders the south of Bogota-, to the port of export in Santa Marta, which is a city located on the Caribbean coast of Colombia. From there, UCO must reach Greenfuel's biodiesel production facilities in Spain, so it is first transported about 7,440 km in a transoceanic ship to the port of Algeciras, which is in the south of the country, and then transported about 324 km in heavy trucks to Los Santos de Maimona -a municipality of the autonomous community of Extremadura-. These locations and the distances between them can be observed in Figures 3-2 to 3-4.

Figure 3-4: Map of Bogota and location of Greenfuel's pretreatment facilities in Soacha



Source: Google Maps

Figure 3-5: Map of Colombia and location of the port of export in Santa Marta

Source: My Maps - Google

Figure 3-6: Location of port of import in Algeciras and Greenfuel's biodiesel production facilities in Los Santos de Maimona

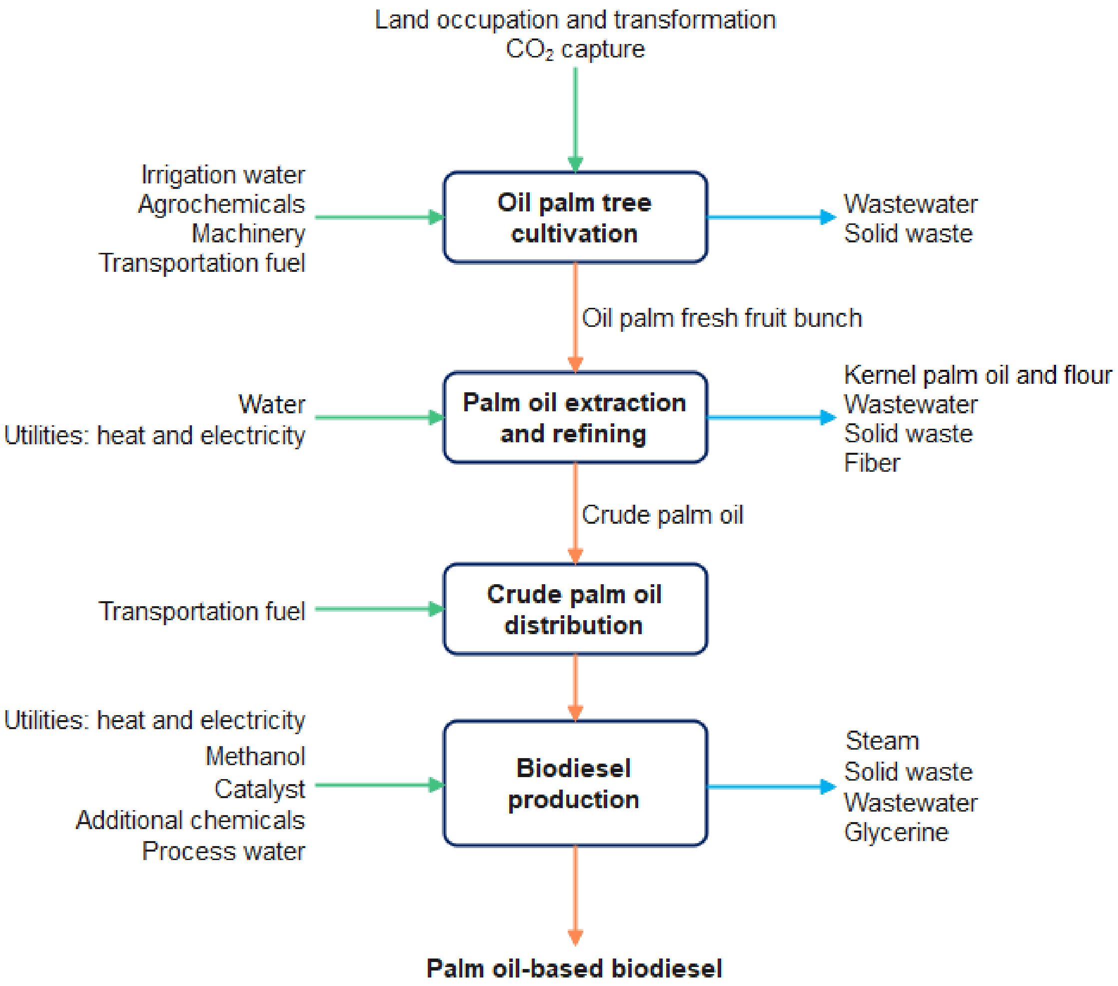
Source: My Maps- Google

For biodiesel production, Greenfuel uses the Westfalia technology, which they have adapted to process feedstock of a wide acidity range [115]. Westfalia technology consists of two main reaction stages: a continuous single- or multi-step acid-catalyzed esterification of FFA and a continuous two-step base-catalyzed transesterification of triglycerides with methanol, at atmospheric pressure and a temperature of at least 60 °C [116]. The reaction stages are followed by separation of glycerin, removal of the catalyst, stripping of the methanol, and washing purification of the esters [117]. This technology includes a closed-loop for methanol recovery and recirculation [116]. The data for the modeling of this last stage was taken from an Ecoinvent dataset and can be seen in Appendix D.

3.3.2 Reference system

Considering that the UCO-based biodiesel of interest is produced in Spain, the definition of the reference system requires to analyze which is the main feedstock for biodiesel production in this country. Spain's biodiesel sector relies heavily on imports of raw materials, mostly palm oil and soybean oil [118]: in 2017, only 1% of the biodiesel feedstock was produced in Spain, and about 62% corresponded to imported palm oil from Indonesia, Malaysia, and Colombia [119]. Within this context, and for a suitable comparison, it makes sense to choose palm oil from Colombia as feedstock for the reference system. The main stages of palm oil-based biodiesel production are schematically shown in Figure 3-7.

Figure 3-7: Life cycle stages of the reference system with respective inputs and outputs of materials and energy



In Colombia, oil palms are cultivated in different regions: the Caribbean plains (northern zone), the middle Magdalena valley (central zone), the low foothills of the plane lands (eastern zone), and the Colombian southwest (southwestern zone) [120]. For the commercial production of oil palms, not only specific climate and soil conditions are required but also selected seeds, land preparation, cover crops, fertilization, and appropriate sanitary management [121]. Once harvested, palm fruits are processed at facilities called oil mills, which are usually located near the crop. Processing consists of sterilizing, shedding, and macerating the fruits to extract the palm oil; afterward, palm oil is filtered, bleached, and deodorized. [120].

For the reference system, it is assumed that crude palm oil is exported from a specific location in the northern zone of Colombia, according to reports of the companies that export the highest volume of crude palm oil to Spain [122]–[124]. It is also assumed that the destination in Spain for biodiesel production is the same, and the transformation process follows the same technology that was previously described. Specific inventory data is shown in Appendix D.

4. Results

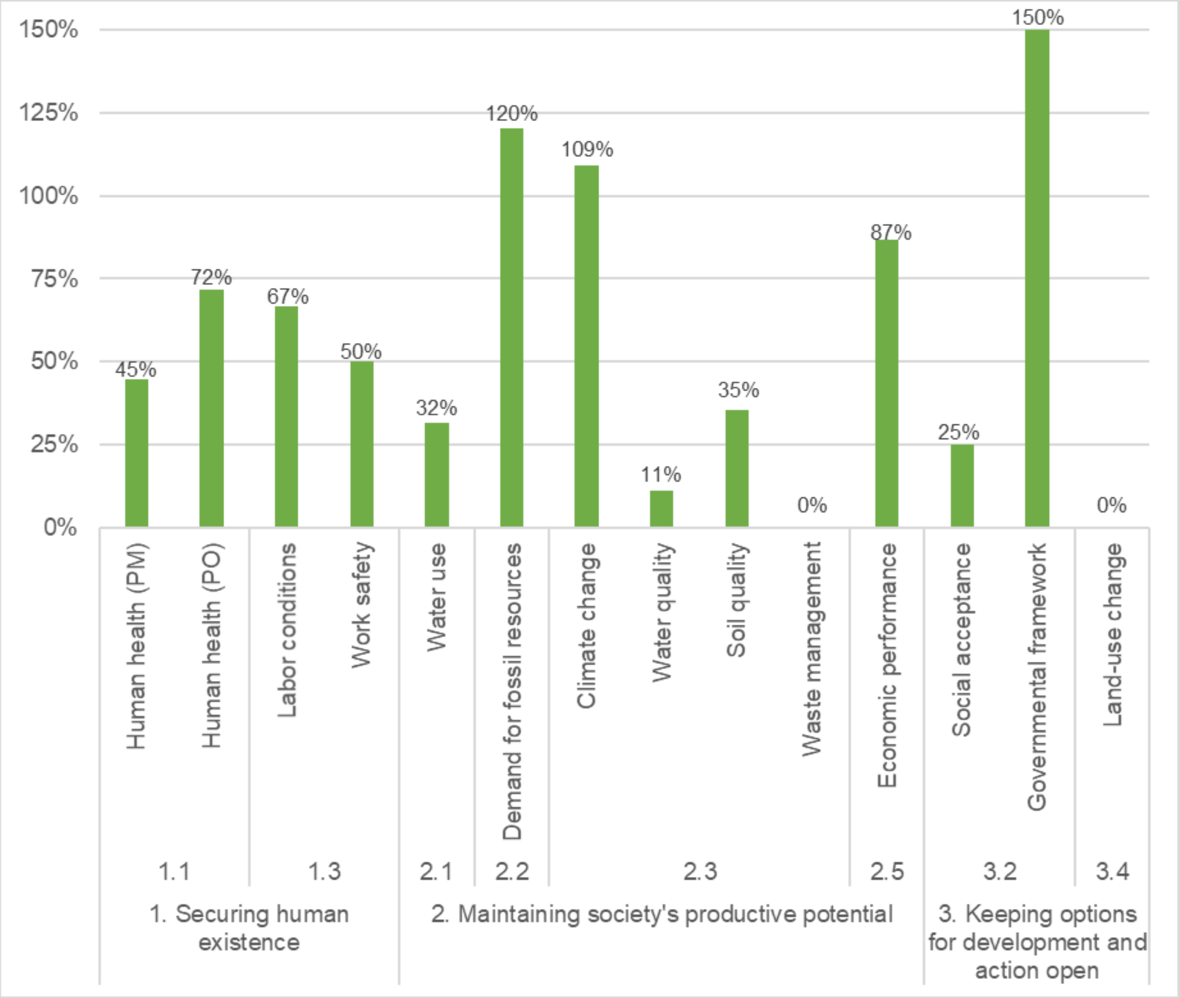
4.1 Overview

Results of the sustainability assessment are displayed in Figure 4-1. In the graph, the assessed criteria have labels that indicate the aligned ICoS rule and goal (see Table 2-1). The bars represent the magnitude of the life cycle impacts or the performance of UCO-based biodiesel relative to palm oil-based biodiesel. In this sense, a lower value than 100% indicates that -for a specific assessed criterion- UCO-based biodiesel has a lower lifecycle impact or a better performance than palm oil-based biodiesel, while a higher value than 100% indicates the opposite.

UCO-based biodiesel displays a very good potential relative to palm oil-based biodiesel, since it has a lower impact or a better performance in 10 out of 13 assessed criteria. In general terms -and within the ICoS framework-, sustainability of UCO-based biodiesel can be interpreted in the following way:

- Securing human existence: The assessed UCO valorization system contributes to the protection of human health, as well as to the securing of an autonomous existence, considering the positive relative performance in terms of labor conditions and work safety.
- Maintaining society's productive potential: The assessed UCO valorization system contributes to the sustainable use of renewable resources, the sustainable use of the environment as a sink for waste and emissions (except for climate change), and the sustainable development of man-made, human and knowledge capital. However, the study system must improve regarding the sustainable use of non-renewable resources.
- Keeping options for development and action open: The assessed UCO valorization system strengthens participation mechanisms in decision-making processes and contributes to the conservation of the cultural function of nature.

Figure 4-1: Life cycle impacts/performance of UCO-based biodiesel relative to palm oil-based biodiesel



Performance of each criterion will be described in detail, but it is important to first mention the two main findings of the hotspot analysis that resulted from the LCA, since these are required to understand the analysis by criterion:

- The UCO distribution stage is a major contributor to many impact categories, especially human health, climate change, and soil quality. Thus, local production of biodiesel was proposed as an improvement scenario, i.e., the stage of exportation was eliminated. The modeling of this scenario was based on the available data in the Ecoinvent database. Providers for the consumption of raw materials and utilities were adapted to the new geographical location.

- The contribution share of the collection stage for the study system was particularly high for many impact categories. For this reason, a sensitivity analysis was performed by varying the average transportation distance for the collection of 1 ton of UCO. Even though the calculated sensitivity ratios were not significantly high (0.11 – 0.21), the analysis confirmed the need to optimize the UCO collection scheme. The detailed sensitivity analysis is presented in Appendix E.

4.2 Analysis by criterion

The following sections describe the assessment results for each criterion in detail. Interactions and relationships between the criteria are pointed out to avoid a segmented analysis. For the indicators that were assessed through LCA, bar graphs present the results and the contribution share of each life cycle stage. Stages were designated a common identity as indicated in Table 4-1.

Table 4-1: Stages identification

Common stage name	UCO-based biodiesel (study system)	Palm oil-based biodiesel (reference system)
Feedstock sourcing	UCO collection	Oil palm cultivation
Oil pretreatment/extraction	UCO pretreatment	Palm oil extraction
Exportation	UCO distribution	Palm oil distribution
Biodiesel production	Biodiesel production	

The graphs include the results of the proposed improvement scenario. Together with local production of UCO-based biodiesel, local production of palm oil-based biodiesel was also considered.

4.2.1 Human health

Figure 4-2 and Figure 4-3 show the detailed results for the emissions of fine particulate matter (kg PM2.5-eq) per ton of biodiesel, and the corresponding for photochemical oxidants (kg NOx-eq) respectively.

Figure 4-2: Life cycle particulate matter emissions (kg PM2.5-eq) per 1 ton of biodiesel

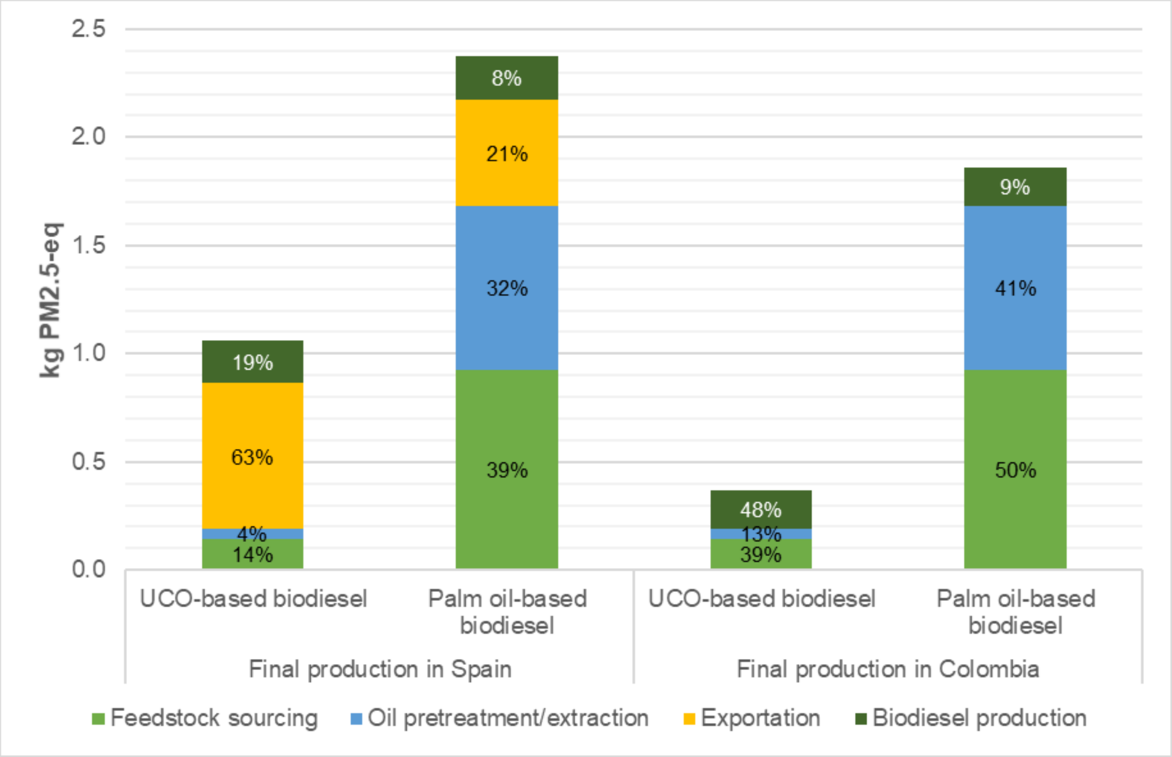
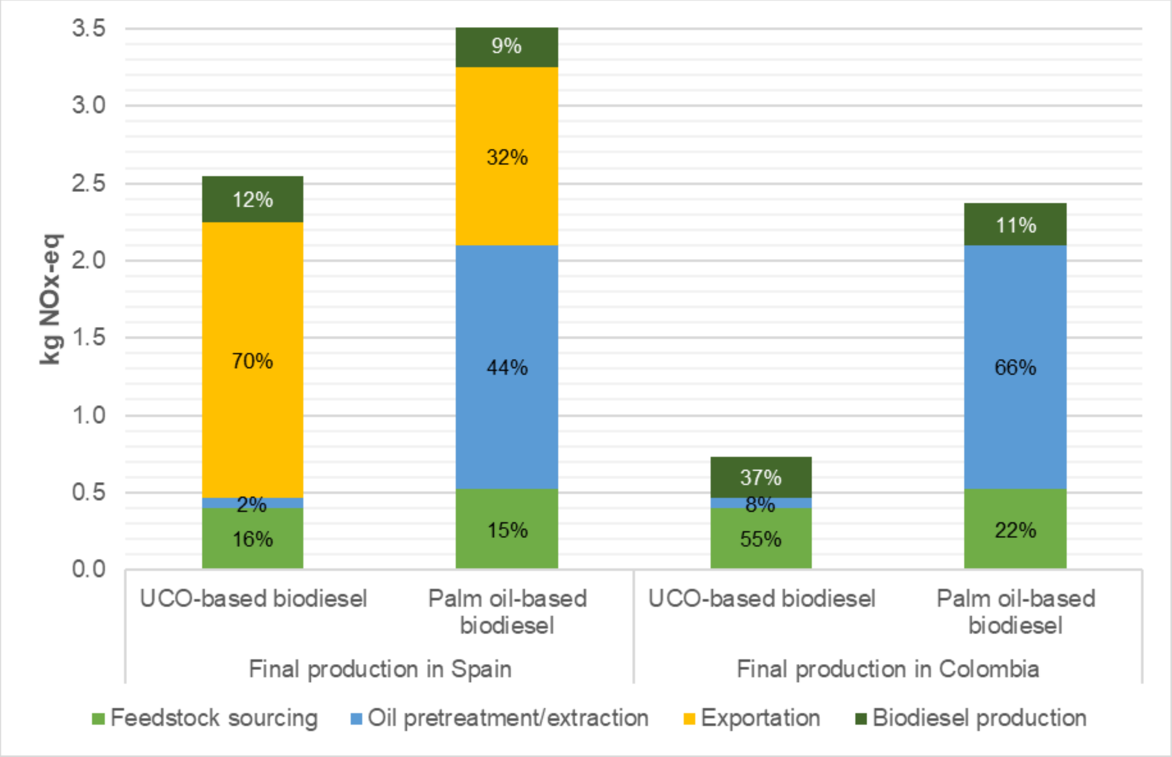


Figure 4-3: Life cycle photochemical oxidants emissions (kg NOx-eq) per 1 ton of biodiesel



For the study system, the greatest contribution for both indicators comes from the stage of exportation. In particular, the process of transoceanic transport accounts for around 40% of the impacts, followed by the process of freight transport with vehicles meeting the Euro IV standards (i.e., the distribution segment in Colombia); the latter process accounts for 20% of the particulate matter emissions and more than 27% of the photochemical oxidants emissions. When the exportation stage is eliminated and biodiesel is produced locally, the magnitude of the impact is reduced by 65% and 71% respectively, and the hotspots shift to the collection stage and the process of methanol production for the stage of biodiesel production. It is important to mention that the improvement scenario does not include specific information about the importation of methanol; in this case, Ecoinvent provided valid data with uncertainty adjustments for the new geographical scope.

Regarding the reference system, the emissions from the exportation stage are also significant, but not to the same extent as in the study system; so, when palm oil is destined for local production, a lower reduction is achieved (22% for particulate matter formation and 33% for photochemical formation). Major hotspots in the reference system are in the stages of palm tree cultivation and oil palm extraction.

4.2.2 Labor conditions

For this criterion, the main differences between both systems lie in the stages of feedstock sourcing and oil pretreatment/extraction, which are carried out in Colombia. The assessment results -which are summarized in Table 4-2- focus on the level of labor formality for the first two life cycle stages.

Table 4-2: Assessment of labor conditions in terms of labor formality

System	Overall performance	Assigned number
UCO-based biodiesel	Good	2
Palm oil-based biodiesel	Acceptable	3

For UCO-based biodiesel, operations of UCO collection and pretreatment are carried out by registered recycling agents, i.e., by formally established companies that are compelled to legally hire their employees. However, there is a risk of labor informality due to the presence of an illegal market. As described in Section 1.2.1., it has been identified that certain organizations illegally collect UCO and conduct a rudimentary treatment to sell it as new oil. Due to the illicit nature of such organizations, employees are not formally involved in these activities. Within this context, the overall performance of the study system was assessed as “good”, because Greenfuel -as well as similar companies- is a legally registered recycling agent. A “very good” categorization was ruled out, considering the risk of labor informality.

As for the reference system, the panorama is more complex. According to the Colombian Federation of Oil Palm Growers (Fedepalma), the percentage of job formality in the Colombian oil palm sector is 82.4%, which strongly contrasts with a low 15% of labor formality in the rural area of the country [125]. Nonetheless, according to a recent study, 83.6% of the oil palm sector employment is outsourced through Associated Work Cooperatives (CTAs) and private companies [126], which means that, even though employees do have a labor contract and the corresponding social security benefits, they may not exercise the right to strike nor belong to a labor association that protects their interests [126]–[129]. Although the specific labor conditions at the company that performs oil palm cultivation and palm oil extraction in the chosen reference system are unknown, the overall performance was assessed as “acceptable” considering that, behind that high percentage of labor formality, there might be precarious employment conditions in terms of labor rights protection.

4.2.3 Work safety

Biodiesel production involves the storage and handling of several hazardous substances, which poses significant risks if appropriate precautions are not taken [87]. In terms of labor incidents, fires and explosions are reported to be the most common in the industry [87]. Also, it has been demonstrated that the growth in the production rate of biodiesel has been accompanied by an increase in incident rates, mainly due to the lack of expert operators and safe technologies [130]. However, and similar to the last criterion, this assessment examined the risks of labor incidents for the stages of feedstock sourcing and oil pretreatment/extraction alone. Results are summarized in Table 4-3.

Table 4-3: Assessment of work safety in terms of risk of labor incidents

System	Negative impact (Risk)	Assigned number
UCO-based biodiesel	Low	2
Palm oil-based biodiesel	High	4

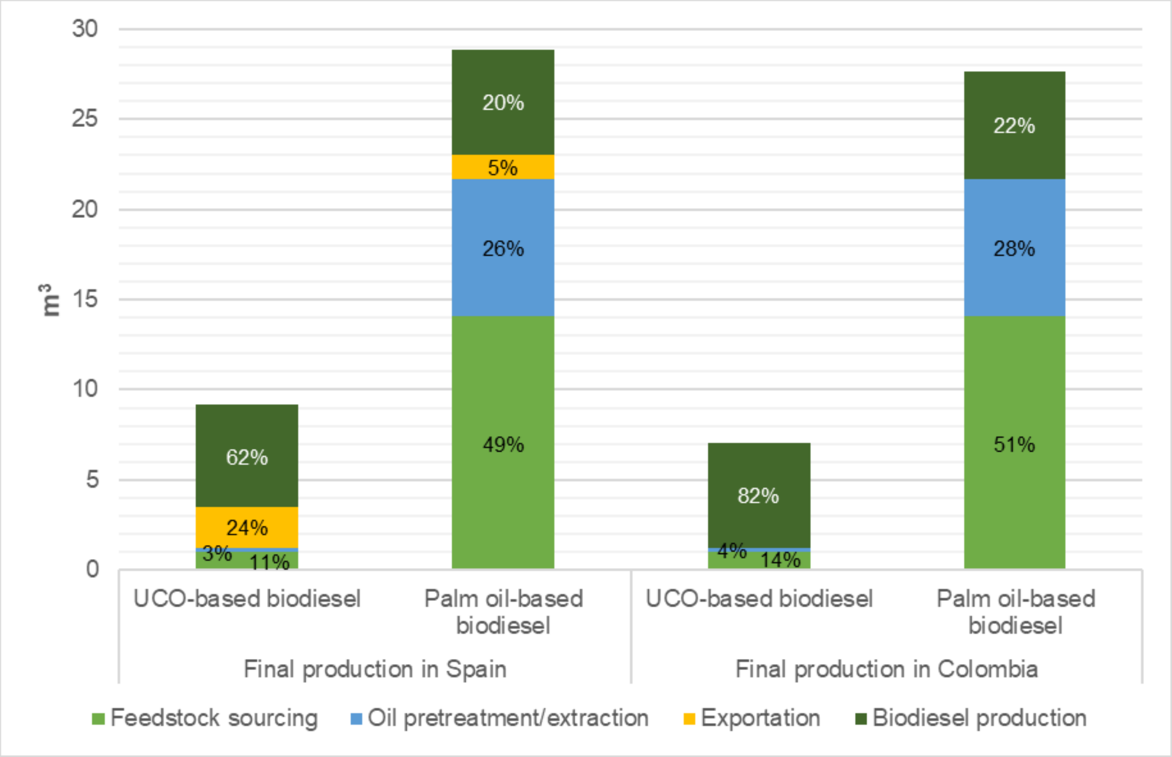
Regarding UCO-based biodiesel, the main potential labor incident associated with the first two life cycle stages is the event of a car accident in a UCO collection journey, which could result in a fire event due to the loaded flammable oil [87].

As for palm oil-based biodiesel, the Colombian Council on Safety reported that, during the first semester of 2020, production of palm oil displayed the third-highest rate of labor incidents among the different economic activities of the country [131]. This can be partially explained by the fact that the Colombian palm oil sector is not as modernized in terms of automatization as other agricultural sectors. Thus, workers must perform tasks of heavy loads lifting and carrying, agrochemicals handling, tilling and plowing, as well as other manual harvesting-related activities, which have a high inherent risk of labor incidents [127], [132]. Furthermore, biological risks are very significant, since workers are exposed to different species that can wound them and cause allergies or transmit zoonoses [133]. Finally, it is also important to mention the risks that arise from the Colombian internal conflict, even though these are not inherent to the nature of the work: the presence of illegal armed groups in oil palm regions has been identified, which represents a fundamental safety risk for the workers of the sector [127].

4.2.4 Water use

As can be observed in Figure 4-4, the study system performs better in terms of water use. By avoiding water consumption from crop cultivation, the study system's WSI is less than a third of the reference system's WSI. This is highly meaningful considering the current debate on using resources for bioenergy crops. For the study system, the main contribution comes from the stage of biodiesel production, particularly from the process of methanol production. When excluding the exportation stage and considering local production, the magnitude of the indicator decreases by 23%, which is not outstandingly high, but neither negligible.

Figure 4-4: Life cycle Water Stress Index (WSI in m^3) per 1 ton of biodiesel



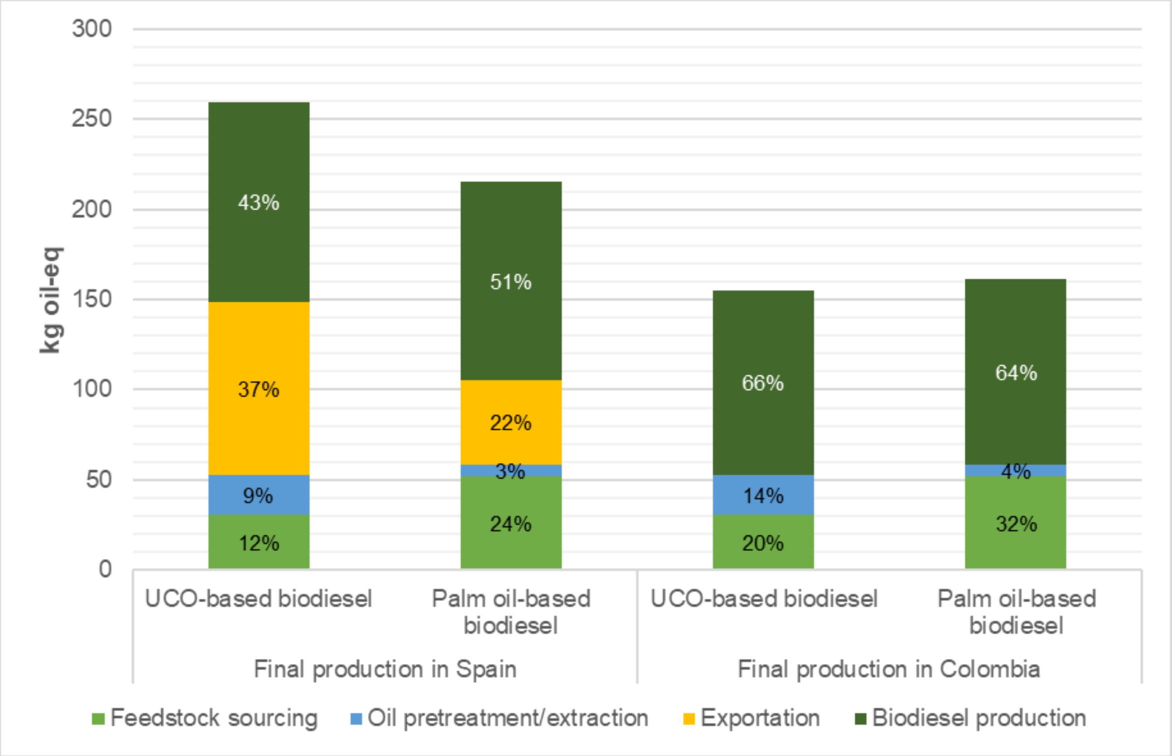
4.2.5 Demand for fossil resources

Despite being conceived to replace fossil fuels, biofuels depend on fossil resources to be produced. Crops for first-generation biofuels require agrochemicals, which are fossil-based substances. Furthermore, without energy subsidies from fossil fuels, it is impossible to achieve the required yield for the industrial-scale production of biofuels [134].

Without the cultivation stage, second-generation biofuels could be far less dependent on fossil fuels. However, recycling of waste can neither be carried out without energy inputs, which mainly come from fossil fuels since their share in the global energy matrix is still 84% [135]. This can also be analyzed from the perspective of the second law of thermodynamics: recycling of waste is highly expensive in terms of materials and energy inputs, because waste cannot become a useful product (and therefore reduce its entropy) without the input of low-entropy flows, such as fossil fuels [136].

Figure 4-5 shows that, in contradiction to what could be expected, the study system is more dependent on fossil resources than the reference system.

Figure 4-5: Life cycle fossil resource use (kg oil-eq) per 1 ton of biodiesel



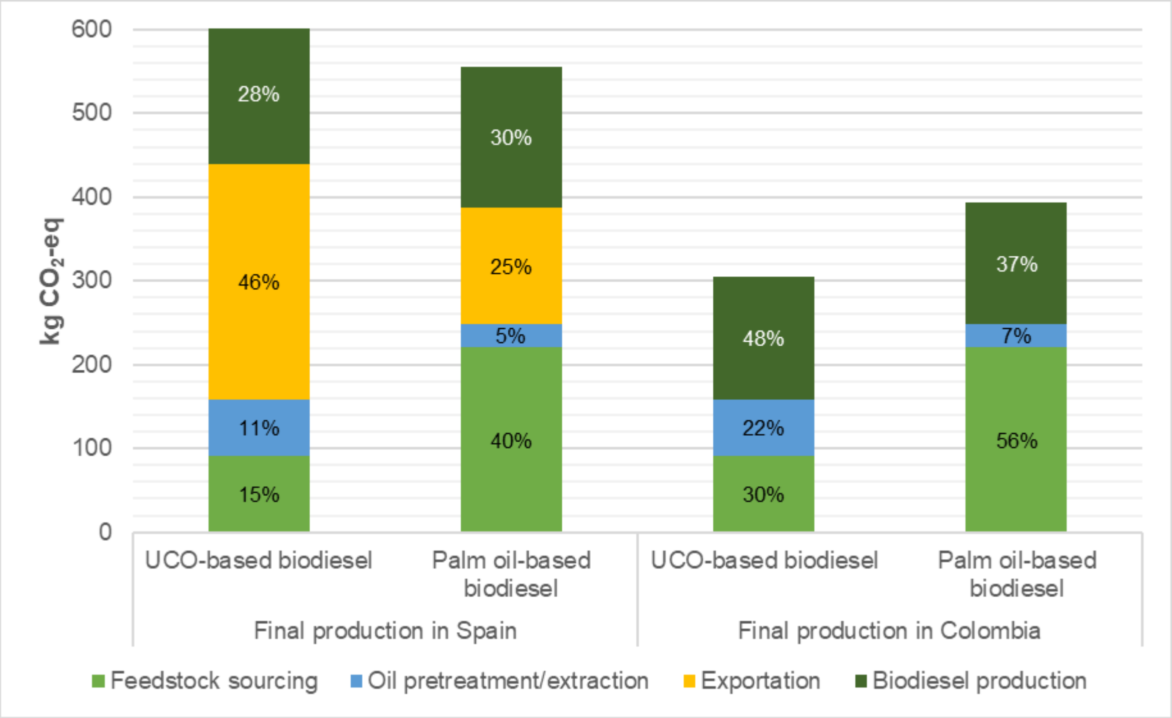
Overall, the main hotspot comes from the process of methanol production for the transesterification stage. However, the exportation stage for the study system is clearly a major contributor to this indicator; when this stage is avoided and biodiesel is produced locally, the magnitude of the indicator is reduced by 40%, becoming slightly less dependent on fossil resources than the reference system under local production.

4.2.6 Climate change

Figure 4-6 presents the life cycle GHG emissions per 1 ton of biodiesel, but without including Land-Use Change (LUC) effects for the reference system; these will be further addressed and discussed in detail.

First, only the performance of the study system is analyzed. According to the RED II, typical life cycle GHG emissions of UCO-based biodiesel are about 400 kg CO_2-eq/ton (excluding the stage of transportation and distribution of the final fuel), which represent savings of 88% with respect to fossil diesel [137]. According to the results of the study system, this value goes up to 607.57 kg CO_2-eq/ton, which is 50% higher than the typical value, but still represents GHG emissions savings of 82% in relation to fossil diesel. Although this value is acceptable within the RED standards, the fact that the stage of exportation accounts for almost 50% of the GHG emissions cannot be ignored: when this stage is eliminated and biodiesel is produced locally, GHG emissions savings rise to 91%. In this scenario, the major contribution comes from the collection stage, which -once again- raises questions about the efficiency of the collection scheme. This hotspot is followed by the process of methanol production for the last stage (with a contribution of 24%), and the process of heat production for the second stage (with a contribution of 22%).

Figure 4-6: Life cycle GHG emissions (kg CO_2-eq) per 1 ton of biodiesel



As for the reference system, it seems to perform better than UCO-based biodiesel, but LUC effects must be included. Without GHG emissions from LUC, the main hotspot is the stage of oil palm cultivation, followed by the stage of biodiesel production.

When oil palm is planted on previously high carbon stock land, such as a tropical forest, biofuels lose their potential to save GHG emissions in relation to their petrochemical counterpart [65]. Since oil palm crops have been associated with the destruction of tropical forests around the world (particularly in Indonesia and Malaysia) [138], it could be presumed that including LUC effects in the assessment of the reference system would increase GHG emissions. However, oil palm crops in Colombia differ substantially from those in Asian countries. From the new oil palm crops that were planted between 2002 and 2008 in Colombia, 51% occurred in pastures, 29.1% in croplands, and 16.1% in natural vegetation (forest and savannas) [139]. Given that the carbon stock of pastures, croplands, and savannas is lower than the carbon stock of an oil palm crop, LUC to oil palm actually increases carbon stocks per unit of area and thereby reduces the GHG intensity of palm oil-derived products [140].

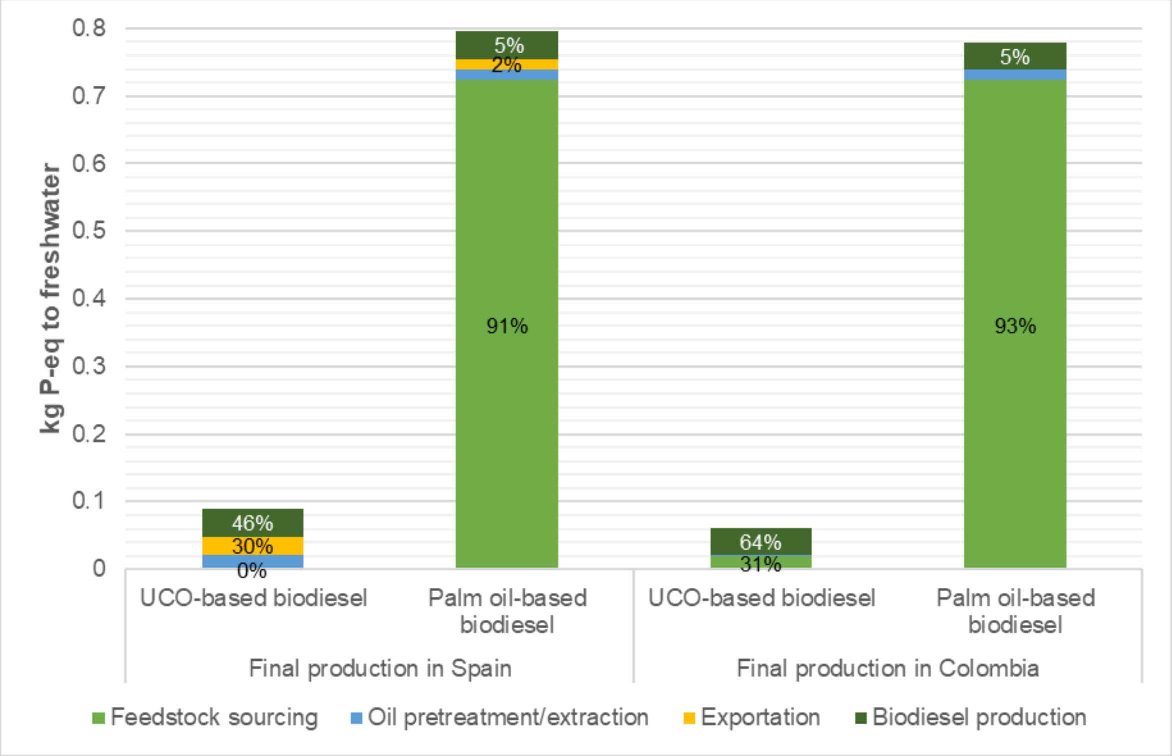
The first two stages of the selected reference system occur in a location in the Northern zone. For this region, land-use transitions to oil palm between 2002 and 2008 occurred mainly in croplands (68.3%) and pastures (26%) [139]. For the Colombian case, GHG emissions from those specific land-use transitions are estimated to range between -93 and -3.254 kg CO2-eq per ton of biodiesel [140]. Consequently, the net GHG intensity of the reference system would be better than that of the study system for any type of direct land-use transition. Nevertheless, indirect LUC remains unexamined due to the high degree of uncertainty posed by its prediction and modeling.

The study system could also display negative GHG emissions, given that recovery of UCO avoids the generated emissions by its disposal, particularly if it ends up in a sanitary landfill without energy recovery. Following the attributional approach of the LCA (as explained in Appendix D), these emissions were not credited to the study system, but this aspect was assessed separately and will be later depicted.

4.2.7 Water quality

Figure 4-7 displays the results for the eutrophication potential, expressed in emissions of kg P-eq per ton of biodiesel. The difference between the study and the reference systems is quite remarkable: the life cycle eutrophication potential of UCO-based biodiesel is about 11% of that of palm oil-based biodiesel. By avoiding the stage of oil palm cultivation, a substantial contribution to mitigating water pollution can be achieved. As for the improvement scenario for the study system, the eutrophication potential is reduced by a third when UCO-based biodiesel is produced locally. It is important to point out that, following the attributional approach of the LCA, the mitigation of the eutrophication potential due to avoided UCO pollution was not accounted for. However, this is certainly a non-negligible contribution of UCO reclaiming and exploitation.

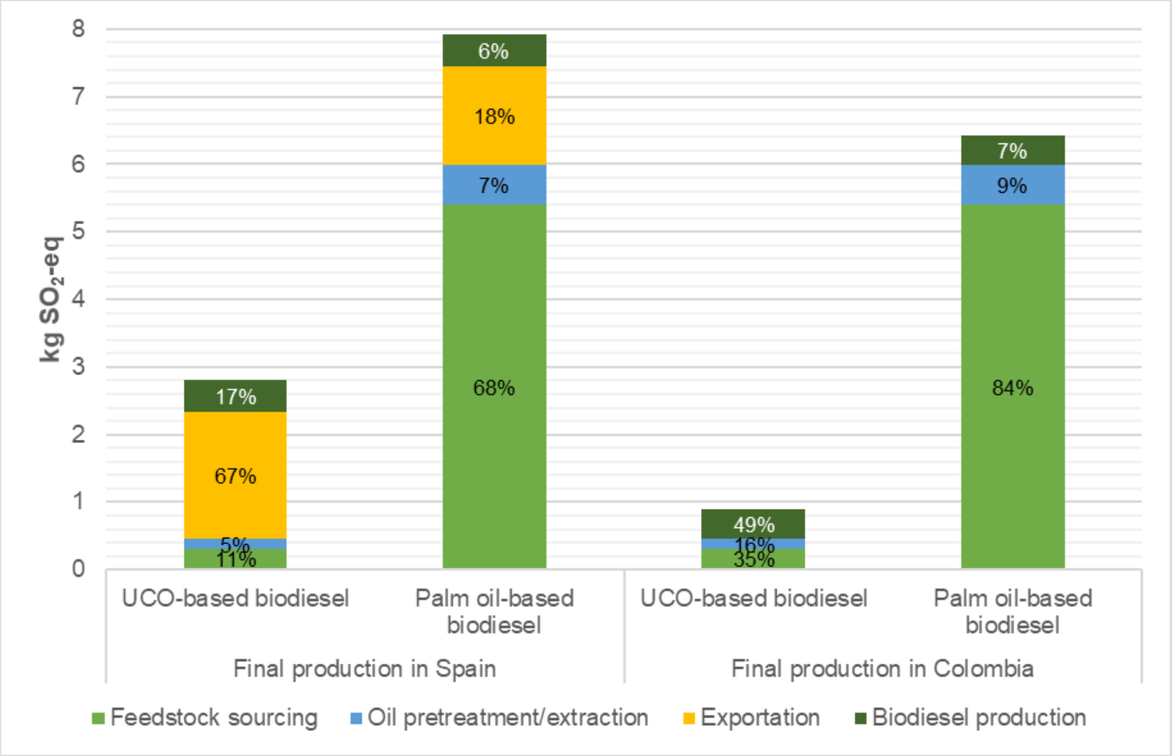
Figure 4-7: Life cycle eutrophication potential (kg P-eq to freshwater) per 1 ton of biodiesel



4.2.8 Soil quality

The assessment results for this criterion led to a similar analysis for the criterion of water quality. As can be seen in Figure 4-8, the stage of oil palm cultivation is highly responsible for the soil pollution effects linked to palm oil-based biodiesel. Therefore, the acidification potential of UCO-based biodiesel is significantly lower (about one-third). In this case, however, the exportation stage is by far the main contributor to the acidification potential of the study system, specifically, transoceanic transport (contribution share of 44%). Thus, when eliminated, this indicator is reduced to a third and the hotspots shift to the collection stage, the processes of methanol production for the last stage (contribution share of 20%), and to the heat generation for the pretreatment stage (contribution share of 14%).

Figure 4-8: Life cycle acidification potential (kg SO_2-eq) per ton of biodiesel



4.2.9 Waste management

UCO valorization prevents the environmental effects of inadequate disposal practices. According to a recent study [1], 90% of the generated UCO in Colombia is disposed of, mainly through the sewage (70%) and also within the solid waste (20%). In this sense, recovery of 1 ton of UCO would avoid -among many other impacts- GHG emissions from 1) the degradation of 200 kg of solid waste in a sanitary landfill, and 2) the treatment of wastewater polluted by 700 kg of UCO.

According to Ecoinvent inventories, 1 kg municipal solid waste emits 0.76 kg CO_2-eq and treatment of 1 L wastewater emits 0.00057 kg CO_2-eq. Hence, the study system could be credited with about 145 kg CO_2-eq per ton of biodiesel for the avoided degradation of solid waste, and at least 418 kg CO_2-eq per ton of biodiesel for the avoided treatment of wastewater. The latter value is highly uncertain, since it has been reported that one liter of cooking oil has the potential to contaminate 1,000 [13], 25,000 [141], 40,000 [142], 500,000 [143], and even 1 million [144] liters of clean water. The lowest value (1,000 liters) was taken for the estimation. Still, if the total value of 563 kg CO_2-eq is credited to the study system, the GHG intensity of UCO-based biodiesel would be about 45 kg CO_2-eq.

However, it is important to recall that Colombia does not count with full coverage of wastewater treatment. By 2018, the proportion of treated urban wastewater was 42% for the whole country [145], and 32% for Bogota [146]. Thus, it is possible to assert that almost 50% of generated UCO in Bogota eventually reaches water bodies. In this case, an increase in GHG emissions is not the main concern, but rather water eutrophication, soil pollution, and toxicity effects on flora and fauna.

Regarding toxicity, this is primarily attributed to the production of long-chain fatty acids (LCFAs), which are the primary hydrolysis intermediates of vegetable oils [147]. Studies on the toxicity of vegetable oils to specific organisms have been carried out: on seawater mussels, for example, very low contamination rates of vegetable oils over 4 weeks led to a significantly lower growth rate and higher mortality [148]. Also, direct toxicity of vegetable oils to benthic organisms at different concentrations was demonstrated [149]. As for soil pollution, it has been concluded that UCO produces a remarkable inhibition in plant growth among a wide range of dosages, as well as toxic effects for terrestrial organisms such as earthworms [150]. These impacts can be prevented if UCO is not discarded as waste.

4.2.10 Economic performance

This criterion was assessed by estimating the operating production costs of the feedstock for biodiesel production before exportation, i.e., the cost of producing 1 ton of pretreated UCO and 1 ton of crude palm oil. The findings correspond to approximate values. In the case of UCO, costs related to the collection stage comprise the buying of the UCO from the HORECA sites, the fuel consumption for the collection vehicles, and the employee salaries. Regarding the stage of UCO pretreatment, the related costs comprise the consumption of utilities (electricity, heating fuel, and water), as well as the employee salaries. Then, the total production costs of 1 ton of pretreated UCO are about 1,300,000 COP (~370 USD) [12], [114].

Regarding palm oil, the production costs originate from activities of crop management such as fertilization, phytosanitary prevention and harvest, in addition to activities of infrastructure and machinery maintenance, transportation, and the industrial processing of the palm fruit bunch. For the chosen geographical zone of the reference system (Northern zone), Fedepalma reports a value of approximately 1,500,000 COP (~430 USD) [151]. A difference of 200,000 COP (~60 USD) is significant considering that biodiesel feedstock is a commodity, and a potential reduction in the production costs of the biofuel has a paramount impact on its economic viability. Also, and due to the attributional approach of the LCA, there are economic benefits that are not accounted for by avoiding the mismanagement of UCO. These include reduction of costs for wastewater treatment, sewage system repairment, public health problems, etc. Therefore, it is expected that the economic performance of UCO-based biodiesel would be much better than estimated.

4.2.11 Social acceptance

A proper assessment of this criterion requires the application of rigorous qualitative assessment techniques, specifically, structured or semi-structured interviews. However, it was possible to get an overview of the degree of public support for UCO- and palm oil-based biodiesel through a process of literature review. Results are shown in Table 4-4.

Table 4-4: Assessment of social acceptance in terms of the degree of public support

System	Overall performance	Assigned number
UCO-based biodiesel	Very good	1
Palm oil-based biodiesel	Insufficient	4

The successful implementation of waste valorization models also relies on a high degree of involvement from stakeholders, consumers and civil society organizations included. This is essential to minimize forms of resistance such as ‘not in my back yard’ and “locally unwanted land use” behaviors [152].

In general, attitudes towards UCO valorization are positive, considering that the ecological pressure of waste is reduced by transforming it into useful products within the framework of circular economy [152]. In some cases, the degree of support increases when there is awareness about the environmental impacts of UCO mismanagement; in other cases, this is irrelevant and perceived benefits play a more important role [153]. For this reason, the performance of the assessed UCO valorization system was categorized as “very good”.

Nonetheless, it is important to point out that the level of involvement from citizens is still low, so when it comes to collect, store, and take the oil to a proper disposal point, there is not enough public engagement.

Regarding palm oil-based biodiesel, the use of palm oil as oleochemical feedstock around the world is being more rejected by society, due to the well-known associated deforestation and impacts on biodiversity [154]. In Colombia, even though oil palm crops are proven not to be major contributors to deforestation [120], it is hard to break the stereotype given the global circulation of negative publicity. Besides, despite the strong institutional and policy framework that has fostered the acceptance of oil palm by using the discourse of a “green” economic development in the regions, conflict victims and academics reject the implementation of oil palm monoculture, as they are aware of the ecological, social, and cultural impacts that come along with industrial energetic crops [139], [155].

4.2.12 Governmental framework

The criterion of governmental framework was assessed by exploring the robustness of the existing policy and regulations around both UCO-based and palm oil-based biodiesel. Results are shown in Table 4-5.

Table 4-5: Assessment of governmental framework in terms of the robustness of the related government policy and regulations

System	Overall performance	Assigned number
UCO-based biodiesel	Acceptable	3
Palm oil-based biodiesel	Good	2

For UCO-based biodiesel, Resolution 316 of 2018 -ruled by the Ministry of Environment and Sustainable Development- constitutes the legal framework that allows valorization of UCO to produce biodiesel. This resolution is complemented by the National Public Policy on Sustainable Production and Consumption, which seeks to promote integrated management of the edible vegetable oils’ value chain. Since the legal requirements to formally exploit UCO have been established, the performance of the study system was assessed as “acceptable”. However, efforts to promote adequate and effective UCO management strategies are still required from a governmental perspective.

As for palm oil-based biodiesel, the panorama is quite different. From the early 2000s, different laws, resolutions and decrees have been ruled to regulate the production of palm oil and its derivatives. In 2007, a National Public Policy was specifically formulated to promote the competitiveness of the Colombian oil palm sector [156]; along with the Law 939 of 2004, which sought to promote production and commercialization of biodiesel from both vegetable and animal sources, production of palm oil-based biodiesel was legally allowed. Since then, several incentives for the oil palm sector have been designed and granted through different political and legal tools, particularly to foster the large-scale expansion of oil palm crops. For this reason, performance of the reference system was assessed as “good”. Nonetheless, it has been pointed out that this framework has been shaped by political and economic elites, who have intervened with specific and direct interests in the agribusiness [126].

4.2.13 Land-use change

Although LUC is not attributed to UCO valorization, this criterion was analyzed to underline the avoided effects in this matter. As described in Section 4.2.6, direct LUC to oil palm crops in Colombia has a positive impact in terms of GHG emissions and climate change mitigation. However, LUC goes beyond the ecological effects and transcends to a cultural dimension. The assessment results in terms of cultural effects are displayed in Table 4-6, and the following paragraphs focus on the role of oil palm crops in the context of the cultural value of land.

Table 4-6: Assessment of land-use change in terms of cultural effects

System	Negative impact	Assigned number
UCO-based biodiesel	None	0
Palm oil-based biodiesel	Very high	5

Support to biofuels in Colombia has contributed to land concentration, a phenomenon that has historically sustained the internal conflict. According to studies on the expansion of oil palm in Colombia, most of the municipalities where oil palm is cultivated have been the stage of social conflict and violence due to the presence of illegal armed groups. Besides, oil palm crops throughout the country have been directly linked to forced displacement and violation of human rights [139], [157], [158]. Oil palm companies could be accomplices of this situation, either by commission or omission, if there is no rigorous control over the operations of the main suppliers, the contractors, active partners, and other major stakeholders [126].

Specifically, traditional peasant, indigenous and Afro-Colombian communities have suffered episodes of illegitimate and violent land appropriation, considering that the property rights of these communities over their lands are not clearly established [155]. Such episodes have been reported to be executed mainly by paramilitary groups and in specific municipalities of the Northern, Central, and Southwestern zones [157]–[160].

Promotion of bioenergy crops has led to conceiving land as a production factor, a source of income, and an axis of local political power [155]. In contrast, the aforementioned traditional communities see land as the ground of their territory and, therefore, their identity, which makes it undeniable that LUC to oil palm crops in Colombia has disrupted their culture and ancestral ways of living [139].

4.3 Discussion in the context of circular economy

The focus of this assessment is a waste valorization system that is promoted within the framework of circular economy. There is no doubt that UCO valorization prevents the ecological and social impacts that originate from its mismanagement, and it is a pertinent strategy to transform UCO into useful products instead of disposing of it. However, it is also important to inquire into the effectiveness of the proposed models, i.e. to examine if the system actually contributes to the fundamental objective of circular economy, which lies in minimizing the magnitude of inputs and outputs of a system by maximizing recirculation of flows. If UCO is being recirculated to be used as oleochemical feedstock, is the demand for virgin vegetable oil consequently decreasing?

Unfortunately, an increase in recycling rates of waste in itself does not guarantee a reduction in demand for virgin materials. Efficiency gains are often shaded by increases in consumption, which is known as the rebound effect (or Jevons paradox) [161]. This paradox does not exactly apply to UCO valorization, since UCO generation is limited by the level of consumption of vegetable oil for edible purposes. However, a parallel phenomenon has arisen as a result of policymaking and market interactions.

UCO valorization was fostered by the RED through a double-counting mechanism, which consists of accounting for twice the share of renewable energies of a country, so that the measurement of progress towards climate action goals seems higher [162]. Unfortunately, this incentive allegedly led to the creation of a ‘fraudulent’ UCO market, that in reality corresponds to virgin palm oil [163].

Have then UCO valorization systems effectively contributed to close the circularity gap and thereby prevented further and accelerated environmental degradation? It is important to recognize that, for a waste valorization system to be efficient and effective, it is not enough with avoiding the disposal of waste; it is also critical to protect natural resources and minimize their use for recycling processes, acknowledging the non-substitutability of natural capital.

5. Conclusions

As a waste valorization model, exploitation of UCO as oleochemical feedstock contributes to preventing the impacts of UCO mismanagement on ecosystems and human health, particularly regarding the generation of GHG emissions, potential pollution of soil and water bodies, potential toxicity effects on flora and fauna, and risks to public health due to the consumption of UCO as new oil. However, when exploring the performance of a specific UCO valorization model in Bogota -which consists of collecting and pretreating UCO in the city to produce biodiesel in Spain-, additional aspects must be examined.

Sustainability of UCO-based biodiesel under the valorization model of interest was assessed within the framework of the Integrative Concept of Sustainability (ICoS) and in relation to palm oil-based biodiesel under comparable conditions. The ICoS framework provides a complete set of sustainability goals and principles that properly guide the analysis of a process, a product, a policy, an organization, or a technology, from a comprehensive and pertinent understanding of sustainability as a whole.

When analyzed from a life cycle perspective and a holistic approach, UCO-based biodiesel represents an improvement towards sustainability compared to palm oil-based biodiesel, considering lower life cycle impacts or better overall performance in 10 out 13 criteria. Results showed that the assessed UCO valorization system contributes to the protection of human health, the securing of an autonomous existence, the sustainable use of renewable resources, the sustainable use of the environment as a sink for waste and emissions, the sustainable development of human and knowledge capital, and the conservation of the cultural function of nature. However, the production model of UCO-based biodiesel must improve regarding the sustainable use of non-renewable resources (specifically the demand for fossil resources), the role in climate change mitigation, and the robustness of the governmental framework.

In terms of climate change mitigation, UCO-based biodiesel still represents important GHG emissions savings in relation to fossil diesel, but it performs worse than palm oil-based biodiesel. This panorama can change if UCO is not exported and biodiesel is produced locally, considering that the UCO distribution stage accounts for almost 50% of the associated GHG emissions. Further improvement can be achieved if the collection scheme is optimized, since the contribution share from this first stage is conspicuous and should not be neglected, as it usually is in the assessment of waste valorization models.

In particular, the UCO distribution stage is a major contributor to many of the life cycle impacts besides generation of GHG emissions (use of fossil resources, emissions of particulate matter and photochemical oxidants, and acidification potential), which makes it worth fostering local production and consumption of biodiesel.

Despite the comparative advantage of UCO-based biodiesel relative to palm oil-based biodiesel, it is imperative to inquire into the effectiveness of the valorization model and thereby analyze, if demand for virgin vegetable oil is decreasing. Since UCO valorization is fostered within the framework of circular economy, it is fundamental to assess if the recirculation of waste flows is indeed leading to reduce the magnitude of the extraction and use of resources for a system.

By highlighting the Life Cycle Thinking approach that underlies sustainability assessments, and by exploring the multiple areas of knowledge that are encompassed by the concept of sustainability, this work sought to contribute to a broader understanding of current waste valorization models. Even though the proposed methodology follows a systemic framework, it is specific for a particular system and suitable for a particular context. In this sense, this work is an example of how an integrated assessment can be performed both originally and rigorously, and therefore represents a modest contribution to the diverse field of sustainability sciences in the Colombian context.

Nonetheless, and considering the presented constraints in time and lack of information, it is recommended for future works on this subject to thoroughly assess and quantify the associated uncertainty to this type of assessment, as well as to properly study and evaluate the qualitative criteria.

A. Appendix: Generation, collection, and valorization alternatives of UCO

Table A-1: Annual consumption of vegetable oil (VO) and generation of UCO per capita among different regions of the world for 2017 – 2018. Source: Orjuela [2]

Country	Annual consumption of VO per capita (kg)	Annual generation of UCO per capita (kg)	Country	Annual consumption of VO per capita (kg)	Annual generation of UCO per capita (kg)
Asia			**Europe**		
China	26.40	4.06	Belgium	20.66	5.55
India	18.39	0.86	Croatia	13.28	5.99
Indonesia	25.41	10.47	Cyprus	12.82	3.42
Iran	23.12	4.62	Czechia	22.58	3.79
Japan	19.41	3.15	Denmark	9.28	4.89
Korea	13.05	7.40	France	19.16	1.32
Pakistan	26.58	5.32	Germany	18.20	5.96
America			Greece	26.74	6.51
Brazil	26.88	1.13	Hungary	20.01	5.09
Canada	27.12	3.72	Ireland	13.83	6.70
Colombia	25.85	5.00	Italy	27.95	4.46
Mexico	30.43	5.20	Netherlands	14.75	3.35
USA	39.38	5.74	Portugal	19.66	5.23
Other countries			Slovenia	14.38	0.97
Australia	21.34	2.07	Spain	28.31	6.46
Nigeria	13.79	1.13	UK	17.35	5.01

Table A-2: Estimations of UCO resources across the EU. Source: Greenea [16]

Country	**Collectable domestic UCO (tons)**	**% of collected domestic UCO**	**Collectable commercial UCO (tons)**	**% of collected commercial UCO**
Austria	7,000	33.6	18,000	83.3
Belgium	13,000	63.8	33,000	87.9
Croatia	12,000	0.0	4,000	75.0
Czech Republic	16,000	3.1	13,000	76.9
Denmark	2,000	0.1	6,000	83.3
Finland	3,000	0.0	5,000	80.0
France	52,000	2.2	53,000	83.0
Germany	65,000	1.9	161,000	87.0
Greece	20,000	0.1	26,000	83.1
Hungary	29,000	1.4	5,000	80.0
Ireland	2,000	0.0	14,000	85.7
Italy	156,000	9.6	73,000	80.8
Netherlands	12,000	30.0	69,000	87.0
Poland	47,000	0.0	42,000	76.2
Portugal	30,000	3.3	26,000	84.6
Spain	232,000	20.5	78,000	83.3
Sweden	3,000	46.7	10,000	80.0
United Kingdom	42,000	20.5	115,000	87.0

Table A-3: Most current attempts on the production of biobased chemicals from UCOs. Reproduced from Orjuela and Clark [3]

Application	Process	Product
Plasticizer	Transesterification of UCOs biodiesel with 2-ethylhexanol and further epoxidation	Epoxidized 2-ethylhexyl fatty ester
	Epoxidation	Epoxidized UCO
	Transesterification of UCO with methanol and epoxidation of methyl ester. Esterification with citric acid, and final acetylation with acetic anhydride	Acetylated FAME citric acid ester (Ac-FAMECAE)
	Esterification and transesterification with methanol and amino methylation (Mannich reaction)	Mannich base of UCO biodiesel
Asphalt/pavement binder	Drop-in	Asphalt binder with light components from UCO
	Drop-in	Macadam pavement
	Co-pyrolysis of UCO with rubber	Rubber/UCO binder
	Drop-in	Binder replacement
	Drop-in	Asphalt binder
Mansonry binder	Drop-in	Construction block
Epoxidized biodiesel	Enzymatic transesterification and epoxidation	Epoxidized UCO biodiesel
Polyol / Polyurethane	Epoxidation of UCO and hydroxylation with diethylene glycol	UCO-based polyol
Lubricant	Epoxidation and hydroxylation with methanol, ethanol, and 2-ethyl hexanol, esterification with hexanoic anhydride	UCO and UCO FAME polyol hexanoic ester
	Epoxidation of UCO	Epoxidized UCO
	Enzymatic hydrolysis and esterification	Fatty acid neopentyl glycol ester
	Drop-in	UCO dispersible Cu nanoparticles

Application	Process	Product
Surfactant	Transesterification with methanol, sulfonation of methyl ester, and neutralization with NaOH	Methyl ester sodium sulfonate
	Saponification of UCO with KOH, acidification to FA, esterification with methanol to FAME, reduction to fatty alcohol, esterification with chloroacetic acid, and amination	Diaminium chloride Gemini-surfactant
Liquid detergent	Transesterification with methanol and sulfonation of methyl ester	Methyl ester sulfonate
Biopolymer precursors	Transesterification and ethenolysis	Ethenolyzed and self-metathesized products
Biobased polymers	Epoxidation, hydroxylation with water, polymerization with Methylene diphenyl diisocyanate	UCO-based polyurethane doped with lithium iodide
	Fermentation	Polyhydroxyalkanoate and astaxanthin-rich carotenoids
	Fermentation	Polyhydroxybutyrate [P(3HB)]
	Fermentation	Polyhydroxyalkanoates (PHAs) - (R)-3 hydroxyoctanoic acid and (R)-3-hydroxydecanoic acid monomers
Fermentation supplement	Drop-in	Microbial oil
	Fermentation	Lipase
	Fermentation	d- and l-Limonene
Structured materials	Double thermal chemical vapor deposition	Graphene
3D printing resin	Acrylation	Triacylglycerol acrylate

Application	Process	Product
Emulsion liquid membrane	Drop-in	Emulsion
Flotation oil	Pyrolysis	Deoxygenated hydrocarbons
Bioadsorbent	Impregnation and pyrolysis	Ordered micro-mesoporous carbon nanocasted on HZSM-5/SBA-15

B. Appendix: Sustainability criteria of biofuels

B.1. Roundtable on Sustainable Biomaterials Standard [64]

The following principles describe how to produce biomass, biofuels, and biomaterials in an environmentally, socially and economically responsible way:

- **Legality:** Operations follow all applicable laws and regulations.
- **Planning, monitoring and continuous improvement:** Sustainable operations are planned, implemented, and continuously improved through an open, transparent, and consultative impact assessment and management process and economic viability analysis.
- **Greenhouse gas emissions:** Biofuels contribute to climate change mitigations by significantly reducing lifecycle GHG emissions as compared to fossil fuels.
- **Human and labor rights:** Operations do not violate human rights or labor rights and promote decent work and the well-being of workers.
- **Rural and social development:** In regions of poverty, operations contribute to the social and economic development of local, rural, and indigenous people and communities.
- **Local food security:** Operations ensure the human right to adequate food and improve food security in food insecure regions.
- **Conservation:** Operations avoid negative impacts on biodiversity, ecosystems, and conservation values.
- **Soil:** Operations implement practices that seek to revenue soil degradation and/or maintain soil health.
- **Water:** Operations maintain or enhance the quality and quantity of surface and groundwater resources, and respect prior formal or customary water rights.

- **Air quality:** Air pollution shall be minimized along the whole supply chain.
- **Use of technology, inputs, and management of waste:** The use of technologies shall seek to maximize production efficiency and social and environmental performance and minimize the risk of damages to the environment and people.
- **Land rights:** Operations shall respect land rights and land-use rights.

B.2. Sustainable Bioenergy: Key Criteria and Indicators [63]

The following criteria can be assessed through the respective indicators:

- Sustainable resource use
  - Land use efficiency
  - Secondary resource use efficiency
- Biodiversity
  - Conservation of land with significant biodiversity values
  - Land management without negative effects on biodiversity
- Climate protection
  - Life cycle GHG emissions and direct land-use changes
  - Inclusion of GHG effects from indirect land-use changes
- Soil quality
  - Avoid erosion
  - Soil organic carbon
- Water use and quality
  - Water availability and use efficiency
  - Water quality
- Limit airborne emissions
  - Emissions of SO_2 equivalents
  - Emissions of PM10
- Food security
  - Prices and supply of national food basket
- Social use of land
  - Allocation and tenure of land
- Healthy livelihoods and labor conditions
  - Adherence to ILO principles for labor rights

B.3. The Global Bioenergy Partnership Sustainability Indicators for Bioenergy [62]

- Life cycle GHG emissions
- Soil quality
- Harvest levels of wood resources
- Emissions of non-GHG air pollutants, including air toxics
- Water use and efficiency
- Water quality
- Biological diversity in the landscape
- Land use and land-use change related to bioenergy feedstock production
- Allocation and tenure of land for new bioenergy production
- Prices and supply of a national food basket
- Change in income
- Jobs in the bioenergy sector
- Change in unpaid time spent by women and children collecting biomass
- Bioenergy used to expand access to modern energy services
- Change in mortality and burden of disease attributable to indoor smoke
- Incidence of occupational injury, illness, and fatalities
- Productivity
- Net energy balance
- Gross value added
- Change in consumption of fossil fuels and traditional use of biomass
- Training and re-qualification of the workforce
- Energy diversity
- Infrastructure and logistics for distribution of bioenergy
- Capacity and flexibility of use of bioenergy

C. Appendix: Previous assessment studies on UCO valorization systems

Study	Aim of the study	Functional unit	Stages	Highlights
A life cycle assessment comparison between centralized and decentralized biodiesel production from raw sunflower oil and waste cooking oils [67] Spain, 2012	Comparative life cycle assessment of biodiesel from raw sunflower oil and UCO, to analyze how influential is the decentralization degree of the production.	50 kg of biodiesel (the required amount to cover 1.000 km in a standard diesel engine vehicle)	UCO collection and transport, pre-treatment, transesterification, purification of biodiesel, transport of biodiesel	Since the disposal of UCO has associated GHG emissions, the production of UCO-based biodiesel is beneficial to the environment in the category of climate change (negative value). For UCO-based biodiesel, environmental performance is better with some degree of decentralization, particularly if it avoids transportation by ship.
A Life Cycle Assessment of Biofuel Produced from Waste Cooking Oil, 2018 [83] United States, 2018	Life cycle assessment of UCO used as biofuel for heating application and comparison with conventional fuels.	Heating value of UCO in MJ	Soybean farming, soy oil refining, cooking process, UCO cleaning/drying, UCO preheating and transportation when required	Use of UCO as fuel has a significantly less global warming potential but higher cumulative energy consumption than traditional fuels.

Study	Aim of the study	Functional unit	Stages	Highlights
Analysis of the costs and logistics of biodiesel production from used cooking oil in the metropolitan region of Campinas (Brazil) [88] Brazil, 2018	Analysis of the costs and logistics of biodiesel production from mixtures of UCOs in the Metropolitan Region of Campinas (RMC, São Paulo State, Brazil).	-	Collection of UCO and transesterification with ethanol and NaOH	It is possible to reuse UCO and reduce the environmental costs of disposal. This model would lead to savings of almost 16.000 million USD/year and environmental gains in the form of credit carbons.
Application of LCSA to used cooking oil waste management [17] Spain, 2013	Life cycle sustainability assessment (LCSA) of three domestic UCO collection systems: through schools, door-to-door and through urban collection centers. LCSA includes environmental life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (s-LCA).	Generated UCO in a neighborhood of 10.000 inhabitants for 1 year	Collection, transportation (for door-to-door systems and collection through schools), storage and transport to biodiesel plant	Urban collection centers display the best environmental and economic performance. Door-to-door and collection through schools present suitable values for social performance. Measuring social impacts is highly complex because perception is very variable.

Study	Aim of the study	Functional unit	Stages	Highlights
Attributional and consequential environmental assessment of using waste cooking oil- and poultry fat-based biodiesel blends in urban buses: a real-world operation condition study [81] 2017	Evaluation of the life cycle emissions attributed to UCO- and PF-based biodiesel when used in urban buses during operation mode, as well as to B5-UCO and B5-PF fuel blends.	1 L of fuel/fuel blend	For UCO: collection, transportation, biodiesel production, combustion	1 L of B5-WCO fuel blend could potentially reduce the environmental burdens in human health, ecosystem quality and resources damage categories compared with B5-PF fuel blend. The opposite occurs for the category of climate change damage.
Biodiesel from Waste Cooking Oils in Portugal: Alternative Collection Systems [18] Portugal, 2015	Environmental assessment of biodiesel from WCO addressing different collection schemes in Portugal: street containers and door-to-door for household and collection for HORECA sites.	1 MJ of biodiesel	WCO collection, pre-treatment, and biodiesel production (transesterification).	GHG emissions savings of WCO-based biodiesel range from 81 to 89%. WCO collection contribution to the overall impacts ranges significantly for the various collection systems and impact categories. Application of different allocation approaches leads to differences in the results up to 11%.
Biodiesel production from waste cooking oil for use as fuel in artisanal fishing boats: Integrating environmental, economic and social aspects [80] Brazil, 2016	Life cycle assessment, and economic and social analysis of a UCO-based biodiesel production plant.	2028 kg of biodiesel	Collection and production (pretreatment, transesterification, aftertreatment)	The proposed system contributes to the development of the local community, since it provides ecological benefits, social gains, and increased income. The collection stage has a 92% contribution to the environmental impacts, but when using an allocation approach, this is reduced to 25%.

Study	Aim of the study	Functional unit	Stages	Highlights
Biofuels and their potential to aid the UK towards achieving emissions reduction policy targets [22] United Kingdom, 2012	Life cycle assessment of biodiesel from soybean, palm, rape and UCO, and bioethanol from sugarcane, sugar beet and corn. The geographical framework is multi-regional. Results are compared with the fossil fuels baseline.	1 kg CO_2-eq	Upstream operations, processing of the biofuel, ILUC if applies, use of the fuel	UCO-based biodiesel and bioethanol from sugar beet offer the biggest potential for GHG emissions savings (89,4% and 64,8% respectively). It is also highlighted that UCO-based biodiesel does not have emissions associated to ILUC.
Comparative LCA of alternative strategies for energy recovery from UCO [6] Italy, 2018	Comparison of the use of UCO as a direct fuel for a combustion engine for cogeneration, with the use of UCO to produce biodiesel (considering four technologies).	1 ton of UCO	Washing of containers at the collection point, delivering of UCO to the plants, pretreatment of UCO, processing of UCO (for cogeneration or biodiesel production).	Regarding only the processing stage, the use of UCO for cogeneration shows a better environmental performance than the use of UCO to produce biodiesel. The opposite occurs when including the substitution of products and by-products, i.e., when including avoided effects (mainly diesel).
Comparative life cycle assessment of diesel production from crude palm oil and waste cooking oil via pyrolysis [71] Thailand, 2016	Life cycle assessment of the production of biodiesel via pyrolysis using two potential feedstocks in Thailand: crude palm oil (CPO) and waste cooking oil (WCO).	1 MJ of diesel	Cultivation, harvesting (for CPO), transportation, pyrolysis, distillation, blending, and vehicle testing (combustion)	Net energy ratio with its co-products of WCO-based diesel (3.12) was higher than that of CPO-based diesel (2.12). Because of the large amount of energy use for diesel production in pyrolysis and distillation processes, global warming potential was the main environmental impact.

Study	Aim of the study	Functional unit	Stages	Highlights
Consequential LCA of two alternative systems for biodiesel consumption in Spain, considering uncertainty [26] Spain, 2014	Assessment of two relevant scenarios for the Spanish transport sector: soybean biodiesel imported from Argentine, and UCO-biodiesel manufactured in Spain.	1 MJ of biodiesel	For UCO-based biodiesel: collection, transportation to biodiesel plant, pretreatment and conditioning, transesterification, and distribution	Analysis of GHG emissions without considering LUC can be misleading: GWP of UCO-based is higher than the one of soybean biodiesel, but this changes when including LUC emissions.
Design of experiments for global sensitivity analysis in life cycle assessment: The case of biodiesel in Vietnam [77] Vietnam, 2017	Life cycle assessment of biodiesel from jatropha, UCO and fish oil. Impact categories were combined into an Overall Environmental Impact OEI score using the Analytic Hierarchy Process AHP. Design of experiments approach was used for a global sensitivity analysis.	1 MJ from engine	For UCO-based biodiesel: collection, transportation, biodiesel production and use	LCA results are often affected by parameter uncertainties. Considering the impact categories of GWP, AP, EP and POFP, using UCO-based or fish oil-based biodiesel as a substitute for diesel has a positive environmental impact.
Determination of Carbon Footprint using LCA Method for Straight Used Cooking Oil as a Fuel in HGVs [25] United Kingdom, 2014	Life cycle assessment of UCO to be directly used in a diesel engine (straight UCO or SUCO) in terms of CO_2 emissions and energy consumption. Comparison with UCO-based biodiesel and fossil diesel.	1 ton of the finished renewable fuel (SUCO or biodiesel)	UCO transportation after collection, processing of UCO (either SUCO or biodiesel), and transportation and dispensing of the finished products.	It is assumed that Tank to Wheel emissions are zero, because these are absorbed by the plants of the oil crops during growth. Carbon footprint of SUCO is 54% less compared to the one of UCO-based biodiesel and 98% less compared to fossil diesel. The transesterification stage of biodiesel production is highly energy-intensive, so SUCO displays a competitive advantage.

Study	Aim of the study	Functional unit	Stages	Highlights
Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow [30] United States, 2014	Assessment of lifecycle GHG emissions and production costs associated with HEFA jet and diesel fuels from tallow and yellow grease derived from used cooking oil.	1 MJ fuel	Feedstock production, feedstock transportation, fuel production, fuel T&D, fuel combustion	Lifecycle GHG emissions reductions of renewable fuels are between 76 and 86% compared to their conventional counterparts.
Environmental and Socioeconomic Analysis of Producing Biodiesel from Used Cooking Oil in Rio de Janeiro [30] Brazil, 2012	Assessment of pilot-scale production of UCO-based biodiesel from HORECA sites in Copacabana.	21,600 MJ energy (1 ton of biodiesel)	Collection and delivery of UCO, pretreatment, transesterification (including ethanol and NaOH production and delivery), fuel delivery and fuel combustion	The greatest contributions to environmental impacts come from the production of ethanol for the transesterification stage and from fuel combustion. When comparing with production of soap, production of UCO-based biodiesel displays more advantages. Production at pilot scale is feasible from the economic perspective. Positive social impacts are related to job creation and higher environmental awareness.

Study	Aim of the study	Functional unit	Stages	Highlights
Environmental life cycle assessment of polypropylene made from used cooking oil [33] The Netherlands, 2020	Life cycle assessment of the polypropylene PP that results from the cracking of the renewable HVO "bio naphtha", a product obtained from the hydrotreatment of UCO to produce hydrotreated vegetable oil HVO of diesel grade.	1 kg of PP	Collection of UCO, hydrotreating of UCO (NEXBTL process), steam cracking, polymerization	The collection of UCO accounts only for 5% of the impacts. Compared to petrochemical PP, UCO-based PP offers impact savings for climate change (62%) and fossil fuel resource use (86%). Savings remain substantial even when UCO is globally imported, when UCO is considered a by-product instead of a waste, or when a different allocation approach is used. However, the change of UCO sources leads to a significant increase in the impact categories (19% on a weighted basis).
GHG intensities from the life cycle of conventional fuels and biofuels [72] Thailand, 2009	Life cycle assessment of foreign conventional fuel production, biodiesel from palm oil grown in neighboring countries (from Singapore), and biodiesel produced from UCO in Thailand.	1 MJ biodiesel	UCO collection, transesterification, transportation of biodiesel. Contribution of reactants is considered as a stage.	Potential of biofuels to reduce GHGs depends on several crucial factors, especially land-use change. For UCO-based biodiesel, the greatest contribution to GHG emissions comes from the use of reactants and the electricity input to the process. A minimal contribution comes from the transportation stage.
Greenhouse gas emissions from production and use of used cooking oil methyl ester as transport fuel in Thailand [73] Thailand, 2009	Comparison of the life cycle GHG emissions from UCO-based biodiesel and conventional diesel.	100 km transportation by light-duty diesel vehicle	Transportation of UCO, transesterification, combustion of biodiesel in a diesel vehicle.	GHG emissions of UCO-based biodiesel are 10 times lower than those of diesel (32,57 kg CO_2-eq vs 2,35 kg CO_2-eq).

Study	Aim of the study	Functional unit	Stages	Highlights
Greenhouse gas footprint of biodiesel production from used cooking oils [164] The Netherlands, 2018	Estimation of life cycle GHG emissions from production of UCO-based biodiesel and HVO in Europe	1 MJ of fuel equivalent	UCO transport, UCO pretreatment, fuel production	UCO-based HVO has favorable attributes when compared to UCO-based biodiesel. The GHG footprint of UCO-based fuels depends on the origin of the feedstock and the subsequent transportation mode. Fuels from locally sourced UCO display the lowest GHG footprint. UCO imports from China show higher GHG emissions than UCO imports from the USA.
Incorporating uncertainty in the life cycle assessment of biodiesel from waste cooking oil addressing different collection systems [68] Portugal, 2016	Life Cycle Assessment (LCA) of biodiesel produced from domestic WCO (collected by drop-off containers or door-to-door systems) and from WCO coming from the foodservice industry.	1 MJ of biodiesel	WCO collection only	WCO collection cannot be neglected or simplified when assessing the overall environmental performance of biodiesel produced from WCO. The higher impacts were calculated for the systems with lower WCO collection efficiency (quantified by a performance indicator (PI) measured in liters of WCO collected per km) as the case of door-to-door collection.

Study	Aim of the study	Functional unit	Stages	Highlights
LCA studies comparing alkaline and immobilized enzyme catalyst processes for biodiesel production under Brazilian conditions [24] Brazil, 2016	Industrial-scale simulation and life cycle assessments of the following scenarios: 1) soybean biodiesel production with alkali catalyst, 2) soybean biodiesel production with enzyme catalyst, and 3) WCO biodiesel with enzyme catalyst.	1 ton of biodiesel	UCO collection, transportation, pretreatment, and transesterification.	Transesterification of WCO has a greater footprint than that of soybean oil, but the lack of the agricultural stage makes UCO a better biodiesel feedstock from a life cycle perspective. Transportation distances could result in immense or mild impacts in different regions, which makes it necessary to conduct a sensitivity analysis. Collection and pretreatment contribute the most to ecological impacts.
Life cycle analysis of biodiesel production from used vegetable oil [82] Colombia, 2016	Life cycle assessment of UCO-based biodiesel, considering the currently available technologies in the country.	100 kg UCO	Collection, pretreatment, transesterification, distribution of biodiesel	Transesterification is the stage with the greatest contribution to ecological impacts. The process is feasible considering the energetic consumption.
Life cycle analysis of biodiesel production [69] Portugal, 2011	Simulation, life cycle assessment, economic analysis and comparison of different alternative processes for the production of biodiesel from palm oil and UCO.	Not specified	Biodiesel production only	Alkali-catalyzed transesterification with acid pretreatment of UCO was the best alternative from the life cycle perspective. The use of UCO displays higher investment costs but is more profitable and has less environmental impacts

Study	Aim of the study	Functional unit	Stages	Highlights
Life cycle assessment of biodiesel production in China [75] China, 2013	Evaluation of energetic, economic, and environmental performances of seven categories of biodiesel feedstocks by using the mixed-unit input-output LCA.	0,2 million tons of biodiesel	Collection of UCO (materials transportation), biodiesel production, biodiesel combustion	UCO-based biodiesel displays large ecotoxicity potentials (HTP, FAETP, MAETP and TETP). Technology improvements could effectively reduce the life cycle environmental impacts. Collection systems of UCO should be improved to reduce costs.
Life cycle assessment of biofuels in China: Status and challenges [58] China, 2018	Overview of LCA studies about environmental impacts of bioethanol and biodiesel in China. Analysis of the effect of methodological choices on LCA results. Identifying key issues to be resolved for a good LCA practice.	-	-	Important aspects of the LCA methodology of biofuel systems include the definition of system boundaries, functional unit, allocation method, treatment of carbon sequestration, selection of impact categories and reference system. LCA results could be confusing and lead to inappropriate decisions.
Life Cycle Assessment of Energy and Energy Carriers from Waste Matter - A Review [59] 2014	Review of current knowledge about the LCA of energy and energy carriers from waste matter as reported in the open literature.	-	-	Significant factors influencing the outcome of the LCA are the allocation issues, the system boundary changes and the definition of the functional unit. In general, the main advantage of waste-based energy is a large reduction in GHG emissions.

Study	Aim of the study	Functional unit	Stages	Highlights
Life cycle assessment of hydrogenated biodiesel production from waste cooking oil using the catalytic cracking and hydrogenation method [74] Japan, 2015	Determination of the environmental benefits of hydrogenated biodiesel HBD produced from WCO via catalytic cracking and hydrogenation, compared with fossil-derived diesel fuel or FAME-type BDF.	Combined functional unit: 1) treatment of 1142 kL/yr and 1108 kL/yr of WCO from households and businesses, respectively; 2) 41,1 TJ of diesel fuel was consumed by diesel vehicles used to collect household waste within Kyoto city	WCO from households and businesses was assumed to be collected with mixed waste and then incinerated, while diesel fuel was used to operate household waste collection vehicles.	If diesel vehicles that comply with the new long-term emissions gas standard are commonly used in the future, the benefit of using FAME-type BDF will be relatively modest. The BDF to HBD in the future would be more effective in reducing total environmental impacts comprising not only global warming but also fossil fuel consumption, urban air pollution, and acidification.
Life cycle assessment of waste cooking oil for biodiesel production using waste chicken eggshell derived CaO as catalyst via transesterification [76] Malaysia, 2019	Life cycle assessment of WCO-based biodiesel production catalyzed by waste chicken eggshell derived CaO catalyst to validate the suitability of waste chicken eggshell as a green catalyst in the biodiesel field.	1000 kg of biodiesel	Raw material collection, transportation, pretreatment, and transesterification	The midpoint of LCA result shows that the transportation phase has the least contribution, while the transesterification process alone has contributed 1.01 + 01 MJ surplus on fuel consumption. Endpoint indicator assessment shows resource depletion has the highest scores for all stages during production. It is found that Jatropha oil biodiesel production contributes to a higher environmental impact than WCO biodiesel production as it involves plantation and fertilizing.

Study	Aim of the study	Functional unit	Stages	Highlights
Probabilistic multi-criteria analysis for evaluation of biodiesel production technologies from used cooking oil [9] Italy, 2020	Definition, analysis, and comparison of four different technologies to produce UCO-based biodiesel, using probabilistic MCDA and considering energy, economic, environmental, and social aspects. Uncertainty assessment with a Montecarlo simulation and data reconciliation.	1 ton of UCO	Containers washing, physical pretreatment of UCO, delivering of UCO to biodiesel plant, biodiesel production	The alkali-catalyzed transesterification process displays a better performance from the energetic, environmental and social point of view. The acid-catalyzed biodiesel production is slightly better from the economic perspective. Following the multi-criteria strategy, the alkali-catalyzed process with NaOH is the most suitable option.
Process simulation and life cycle analysis of biodiesel production [29] 2016	Assessment of the environmental impacts of biodiesel production from non-edible Jatropha oil and waste cooking oil (WCO). Comparison using a systematic LCA.	1 ton of biodiesel	For Jatropha oil biodiesel: cultivation and harvesting crops, transportation, and extraction of seeds, chemical conversion to biodiesel by alkali-catalyzed transesterification. For WCO-based biodiesel: WCO supply chain and collection, transportation to the plant, pretreatment and the alkali-catalyzed transesterification.	Biodiesel produced from WCO has fewer impacts on the environment because of its less demanding raw material. The study showed that the preparation of raw material for WCO requires no special energy other than collecting it from various sources.

Study	Aim of the study	Functional unit	Stages	Highlights
Recycling Waste Cooking Oil into Biodiesel: A Life Cycle Assessment [70] Italy, 2014	Dual aim: 1) assessment of the environmental effectiveness of biodiesel production from WCO, and 2) identification of hotspots throughout the entire biodiesel production chain and suggests future improvements.	1 kilogram of diesel/biodiesel produced.	1) collection of WCO, 2) pre-treatment, 3) delivery of treated oil to the biodiesel facility and 4) its conversion into biodiesel through trans-esterification	The use of biodiesel from WCO shows promising potential: 1) it contributes to the reduction of environmental impacts of WCO disposal; 2) it reduces the economic load related to the operational problems in municipal sewage treatment plants and, 3) it contributes a small but non-negligible fraction of renewable energy to society.
Simulation and life cycle assessment of process design alternative for biodiesel production from waste vegetable oils [19] Portugal, 2010	Comparison of the potential environmental impacts of three process design alternatives for biodiesel production from waste vegetable oils.	1 kg of biodiesel	Pretreatment, transesterification	The supercritical methanol transesterification process is the most environmentally favorable alternative. The acid-catalyzed transesterification shows the highest potential environmental impacts due to the high energy requirements.
The Used Cooking Oil-to-biodiesel chain in Europe assessment of best practices and environmental performance [27] Europe, 2016	Display of the best methods to process the UCO-to-biodiesel chain. Evaluation of the most common transesterification processes according to environmental, technical, health and safety, market and EU policy criteria.	1 ton of UCO-based biodiesel	Collection, pretreatment, delivery, and transesterification of UCO	Transesterification is the stage that contributes the most to the environmental impacts, so its optimization is critical for the full chain feasibility. Contribution of pretreatment is also significant. Collection and delivery have a small contribution to the overall impacts.

Study	Aim of the study	Functional unit	Stages	Highlights
Thermoeconomic Analysis of Biodiesel Production from Used Cooking Oils [14] Europe, 2015	Thermoeconomic analysis of the UCO-based biodiesel life cycle. Calculation of the ExROI value and the renewability factor.	Different for each stage: 1 kg of UCO, 1 kg of refined oil, 1 kg of biodiesel	Collection of UCO, pretreatment, transesterification, after-treatment of biodiesel	For UCO-based biodiesel, from each unit of non-renewable resources, it is possible to obtain 4,10 units of energy (ExROI) and the percentage of renewable energy contained in the fuel is about 83% (renewability factor). These values are better than those displayed by virgin vegetable oil-based biodiesel.
Used-cooking-oil biodiesel: Life cycle assessment and comparison with first- and third-generation biofuel [11] Greece, 2020	Study on the environmental performance of second-generation (UCO) biodiesel produced in the Greek setting and, and identification of the main environmental hotspots.	1 ton of UCO-based biodiesel	UCO collection, pre-treatment and a two-step acid-base catalyzed transesterification process, i.e. acid-catalyzed esterification, and alkaline-catalyst transesterification	The total environmental footprint of UCO-based biodiesel was found to be about 3 times lower compared to petrodiesel's total environmental footprint of the same calorific value. It was also around 40% lower than the first-generation and at least one order of magnitude lower than the third-generation biodiesel.
Water footprint profile of crop-based vegetable oils and waste cooking oil: Comparing two water scarcity footprint methods [20] 2018	Assessment of freshwater-related environmental impacts of production of biodiesel from different oils (including UCO) throughout the entire lifecycle. Calculation of the WSI and the AWARE index.	1 kg of vegetable oil refined for biodiesel production	For UCO: collection, refining (pretreatment), and production of biodiesel	The quality of UCO (mainly FFA content) has a great influence on the refining process. For high-quality UCO, there is no freshwater consumption in the refining process. When compared to palm oil biodiesel, WSI and the AWARE index of palm oil are 76 and 42 times the values of UCO respectively.

D. Appendix: Life Cycle Assessment Report

D.1. Goal definition

As part of a broader sustainability assessment, this LCA sought to assess the potential environmental impacts of one of the current UCO valorization systems in Bogota, where UCO is collected from HORECA sites, pretreated and exported to Spain to be converted into biodiesel. The study system was compared to a reference system, namely production of palm oil-based biodiesel under similar conditions.

- **Decision context:** This LCA study is mainly informative and does not explicitly intend to serve as criteria for decision making. Nevertheless, it could motivate stakeholders and potential stakeholders to undertake improvement actions.
- **Target audience:** This work is developed within the framework of an academy-industry cooperation program, so the intended audience is both universities and an industrial partner.
- **Disclosure:** Due to the academic nature of this work, results are intended to be public.

D.2. Scope definition

D.2.1. Function, reference flow, and functional unit

The main function of this product system is the production of UCO-based biodiesel. The reference flow is therefore UCO-based biodiesel, and the selected functional unit is 1 ton of UCO-based biodiesel, which enables a feasible comparison with palm oil-based biodiesel.

D.2.2. LCI modeling framework

There are two main types of life cycle modeling: attributional and consequential. The choice of the modeling approach is still a subject of debate among LCA practitioners and there is no solid consensus on this issue [65]. While attributional modeling accounts for impacts directly related to the study system, consequential modeling also analyzes potential indirect consequences of the study system by including various “what if” scenarios that could emerge [60].

For biofuels, attributional modeling has been conventionally used [65]; however, a consequential approach has been introduced in recent years to explore the indirect effects of LUC and market dynamics. Since biofuels can be produced from so many different feedstocks, modeling of markets can be very complex; examples of this approach for biodiesel can be found in the work of Escobar et al. [26] and Rajaeifar et al. [81].

Considering the informative character of this LCA study, and following the recommendations of the International Reference Life Cycle Data System (ILCD) [110], attributional modeling was applied. This choice must be consistent with the model system of the available database, namely, Ecoinvent 3.5.

Version 3 of Ecoinvent distinguishes three system models, two for attributional modeling (allocation and cutoff by classification, and allocation at the point of substitution), and one for consequential modeling. Allocation and cutoff by classification was chosen because of the following fact: since this model removes recyclable materials burden-free from the producing activity and does not allocate impacts or benefits to them [165], it is suitable for the treatment of UCO as a burden-free feedstock, as accepted in similar studies [9], [33], [68], [71], [77]. Therefore, UCO-based biodiesel only bears the burden of the valorization process.

The selection of the system model also affects the handling of multifunctionality, which applies to the product system since glycerin is a by-product of biodiesel production. Although the ISO standard recommends system expansion above allocation [109], most biofuel LCA studies adopt an allocation approach, which is supported by the RED [18]. Still, there is no consensus about the most adequate allocation factor, so this choice must be acknowledged as a source of uncertainty. Under the selected system model, Ecoinvent provides allocated datasets for multifunctional processes based on specific allocation factors (physical relations, exergy, prices, or mass) [165]. For the study and reference systems, the available datasets are the result of an economic allocation with a factor of 87.1% to biodiesel and 12.9% to glycerin. Although the allocation factor can affect the magnitude of the environmental impacts -and sensitivity analyses are usually conducted to evaluate this issue-, this is not considered as necessary for the goal of this LCA.

D.2.3. System boundaries and completeness requirements

A cradle-to-gate approach was chosen for this LCA, so the considered life cycle stages for the study system included UCO collection, UCO pretreatment, UCO distribution, and UCO-based biodiesel production. Analogous stages were considered for the reference system, namely oil palm cultivation, palm oil extraction, palm oil distribution, and palm oil-based biodiesel production. These can be collectively identified as feedstock sourcing, oil pretreatment/extraction, exportation, and biodiesel production. The use of biodiesel as fuel was excluded from the study since it is not relevant to the LCA goal. Figure 3-3 and Figure 3-7 of the main document present the life cycle stages of each product system.

Background supply chains were fully included, provided by Ecoinvent. Version 3 of the database contains consistent global datasets, as well as market datasets that represent the consumption mixes for a given region and product [165]; market datasets were used when no specific information about the supply chain was available.

D.2.4. Basis for impact assessment

There is no consensus on a standardized impact assessment methodology for LCA of biofuels [65], as identified in the literature review. Among the available methodologies, ReCiPe 2016 was selected, as it is often seen as the state of the art [166]. Impact factors are provided by ReCiPe according to three cultural perspectives, each of which represents a set of choices regarding time or expectations on environmental management and technology development [167]. These perspectives are [168]:

- **Individualist:** It is based on the short-term interest, impact types that are undisputed, and technological optimism regarding human adaptation.
- **Hierarchist:** It is based on scientific consensus regarding the time frame and plausibility of impact mechanisms. For this LCA study, this perspective was taken and accepted as default.
- **Egalitarian:** It is based on the precautionary principle, so it takes the longest time frame and all impact pathways for which data is available.

Table D-1 displays the selected impact categories from the methodology for each assessment criterion.

Table D-1: Selected impact categories for each assessment criterion

Assessment criterion	Impact category	Unit
Human health	Fine particulate matter formation	kg PM2.5-eq
	Photochemical oxidant formation	kg NOx-eq
Demand for fossil resources	Fossil resource use	kg oil-eq
Climate change	Climate change	kg CO_2-eq
Water quality	Freshwater eutrophication	kg P-eq
Soil quality	Terrestrial acidification	kg SO_2-eq

The criterion of water use was the only one that was assessed through a different impact assessment methodology, namely the Water Scarcity methodology proposed by Boulay et al. in 2011, which uses the water stress index (WSI) as assessment indicator (m^3).

D.3. Life Cycle Inventory Analysis

A detailed description of the systems can be found in the main document, Section 3.3. This section presents the inventory data for the LCA study with the corresponding database providers for the modelling in OpenLCA.

D.3.1. Study System

- **UCO collection**

Calculation of the average transportation distance for the collection of 1 ton of UCO was made upon the work of Rodríguez [114], who characterized the whole logistic scheme involved in this stage of the study system. For modeling purposes, it was assumed that all collection vehicles are light commercial vehicles.

Some studies include the washing of the plastic containers [6], but this can be neglected for the present case, since drums are reused multiple times without being washed, and when no longer suitable for UCO storage, these are handed to another recycling company that processes and transforms the plastic into building materials.

Table D-2: Inventory data for the UCO collection stage

Inputs		
Flow	**Value**	**Provider**
Available UCO	1 t	-
Transport, freight, light commercial vehicle	50 t*km	Transport, freight, light commercial vehicle (Rest of the world)
Outputs		
Flow	**Value**	**Provider**
Collected UCO	1 t	-

- **UCO pretreatment**

Inventory data were provided directly by the recycling agent that performs this stage. Although the heating fuel is a mixture of light and heavy fuel oil, the latter was neglected for modeling purposes, and features of the boiler were assumed to be those of the available provider.

Table D-3: Inventory data for the UCO pretreatment stage

Inputs		
Flow	**Value**	**Provider**
Collected UCO	1.03 t	UCO Collection
Electricity, medium voltage	8 kWh	Market for electricity, medium voltage (Colombia)
Heat, central or small scale	800 MJ	Heat production, light fuel oil, at boiler 100 kW condensing, non-modulating (Rest of the world)
Outputs		
Flow	**Value**	**Provider**
Pretreated UCO	1 t	-
Water vapor	0.0214 t	(Emission to air/high population density)
Biowaste	0.0086 t	Treatment of biowaste, industrial composting

- **UCO distribution**

Based on the locations of the pretreatment and biodiesel production facilities, as well as the ports in Colombia and Spain, it was possible to estimate transportation distances. For modeling purposes, it was assumed that lorries in Colombia still follow the Euro IV standards, while lorries in Spain must comply with stricter regulations and therefore follow the Euro VI standards.

Table D-4: Inventory data for the UCO distribution stage

Inputs		
Flow	**Value**	**Provider**
Pretreated UCO	1 t	UCO Collection
Transport, freight, lorry 16-32 metric ton, EURO4	1.000 t*km	Transport, freight, lorry 16-32 metric ton, EURO4 (Rest of the world)
Transport, freight, lorry 16-32 metric ton, EURO6	324 t*km	Transport, freight, lorry 16-32 metric ton, EURO6 (Rest of the world)
Transport, freight, sea, transoceanic ship	7.440 t*km	Transport, freight, sea, transoceanic ship (Global)

Outputs		
Flow	**Value**	**Provider**
Distributed UCO	1 t	-

- **Biodiesel production**

Inventory data was based on the Ecoinvent dataset "Treatment of waste cooking oil, purified, esterification, vegetable oil methyl ester (Rest of the world)", which applies to the Westfalia technology for biodiesel production. Providers of the dataset were modified to fit the geographical location (Spain). The magnitude of data is consistent with that reported in similar LCA studies [6], [19], [29], [70], [169].

Table D-5: Inventory data for the biodiesel production stage

Inputs		
Flow	**Value**	**Provider**
Distributed UCO	0.930 t	UCO distribution
Electricity	38.25 kWh	Market for electricity, medium voltage (Spain)
Heat, district or industrial, natural gas	835.44 MJ	Market for heat, district or industrial, natural gas (Europe without Switzerland)
Tap water	15.12 kg	Market for tap water (Europe without Switzerland)
Water, deionized, from tap water, at user	5.32E-4 kg	Market for water, deionized, from tap water, at user (Europe without Switzerland)
Methanol	102.74 kg	Market for methanol (Global)
Phosphoric acid, industrial grade, without water, in 85% solution	4.16 kg	Market for phosphoric acid, industrial grade, without water, in 85% solution state (Global)
Potassium hydroxide	10.27 kg	Market for potassium hydroxide (Global)
Sodium hydroxide, without water, in 50% solution state	4.96E-4 kg	Market for sodium hydroxide, without water, in 50% solution state (Global)
Sodium methoxide	0.057 kg	Market for sodium methoxide (Global)
Sulfuric acid	0.0047 kg	Market for sulfuric acid (Europe)

Outputs		
Flow	**Value**	**Provider**
UCO-based biodiesel	1 ton	-
Municipal solid waste	1.30E-3 kg	Market for municipal solid waste (Spain)
Wastewater, average	0.0566 m^3	Market for wastewater, average (Europe without Switzerland)

D.3.2. Reference System

The following datasets were taken to build the reference system:

Table D-6: Used datasets for the reference system

Stage	Dataset	Remarks
Oil palm cultivation	Palm fruit bunch production (Colombia)	-
Palm oil extraction	Palm oil mill operation, crude palm oil (Rest of the world)	Providers of the dataset were modified to fit the geographical location (Colombia)
Biodiesel production	Esterification of palm oil, vegetable oil methyl ester (Rest of the world)	Providers of the dataset were modified to fit the geographical location (Spain)

As for the palm oil distribution stage, transportation distances were the same as for the study system, except for the first segment to the exportation port. As described in the main document, it was assumed that crude palm oil is exported from a specific location in the northern zone of Colombia, according to reports of the companies that export the highest volume of crude palm oil to Spain [122]–[124], which is located 80 km away from the port.

D.4. Sources of uncertainty

Analysis of uncertainties is fundamental to appraise the robustness of the results and to prevent misleading conclusions or comparative assertions. In this sense, uncertainty must be acknowledged, evaluated and communicated [65]. However, quantification of uncertainties requires collecting information on the statistical distribution of the quantitative parameters in the foreground system. For this specific LCA, such information is only available for the parameter of travel distance per ton of UCO in the collection stage, so it is not possible to properly quantify the uncertainty of the results.

For the study system, the following are sources of uncertainty:

- Collected data from primary sources correspond to average values, and except for transportation distance per ton of collected UCO, there is no information about the variability of the rest of the parameters.
- For the stages of UCO collection and pretreatment, assumptions regarding the choice of the vehicles, the features of the boiler in the pretreatment facilities, and the used heating fuel were assumed for modeling purposes.
- For the stage of UCO distribution, transportation distances were taken from a web mapping service assuming that the shortest route is taken.
- Data for the stage of biodiesel production was taken from the Ecoinvent database. For the specific inventory, the reported data quality indicates that values are reliable, since these are based on measurements; and complete, because these are representative from the relevant locations for the considered market over an adequate period. Besides, the geographical and technological correlation is adequate. Nonetheless, the temporal correlation is not optimal, because the age of the data is more than 10 years.

As for the reference system, uncertainty is also inherent to the specific inventories that were taken from the Ecoinvent database. The reported data quality indicates good reliability and completeness, as well as an adequate technological correlation, but not a good geographical and temporal correlation.

Finally, it is important to emphasize the fact that methodological choices also pose an important degree of uncertainty in the results. In particular, the choice of the impact assessment methodology can have an important influence on the results, since some impact categories still lack standardization and can have a significant degree of variability among the existing possibilities.

E. Appendix: Sensitivity analysis

Previous LCA studies on UCO valorization reveal contradictory results regarding the role of the UCO collection stage: while some conclude that the contribution share from this stage is small [27], [30], [33], [72], [76], [78], [170], others argue that the collection impacts are usually overlooked and can be very significant [18], [24], [58], [68], [80]. Essentially, results depend on the type of collection scheme and its efficiency [18]. Thus, a sensitivity analysis was conducted to delve into the role of the UCO collection stage, by varying the parameter of transportation distance per unit of collected UCO, which is an indicator of the collection scheme's efficiency.

For the study system of this work, an average transportation distance of 50 km/ton UCO was calculated according to the findings of Rodríguez [114]. However, a high degree of dispersion was observed among the values for different collection routes, ranging from 10 to even 1,200 km/ton UCO, and with a standard deviation of 220 km/ton UCO. It was identified that about 90% of the values are in the range of 10 to 250 km/ton UCO; therefore, it was decided to use these values for the sensitivity analysis, which correspond to one-fifth and five times the calculated average transportation distance. Three scenarios were then considered:

Table E-1: Sensitivity analysis scenarios

Scenario	Transportation distance
Best case	10 km/ton UCO
Baseline	50 km/ton UCO
Worst case	250 km/ton UCO

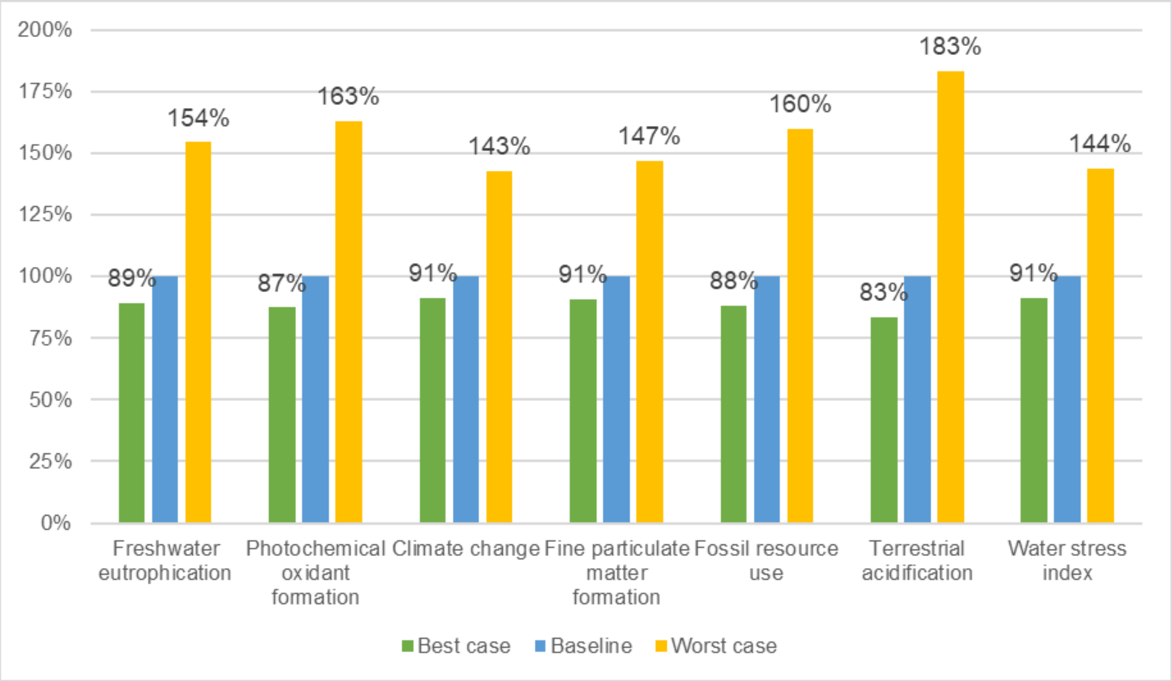
A sensitivity ratio was calculated according to the following formula [6]:

$$Sensitivity\ ratio = \frac{\frac{\Delta\ result}{Baseline\ result}}{\frac{\Delta\ result}{Baseline\ parameter}}$$

The calculated sensitivity ratios for the different impact categories range between 0.11 and 0.21. Hence, it is possible to state that the parameter does not significantly influence the overall results [6].

Nonetheless, it is important to acknowledge that such high values of the transportation distance reflect a low level of efficiency of the current UCO collection scheme. Figure E-1 presents the magnitude of the different impact categories relative to the baseline scenario, pointing out the potential increase of the results for the worst-case scenario It can be identified that the most sensitive impact categories are terrestrial acidification, photochemical oxidant formation, and fossil resource use; on the other hand, the least sensitive impact categories are climate change, water use, and fine particulate matter formation.

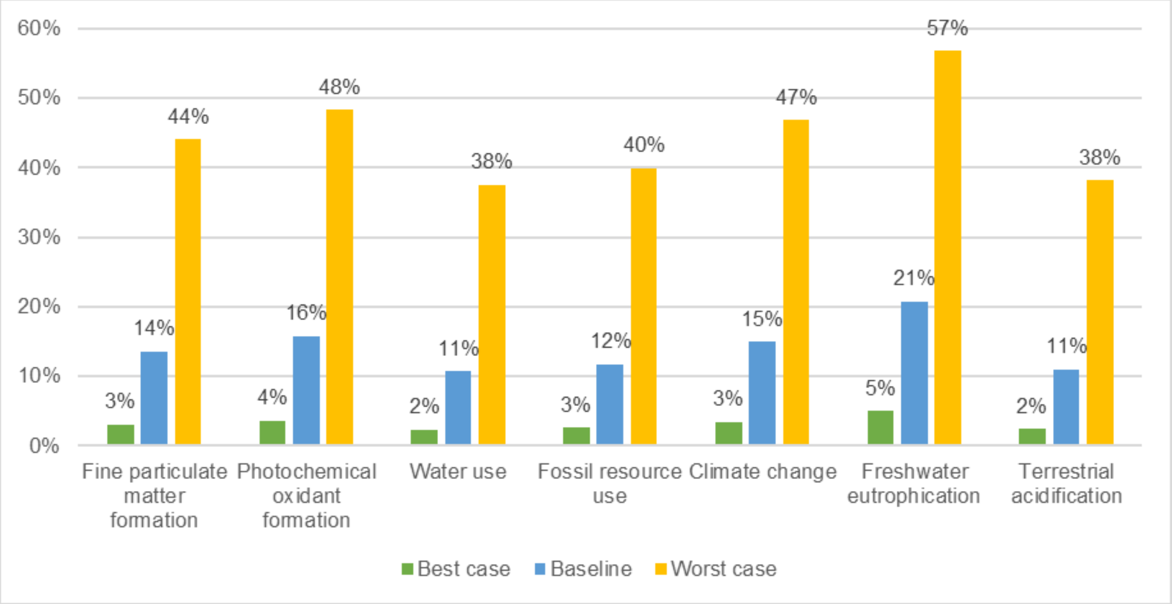
Figure E-1: Impact results of the best- and worst-case scenarios relative to the baseline



Variation parameter: Transportation distance per unit of collected UCO (See Table E-1)

Figure E-2 shows the contribution share of the UCO collection stage. For the baseline scenario, these values range between 11% and 21%, which are low but non-negligible. For the best-case scenario, contribution shares can be considered insignificant, since the maximum value is 5%. As for the worst-case scenario, these values are at least 38% and even reach 57% for the impact category of freshwater eutrophication.

Figure E-2: Contribution share of the UCO collection stage for each of the considered scenarios



Variation parameter: Transportation distance per unit of collected UCO (See Table E-1)

It is then crucial to design strategies to optimize the UCO collection scheme by minimizing the parameter of transportation distance per unit of collected UCO.

Bibliography

[1] L. A. Rincón, J. G. Cadavid, and A. Orjuela, “Used cooking oils as potential oleochemical feedstock for urban biorefineries – Study case in Bogota, Colombia,” *Waste Manag.*, vol. 88, pp. 200–210, 2019.

[2] A. Orjuela, “Industrial Oleochemicals from Used Cooking Oils (UCOs) - Sustainability Benefits and Challenges,” in *Advances in Carbon Management Technologies*, S. K. Sikdar and F. Princiotta, Eds. CRC Press, 2019.

[3] A. Orjuela and J. Clark, “Green Chemicals from Used Cooking Oils: Trends, Challenges and Opportunities,” no. 361. 2020.

[4] M. I. Loizides, X. I. Loizidou, D. L. Orthodoxou, and D. Petsa, “Circular bioeconomy in action: Collection and recycling of domestic used cooking oil through a social, reverse logistics system,” *Recycling*, vol. 4, no. 16, 2019.

[5] European Biomass Industry Association, “Used Cooking Oil.” [Online]. Available: https://www.eubia.org/cms/wiki-biomass/biomass-resources/challenges-related-to-biomass/used-cooking-oil-recycling/. [Accessed: 28-Apr-2020].

[6] L. Lombardi, B. Mendecka, and E. Carnevale, “Comparative life cycle assessment of alternative strategies for energy recovery from used cooking oil,” *J. Environ. Manage.*, vol. 216, pp. 235–245, 2018.

[7] M. Ribau Teixeira, R. Nogueira, and L. M. Nunes, “Quantitative assessment of the valorisation of used cooking oils in 23 countries,” *Waste Manag.*, vol. 78, pp. 611–620, 2018.

[8] M. S. Ruiz, R. B. De Oliveira, A. Struffaldi, M. L. D. Da Silva Gabriel, and E. Bocatto, “Cooking oil waste recycling experiences worldwide: A preliminary analysis of the emerging networks in the São Paulo Metropolitan Region, Brazil,” *Int. J. Energy Technol. Policy*, vol. 13, no. 3, pp. 189–206, 2017.

[9] B. Mendecka, L. Lombardi, and J. Kozioł, “Probabilistic multi-criteria analysis for evaluation of biodiesel production technologies from used cooking oil,” *Renew. Energy*, vol. 147, pp. 2542–2553, 2020.

[10] G. Seber, R. Malina, M. N. Pearlson, H. Olcay, J. I. Hileman, and S. R. H. Barrett, "Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow," *Biomass and Bioenergy*, vol. 67, pp. 108–118, 2014.

[11] S. Foteinis, E. Chatzisymeon, A. Litinas, and T. Tsoutsos, "Used-cooking-oil biodiesel: Life cycle assessment and comparison with first- and third-generation biofuel," *Renew. Energy*, vol. 153, pp. 588–600, 2020.

[12] P. A. Torres Ulloa, "Análisis de ciclo de vida del proceso de aprovechamiento y valorización de aceite de cocina usado en Bogotá como materia prima oleoquímica," Universidad Nacional de Colombia, 2019.

[13] L. Á. Rincón Vija, "Reutilización de aceites de cocina usados en la producción de aceites epoxidados," Universidad Nacional de Colombia, 2018.

[14] E. Font de Mora, C. Torres, and A. Valero, "Thermoeconomic analysis of biodiesel production from used cooking oils," *Sustainability*, vol. 7, pp. 6321–6335, 2015.

[15] D. Phillips, "Implications of Imported Used Cooking Oil (UCO) as a Biodiesel Feedstock," York, 2019.

[16] Greenea, "Analysis of the current development of household UCO collection systems in the EU," 2016.

[17] E. Vinyes, J. Oliver-Solà, C. Ugaya, J. Rieradevall, and C. M. Gasol, "Application of LCSA to used cooking oil waste management," *Int. J. Life Cycle Assess.*, vol. 18, no. 2, pp. 445–455, 2013.

[18] C. Caldeira, F. Freire, and J. Queiro, "Biodiesel from Waste Cooking Oils in Portugal : Alternative Collection Systems," pp. 771–779, 2015.

[19] S. Morais, T. M. Mata, A. A. Martins, G. A. Pinto, and C. A. V. Costa, "Simulation and life cycle assessment of process design alternatives for biodiesel production from waste vegetable oils," *J. Clean. Prod.*, vol. 18, no. 13, pp. 1251–1259, 2010.

[20] C. Caldeira *et al.*, "Water footprint profile of crop-based vegetable oils and waste cooking oil: Comparing two water scarcity footprint methods," *J. Clean. Prod.*, vol. 195, pp. 1190–1202, 2018.

[21] Consejo de la Unión Europea, "Directiva 2009/28/CE del Parlamento Europeo y del Consejo de 23 de abril de 2009," *D. Of. la Unión Eur.*, vol. 2008, no. 2, pp. 16–62, 2009.

[22] A. A. Acquaye, T. Sherwen, A. Genovese, J. Kuylenstierna, S. Lenny Koh, and S.

McQueen-Mason, “Biofuels and their potential to aid the UK towards achieving emissions reduction policy targets,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 7, pp. 5414–5422, 2012.

[23] P. Upham and B. Smith, “Using the Rapid Impact Assessment Matrix to synthesize biofuel and bioenergy impact assessment results: The example of medium scale bioenergy heat options,” *J. Clean. Prod.*, vol. 65, pp. 261–269, 2014.

[24] I. A. Peñarrubia Fernandez, D. H. Liu, and J. Zhao, “LCA studies comparing alkaline and immobilized enzyme catalyst processes for biodiesel production under Brazilian conditions,” *Resour. Conserv. Recycl.*, vol. 119, pp. 117–127, 2017.

[25] H. Li, J. Ebner, P. Ren, L. Campbell, B. Dizayi, and S. Hadavi, “Determination of Carbon Footprint using LCA Method for Straight Used Cooking Oil as a Fuel in HGVs,” *SAE Int. J. Fuels Lubr.*, vol. 7, no. 2, pp. 623–630, 2014.

[26] N. Escobar, J. Ribal, G. Clemente, and N. Sanjuán, “Consequential LCA of two alternative systems for biodiesel consumption in Spain, considering uncertainty,” *J. Clean. Prod.*, vol. 79, pp. 61–73, 2014.

[27] T. D. Tsoutsos, S. Tournaki, O. Paraíba, and S. D. Kaminaris, “The Used Cooking Oil-to-biodiesel chain in Europe assessment of best practices and environmental performance,” *Renew. Sustain. Energy Rev.*, vol. 54, pp. 74–83, 2016.

[28] A. Demirbas, “Political, economic and environmental impacts of biofuels: A review,” *Appl. Energy*, vol. 86, no. SUPPL. 1, pp. S108–S117, 2009.

[29] Z. Sajid, F. Khan, and Y. Zhang, “Process simulation and life cycle analysis of biodiesel production,” *Renew. Energy*, vol. 85, pp. 945–952, 2016.

[30] D. De Pontes Souza, F. M. Mendonça, K. R. Alves Nunes, and R. Valle, “Environmental and socioeconomic analysis of producing biodiesel from used cooking oil in Rio de Janeiro: The case of the Copacabana district,” *J. Ind. Ecol.*, vol. 16, no. 4, pp. 655–664, 2012.

[31] F. Hillairet, A. Djelouadji, G. Prieto, and O. Madiot, “Are biofuels producers ready for the next EU energy transition?,” 2019.

[32] S. Achinas, J. Horjus, V. Achinas, and G. J. W. Euverink, “A PESTLE analysis of biofuels energy industry in Europe,” *Sustainability*, vol. 11, no. 21, pp. 1–24, 2019.

[33] C. Moretti, M. Junginger, and L. Shen, “Environmental life cycle assessment of polypropylene made from used cooking oil,” *Resour. Conserv. Recycl.*, vol. 157, no. September 2019, p. 104750, 2020.

[34] M. Kurańska, H. Beneš, A. Prociak, O. Trhlíková, Z. Walterová, and W.

Stochlińska, “Investigation of epoxidation of used cooking oils with homogeneous and heterogeneous catalysts,” *J. Clean. Prod.*, vol. 236, 2019.

[35] E. Leff, *Saber ambiental: sustentabilidad, racionalidad, complejidad, poder*, Primera. 1998.

[36] J. Martínez Alier and J. Roca Jusmet, *Economía ecológica y política ambiental*, 3a ed. México D.F.: Fondo de Cultura Económica, 2013.

[37] WCED, “Our Common Future,” 1987.

[38] S. Sala, F. Farioli, and A. Zamagni, “Progress in sustainability science: Lessons learnt from current methodologies for sustainability assessment: Part 1,” *Int. J. Life Cycle Assess.*, vol. 18, no. 9, pp. 1653–1672, 2013.

[39] K. Ott, “‘Friendly Fire’ Bemerkungen zum integrativen Konzept nachhaltiger Entwicklung,” in *Ein Konzept auf dem Prüfstand Das integrative Nachhaltigkeitskonzept in der Forschungspraxis*, J. Kopfmüller, Ed. Berlin: Edition Sigma, 2006, pp. 63–82.

[40] J. M. Naredo, “Sobre el origen, el uso y el contenido del término ‘sostenible.’” Madrid, 1996.

[41] L. Rodríguez Tapia and D. Ruiz Sandoval Valvende, “El concepto de capital natural en los modelos de crecimiento exógeno,” *Análisis Económico*, vol. XVI, no. 33, pp. 109–128, 2001.

[42] H. E. Daly and J. Farley, *Ecologial Economics: Principles and Applications*. Washington: Island Press, 2004.

[43] C. S. Boda and T. Faran, “Paradigm found? Immanent critique to tackle interdisciplinarity and normativity in science for sustainable development,” *Sustain.*, vol. 10, no. 10, 2018.

[44] P. Kravets, “An integral model of sustainable forest management in the context of natural capital theory,” *Econ. Nat. usage*, no. 5, pp. 28–31, 2012.

[45] L. Andes, T. Lützkendorf, B. Ströbele, J. Kopfmüller, and C. Rösch, “Methodensammlung zur Nachhaltigkeitsbewertung - Grundlagen, Indikatoren, Hilfsmittel.” Karlsruher Institut für Technologie KIT, Karlsruhe, 2019.

[46] E. Giovannoni and G. Fabietti, “What is Sustainability? A review of the Concept and its Applications,” in *Integrated Reporting: Concepts and Cases that Redefine Corporate Accountability*, C. Busco, M. L. Frigo, A. Riccaboni, and P. Quattrone, Eds. Springer, 2013, pp. 21–40.

[47] S. Sala, B. Ciuffo, and P. Nijkamp, “A systemic framework for sustainability assessment,” *Ecol. Econ.*, vol. 119, pp. 314–325, 2015.

[48] L. K. Ozanne *et al.*, “Managing the tensions at the intersection of the triple bottom line: A paradox theory approach to sustainability management,” *J. Public Policy Mark.*, vol. 35, no. 2, pp. 249–261, 2016.

[49] A. Ángel Maya, *El reto de la vida. Ecosistema y Cultura: Una introducción al estudio del medio ambiente*, 2a ed. Bogotá, 2013.

[50] B. Ness, E. Urbel-Piirsalu, S. Anderberg, and L. Olsson, “Categorising tools for sustainability assessment,” *Ecol. Econ.*, vol. 60, no. 3, pp. 498–508, 2007.

[51] T. Hacking and P. Guthrie, “A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment,” *Environ. Impact Assess. Rev.*, vol. 28, no. 2–3, pp. 73–89, 2008.

[52] A. Grunwald and J. Kopfmüller, *Nachhaltigkeit*, 2nd ed. Frankfurt am Main: Campus Verlag, 2012.

[53] E. Smeets, R. Weterings, T. N. O. Centre, P. Bosch, M. Büchele, and D. Gee, “Environmental indicators: Typology and overview,” no. 25.

[54] United Nations Statistics Division, “SDG Indicators: Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development,” 2017. [Online]. Available: https://unstats.un.org/sdgs/indicators/indicators-list/. [Accessed: 01-Apr-2020].

[55] A. Grunwald, “Sustainability Assessment of Technologies – An Integrative Approach,” in *Sustainable Development - Energy, Engineering and Technologies - Manufacturing and Environment*, C. Ghenai, Ed. Rijeka: InTech, 2012, pp. 35–62.

[56] J. Kopfmüller *et al.*, “Nachhaltige Entwicklung integrativ betrachtet - Konstitutive Elemente, Regeln, Indikatoren,” Berlin, 2001.

[57] H. Dhaliwal, “A Look Back: The Evolution of LCA and Life Cycle Impact Assessment,” *Triple Pundit*, 2016. [Online]. Available: https://www.triplepundit.com/story/2016/look-back-evolution-lca-and-life-cycle-impact-assessment/22321.

[58] H. Liu, Y. Huang, H. Yuan, X. Yin, and C. Wu, “Life cycle assessment of biofuels in China: Status and challenges,” *Renew. Sustain. Energy Rev.*, vol. 97, no. September, pp. 301–322, 2018.

[59] A. Quek and R. Balasubramanian, “Life cycle assessment of energy and energy carriers from waste matter - A review,” *J. Clean. Prod.*, vol. 79, pp. 18–31, 2014.

[60] Royal Academy of Engineering, “Sustainability of liquid biofuels.” London, pp. 1–96, 2017.

[61] EPFL Energy Center, “Newsletter - January 2009. Roundtable on Sustainable Biofuels.” 2009.

[62] Global Bioenergy Partnership, *The global bioenergy partnership sustainability indicators for bioenergy*, First. FAO, 2011.

[63] U. R. Fritsche, “Sustainable Bioenergy: Key Criteria and Indicators,” 2012.

[64] Roundtable on Sustainable Biomaterials, “RSB PRINCIPLES & CRITERIA,” 2016.

[65] M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, *Life Cycle Assessement: Theory and Practice*. Springer Nature, 2017.

[66] Y. T. Chong, K. M. Teo, and L. C. Tang, “A lifecycle-based sustainability indicator framework for waste-to-energy systems and a proposed metric of sustainability,” *Renew. Sustain. Energy Rev.*, vol. 56, pp. 797–809, 2016.

[67] L. Iglesias, A. Laca, M. Herrero, and M. Díaz, “A life cycle assessment comparison between centralized and decentralized biodiesel production from raw sunflower oil and waste cooking oils,” *J. Clean. Prod.*, vol. 37, pp. 162–171, 2012.

[68] C. Caldeira, J. Queirós, A. Noshadravan, and F. Freire, “Incorporating uncertainty in the life cycle assessment of biodiesel from waste cooking oil addressing different collection systems,” *Resour. Conserv. Recycl.*, vol. 112, pp. 83–92, 2016.

[69] M. G. Varanda, G. Pinto, and F. Martins, “Life cycle analysis of biodiesel production,” *Fuel Process. Technol.*, vol. 92, no. 5, pp. 1087–1094, 2011.

[70] M. Ripa, C. Buonaurio, S. Mellino, G. Fiorentino, and S. Ulgiati, “Recycling waste cooking oil into biodiesel: A life cycle assessment,” *Int. J. Performability Eng.*, vol. 10, no. 4, pp. 347–356, 2014.

[71] P. Intarapong, S. Papong, and P. Malakul, “Comparative life cycle assessment of diesel production from crude palm oil and waste cooking oil via pyrolysis,” *Int. J. Energy Res.*, no. 40, pp. 702–713, 2016.

[72] H. H. Khoo, R. B. H. Tan, and Z. Tan, “GHG intensities from the life cycle of conventional fuel and biofuels,” *WIT Trans. Ecol. Environ.*, vol. 123, pp. 329–340, 2009.

[73] S. Pleanjai, S. H. Gheewala, and S. Garivait, “Greenhouse gas emissions from production and use of used cooking oil methyl ester as transport fuel in Thailand,” *J. Clean. Prod.*, vol. 17, no. 9, pp. 873–876, 2009.

[74] J. Yano, T. Aoki, K. Nakamura, K. Yamada, and S. ichi Sakai, "Life cycle assessment of hydrogenated biodiesel production from waste cooking oil using the catalytic cracking and hydrogenation method," *Waste Manag.*, vol. 38, no. 1, pp. 409–423, 2015.

[75] S. Liang, M. Xu, and T. Zhang, "Life cycle assessment of biodiesel production in China," *Bioresour. Technol.*, vol. 129, pp. 72–77, 2013.

[76] Z. L. Chung *et al.*, "Life cycle assessment of waste cooking oil for biodiesel production using waste chicken eggshell derived CaO as catalyst via transesterification," *Biocatal. Agric. Biotechnol.*, vol. 21, no. September, p. 101317, 2019.

[77] D. S. Khang *et al.*, "Design of experiments for global sensitivity analysis in life cycle assessment: The case of biodiesel in Vietnam," *Resour. Conserv. Recycl.*, vol. 119, pp. 12–23, 2017.

[78] C. B. H. Chua, H. M. Lee, and J. S. C. Low, "Life cycle emissions and energy study of biodiesel derived from waste cooking oil and diesel in Singapore," *Int. J. Life Cycle Assess.*, vol. 15, no. 4, pp. 417–423, 2010.

[79] W. M. J. Achten, P. Vandenbempt, J. Almeida, E. Mathijs, and B. Muys, "Life cycle assessment of a palm oil system with simultaneous production of biodiesel and cooking oil in Cameroon," *Environ. Sci. Technol.*, vol. 44, no. 12, pp. 4809–4815, 2010.

[80] E. H. S. Moecke *et al.*, "Biodiesel production from waste cooking oil for use as fuel in artisanal fishing boats: Integrating environmental, economic and social aspects," *J. Clean. Prod.*, vol. 135, pp. 679–688, 2016.

[81] M. A. Rajaeifar *et al.*, "Attributional and consequential environmental assessment of using waste cooking oil- and poultry fat-based biodiesel blends in urban buses: A real-world operation condition study," *Biofuel Res. J.*, vol. 4, no. 3, pp. 638–653, 2017.

[82] A. I. Vidal-Benavides, J. C. Quintero-Díaz, and I. Herrera-Orozco, "Análisis de ciclo de vida de la producción de biodiesel a partir de aceite vegetal usado," *DYNA*, vol. 84, no. 201, pp. 155–162, 2017.

[83] S. Spencer, M. Scott, and N. Macken, "A life cycle assessment of biofuel produced from waste cooking oil," *ASME Int. Mech. Eng. Congr. Expo. Proc.*, vol. 6A-144113, pp. 1–8, 2018.

[84] S. Bezergianni, A. Dimitriadis, and L. P. Chrysikou, "Quality and sustainability

comparison of one- vs. Two-step catalytic hydroprocessing of waste cooking oil," *Fuel*, vol. 118, pp. 300–307, 2014.

[85] S. Bezergianni and L. P. Chrysikou, "Sustainability Assessment of Fuels Production via Hydrotreating Waste Lipids and Co-processing Waste Lipids with Petroleum Fractions," in *Energy,Transportation and Global Warming*, P. Grammelis, Ed. Springer, 2016, pp. 387–400.

[86] M. S. Mancini *et al.*, "Exploring ecosystem services assessment through Ecological Footprint accounting," *Ecosyst. Serv.*, vol. 30, pp. 228–235, 2018.

[87] M. Hatzisymeon, S. Kamenopoulos, and T. Tsoutsos, "Risk assessment of the life-cycle of the Used Cooking Oil-to-biodiesel supply chain," *J. Clean. Prod.*, vol. 217, pp. 836–843, 2019.

[88] A. C. Miranda, S. C. da Silva Filho, E. B. Tambourgi, J. C. CurveloSantana, R. M. Vanalle, and F. Guerhardt, "Analysis of the costs and logistics of biodiesel production from used cooking oil in the metropolitan region of Campinas (Brazil)," *Renew. Sustain. Energy Rev.*, vol. 88, no. January 2017, pp. 373–379, 2018.

[89] S. Eguchi, S. Kagawa, and S. Okamoto, "Environmental and economic performance of a biodiesel plant using waste cooking oil," *J. Clean. Prod.*, vol. 101, no. March 2013, pp. 245–250, 2015.

[90] J. Yang, T. Fujiwara, and Q. Geng, "Life cycle assessment of biodiesel fuel production from waste cooking oil in Okayama City," *J. Mater. Cycles Waste Manag.*, vol. 19, no. 4, pp. 1457–1467, 2017.

[91] A. N. Benavides and J. A. Lozano-Moreno, "Waste cooking oil logistics and environmental assessment for biodiesel production in Cali," *Rev. Fac. Ing.*, no. 88, pp. 9–15, 2018.

[92] International Health Conference, "Preamble to the Constitution of WHO." New York, 1946.

[93] UNEP, "First International Day for Clean Air calls for decisive global action to beat air pollution," 2020. [Online]. Available: https://www.unenvironment.org/news-and-stories/press-release/first-international-day-clean-air-calls-decisive-global-action-beat.

[94] Eurofound and International Labour Organization, "Working conditions in a global perspective," 2019.

[95] International Labour Organization, "Informal economy," 2020. [Online]. Available:

https://www.ilo.org/global/topics/employment-promotion/informal-economy/lang--en/index.htm.

[96] UNEP, “Options for decoupling economic growth from water use and water pollution: A report of the water working group of the International Resource Panel,” 2015.

[97] UNEP, “Can carbon dioxide storage help cut greenhouse emissions?,” Geneve, 2006.

[98] United Nations, “Climate change,” 2020. [Online]. Available: https://www.un.org/en/sections/issues-depth/climate-change/.

[99] NASA, “Scientific Consensus: Earth’s Climate is Warming,” 2020. [Online]. Available: https://climate.nasa.gov/scientific-consensus/.

[100] IPCC, “Annex I: Glossary,” *Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climat change*, 2018. [Online]. Available: https://www.ipcc.ch/sr15/chapter/glossary/.

[101] L. Volterra, M. Boualam, A. Menesguen, J. P. Duguet, J. Duchemin, and X. Bonnefoy, “Eutrophication and Health,” 2002.

[102] S. Andrews and M. Wander, “Soil Quality Basics,” *Soil Quality for Environmental Health*, 2011. [Online]. Available: http://soilquality.org/basics.html.

[103] Soil Quality Pty Ltd, “Soil Acidity Fact Sheet,” 2020. [Online]. Available: http://soilquality.org.au/factsheets/soil-acidity.

[104] M. A. J. Huijbregts *et al.*, “ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level,” *Int. J. Life Cycle Assess.*, pp. 138–147, 2017.

[105] EPA, “What are the trends in wastes and their effects on human health and the environment?,” *Report on the Environment*, 2020. [Online]. Available: https://www.epa.gov/report-environment/wastes#effects.

[106] M. Courtois, “Social strategies for FISSAC: Strategies for social engagement and acceptance,” 2017.

[107] R. Wüstenhagen, M. Wolsink, and M. J. Bürer, “Social acceptance of renewable energy innovation: An introduction to the concept,” *Energy Policy*, vol. 35, no. 5, pp. 2683–2691, 2007.

[108] F. Cherubini, N. D. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger, and S.

Woess-Gallasch, “Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations,” *Resour. Conserv. Recycl.*, vol. 53, no. 8, pp. 434–447, 2009.

[109] ISO, “ISO 14040:2006.” 2006.

[110] European Commission - Joint Research Centre - Institute for Environment and Sustainability, *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance*, First. Luxemburg: Office of the European Union, 2010.

[111] C. M. R. Pastakia, “The Rapid Impact Assessment Matrix (RIAM) – A New Tool for Environmental Impact Assessment,” 1998.

[112] L. B. Leopold, F. E. Clarke, B. B. Hanshaw, and J. R. Balsley, “A Procedure for Evaluating Environmental Impact,” *Geol. Surv. Circ.*, no. 645, 1971.

[113] J. A. Maxwell and B. A. Miller, “Categorizing and Connecting Strategies in Qualitative Data Analysis,” *Handbook of emergent methods*. pp. 461–477, 2008.

[114] J. S. Rodríguez Flórez, “Estudio de factibilidad para el aprovechamiento de ACUs en la ciudad de Bogotá,” National University of Colombia, 2020.

[115] Greenfuel Extremadura S.A., “La empresa,” 2018. [Online]. Available: http://www.greenfuel.es/es/empresa-biodiesel-y-glicerina-en-extremadura-greenfuel.html.

[116] J. C. J. Bart, N. Palmeri, and S. Cavallaro, *Biodiesel Science and Technology. From Soil to Oil*. Woodhead Publishing, 2010.

[117] J. Connemann, A. Krallmann, and E. Fischer, “United States Patent,” 5,354,878, 1994.

[118] N. Escobar L., *Contribution to the environmental impact assessment of biodiesel in the context of Spain*. Universidad Politécnica de Valencia, 2015.

[119] R. Soley, “Bioenergía en España: ¿Es realmente una alternativa?,” 2019.

[120] Fedepalma, “Statistical Yearbook 2020. The Oil Palm Agroindustry in Colombia and the World. 2015 - 2019,” 2020.

[121] Fedepalma, “The oil plam agribusiness in Colombia,” 2019.

[122] Investigadores Treid, “Así es la relación comercial de Colombia y España en el primer semestre de 2019 y 2020,” 2020. [Online]. Available: https://www.treid.co/post/asi-es-la-relacion-comercial-de-colombia-y-espana-en-el-primer-semestre-de-2019-y-2020.

[123] Investigadores Treid, "Exportaciones de aceite de palma en Colombia en 2019," 2020. [Online]. Available: https://www.treid.co/post/exportaciones-de-aceite-de-palma-en-colombia-en-2019.

[124] Biología Aplicada S.A.S., "Estudio de altos valores de conservación en predios de cultivo de palma de aceite del grupo C.I. Biocosta S.A. en el caribe Colombiano," 2016.

[125] Fedepalma, "Informe de gestión Fedepalma 2019," 2019.

[126] S. Seeboldt and Y. S. Abdala, "Responsibility and sustainability of the palm oil industry: Are the principles and criteria of the RSPO feasible in Colombia?," 2010.

[127] O. Gallo, D. Hawkins, J. E. Luna-García, and M. Torres-Tovar, "Producción de aceite de palma en Colombia: ¿trabajo decente y saludable?," *Rev. Ciencias la Salud*, vol. 18, no. 2, 2020.

[128] G. La Rotta Amaya, "Efectos Sociales del Cultivo de Palma de Aceite: Condiciones Laborales, Seguridad Social y Educación en los Trabajadores Palmeros de Cumaral," 2010.

[129] W. H. Cruz Medina, "Análisis de las condiciones laborales del sector palmicultor y sus efectos sociales en el municipio de Maní Casanare," Universidad Nacional Abierta y a Distancia, 2018.

[130] R. D. C. Olivares, S. S. Rivera, J. E. Núñez, and M. Leod, "Analysis of Active Failures and Latent Conditions on Biodiesel Production Facilities," no. July, 2014.

[131] Consejo Colombiano de Seguridad, "El CCS y la OIT trabajo proponen al gobierno un pacto por la seguridad y salud en el campo," *Boletin CCS al día*, 2020. .

[132] O. Gallo, "Salud laboral en la industria de aceite de palma en Colombia," *Agencia de Información Laboral - AIL*, 2018. [Online]. Available: https://ail.ens.org.co/informe-especial/salud-laboral-en-la-industria-de-aceite-de-palma-en-colombia/. [Accessed: 27-Nov-2020].

[133] C. A. Rudas Carvajal, "Diagnóstico, diseño y evaluación del sistema de vigilancia epidemiológica por factores de riesgo para la empresa Palmas del Sur S.A.," Universidad Pontificia Bolivariana, 2016.

[134] H. T. Odum, *Energy, ecology, and economics*. 1973.

[135] R. Rapier, "Fossil Fuels Still Supply 84 Percent Of World Energy — And Other Eye Openers From BP's Annual Review," *Forbes*, 2020. [Online]. Available: https://www.forbes.com/sites/rrapier/2020/06/20/bp-review-new-highs-in-global-energy-consumption-and-carbon-emissions-in-2019/?sh=71778f9366a1.

[136] H. E. Daly, "Ecological economics and sustainable development. Selected essays of Herman Daly." 2007.

[137] European Parliament, "Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources," 2018.

[138] National Geographic, "Palm oil is unavoidable. Can it be sustainable?," 2018. [Online]. Available: https://www.nationalgeographic.com/magazine/2018/12/palm-oil-products-borneo-africa-environment-impact/.

[139] C. Castiblanco Rozo, "Scenarios of the future expansion of Oil Palm in Colombia: impacts generated by the biofuels sector Carmenza Castiblanco Rozo," Pontificia Universidad Javeriana, 2014.

[140] É. G. Castanheira, H. Acevedo, and F. Freire, "Greenhouse gas intensity of palm oil produced in Colombia addressing alternative land use change and fertilization scenarios," *Appl. Energy*, vol. 114, pp. 958–967, 2014.

[141] Cargill, "In Brazil, Cargill recycles 1.2 million liters of cooking oil," 2016. [Online]. Available: https://www.cargill.com/story/in-brazil-cargill-recycles-1.2-million-liters-of-cooking-oil.

[142] Waste 4think, "The commitment to gather household used vegetable oil," 2017. [Online]. Available: https://waste4think.eu/commitment-gather-household-used-vegetable-oil.

[143] D. C. Panadare and V. K. Rathod, "Applications of Waste Cooking Oil Other Than Biodiesel: A Review," vol. 12, no. 3, pp. 55–76, 2015.

[144] D. Singh-Ackbarali, R. Maharaj, N. Mohamed, and V. Ramjattan-Harry, "Potential of used frying oil in paving material: solution to environmental pollution problem," *Environ. Sci. Pollut. Res.*, vol. 24, no. 13, pp. 12220–12226, 2017.

[145] Consejo Nacional de Política Económica y Social and Departamento Nacional de Planeación, "Política de Crecimiento Verde (CONPES 3934)," 2018.

[146] DNP, "Reporte Nacional Voluntario - Colombia 2018," Bogota, 2018.

[147] D. A. Salam, M. T. Suidan, and A. D. Venosa, "Biodegradation and toxicity of vegetable oils in contaminated aquatic environments: Effect of antioxidants and oil composition," *Sci. Total Environ.*, vol. 547, no. 2016, pp. 95–103, 2016.

[148] M. Fingas, "Vegetable Oil Spills: Oil Properties and Behavior," *Handb. Oil Spill Sci. Technol.*, no. April, pp. 79–91, 2015.

[149] Z. Li and B. A. Wrenn, “Effects of ferric hydroxide on the anaerobic biodegradation kinetics and toxicity of vegetable oil in freshwater sediments,” *Water Res.*, vol. 38, no. 18, pp. 3859–3868, 2004.

[150] S. Thode Filho, J. L. de Paiva, H. A. Franco, D. V. Perez, and M. R. da C. Marques, “Environmental Impacts Caused By Residual Vegetable Oil in the Soil-Plant System,” *Ciência e Nat.*, vol. 39, no. 3, p. 748, 2017.

[151] M. Mosquera Montoya, E. Ruiz Álvarez, L. E. Castro Zamudio, D. F. López Alfonso, and D. E. Munévar Martínez, “Estimación del costo de producción para productores de palma de aceite de Colombia que han adoptado buenas prácticas agrícolas,” *Palmas*, vol. 40, no. 2, pp. 3–20, 2019.

[152] P. Morone and E. Imbert, “ScienceDirect Food waste and social acceptance of a circular bioeconomy: the role of stakeholders,” *Curr. Opin. Green Sustain. Chem.*, vol. 23, pp. 55–60, 2020.

[153] X. Yuan *et al.*, “Public perception towards waste-to-energy as a waste management strategy: A case from Shandong, China,” *Int. J. Environ. Res. Public Health*, vol. 16, no. 16, 2019.

[154] European Palm Oil Alliance, “Deforestation & Palm oil,” 2017. [Online]. Available: https://palmoilalliance.eu/wp-content/uploads/2019/06/Deforestations-and-Forest-Fires-2019-online.pdf. [Accessed: 06-Dec-2020].

[155] C. Castiblanco Rozo and S. Hortúa Romero, “El paradigma energético de los biocombustibles y sus implicaciones,” *Rev. Gestión y Ambient.*, vol. 15, no. 3, pp. 5–26, 2012.

[156] Departamento Nacional de Planeación, “Documento Conpes 3477,” 2007.

[157] C. Rey Sabogal, “Análisis espacial de la correlación entre cultivo de palma de aceite y desplazamiento forzado en Colombia,” *Cuad. Econ.*, vol. 32, no. 61 ESPECIAL, pp. 683–719, 2013.

[158] M. Hurtado, C. Pereira-Villa, and E. Villa, “Oil palm development and forced displacement in Colombia: Causal or spurious?,” *Cuad. Econ.*, vol. 36, no. 71, pp. 441–468, 2017.

[159] L. Potter, “Colombia’s oil palm development in times of war and ‘peace’: Myths, enablers and the disparate realities of land control,” *J. Rural Stud.*, vol. 78, no. September 2017, pp. 491–502, 2020.

[160] F. E. Osorio Pérez, “Tramas entre paramilitarismo y palmicultura en Colombia,” *Mem. y Soc.*, vol. 19, no. 39, pp. 11–28, 2015.

[161] W. S. Jevons, “The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-Mines.” Macmillan, London, 1865.

[162] Euractiv, “RED II Council pressure for double counting renewables must be rejected,” 2018. [Online]. Available: https://www.euractiv.com/section/economy-jobs/opinion/red-ii-council-pressure-for-double-counting-renewables-must-be-rejected/. [Accessed: 04-Dec-2020].

[163] S. Michalopoulos, “Netherlands mulls end to used cooking oil double-counting,” *Euractiv*, 2019.

[164] F. J. F. Behrends, “Greenhouse gas footprint of biodiesel production from used cooking oils,” 2018.

[165] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, “The ecoinvent database version 3 (part I): overview and methodology,” *Int. J. Life Cycle Assess.*, vol. 21, no. 9, pp. 1218–1230, 2016.

[166] J. Ren, A. Scipioni, A. Manzardo, and H. Liang, *Biofuels for a more Sustainable Future: Life Cycle Sustainability Assessment and Multi-Criteria Decision Making*. Elsevier, 2020.

[167] Pre-Sustainability, “ReCiPe,” 2016. [Online]. Available: https://pre-sustainability.com/articles/recipe/. [Accessed: 11-May-2021].

[168] National Institute for Public Health and the Environment, “ReCiPe 2016 v1.1,” 2017.

[169] L. T. Peiró, G. V. Méndez, and X. G. I. Durany, “Exergy analysis of integrated waste management in the recovery and recycling of used cooking oils,” *Environ. Sci. Technol.*, vol. 42, no. 13, pp. 4977–4981, 2008.

[170] L. Talens Peiró, L. Lombardi, G. Villalba Méndez, and X. Gabarrell i Durany, “Life cycle assessment (LCA) and exergetic life cycle assessment (ELCA) of the production of biodiesel from used cooking oil (UCO),” *Energy*, vol. 35, no. 2, pp. 889–893, 2010.