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Life Cycle Assessment of Recycling Used Cooking Oil

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Abstract

This dissertation assesses the environmental impact associated with the disposal of domestic used cooking oil (UCO) and explores sustainable solutions. The research aligns with key sustainable development goals, specifically those related to a responsible consumption and production as well as climate action. These objectives underscore the critical importance of prudent resource management, waste reduction, and climate change mitigation, all of which are central themes within this study.

The research seeks to provide clear answers to crucial questions regarding UCO, a prevalent waste product and a valuable resource. It explores the impacts of used cooking oil disposal on the water management cycle, compares recycling versus disposal in wastewater treatment services, and evaluates the potential of recycling used cooking oil to produce various bioproducts using environmental indicators like global warming potential.

This work uses the life cycle assessment to evaluate global warming potential, environmental aspects and impacts associated with UCO throughout its domestic disposal until its treatment/use.

Analyzing three distinct scenarios to assess their environmental implications objectively. Scenario I replicates existing waste management practices within the European Union. Scenario II introduces a shift in focus, emphasizing the potential of UCO in biodiesel production. Scenario III explores the concept of using UCO to manufacture wax and candles. Scenario I is the only one with positive emissions, of 826 ktonCO$_2$e/FU. The remaining scenarios reduce significantly emissions reusing the UCO for different bioproducts, Scenario II reduces 2 624 ktonCO$_2$e/FU, while Scenario III reduces 1 090 ktonCO$_2$e/FU.

A sensitivity analysis is conducted, regarding the main sources of emissions, with an emphasis on the electricity consumption. Notably, the study highlights that a transition to net-neutral electricity generation by 2050 holds significant promise in mitigating emissions.

The methodology offers broader applicability for product assessments in a circular economy.

Keywords: European used cooking oil flow, wastewater treatment, biodiesel production, paraffin candles production, global warming potential.

Resumo

Esta dissertação avalia o potencial de aquecimento global associado ao fim de vida do óleo de cozinha usado doméstico. Numa primeira etapa, avalia o contexto atual Europeu e explora soluções alternativas. A investigação está alinhada com os objetivos de desenvolvimento sustentável das Nações Unidas, especificamente aos objetivos relacionados ao consumo e produção responsáveis, bem como à ação climática, dado que o potencial de aquecimento engloba as emissões de gases com efeito de estufa. Estes objetivos sublinham a importância da gestão prudente dos recursos, da redução de resíduos e da mitigação das alterações climáticas, todos temas centrais deste estudo.

A investigação procura formular perguntas e obter respostas cruciais sobre o óleo de cozinha usado doméstico, um resíduo comum, mas que pode ser um recurso valioso. São discutidas as repercussões da eliminação do óleo de cozinha usado doméstico no complexo ciclo de gestão de águas residuais, ao realizar uma análise comparativa da reciclagem do óleo de cozinha usado doméstico versus a eliminação convencional nos serviços de tratamento de águas residuais e a viabilidade da reciclagem do óleo de cozinha usado doméstico para diversos bioprodutos usando uma análise de ciclo de vida com expansão do sistema.

A eliminação inadequada de óleos de cozinha usados gera problemas em sistemas de esgotos e estações de tratamento de águas residuais, causando obstruções parciais ou totais em esgotos, aumentando os custos de manutenção, até mesmo a contaminação de aquíferos. Nas estações de tratamento, a presença destes óleos usados prejudica o seu tratamento, aumentando os custos de operação e o consumo de energia. Portanto, torna-se essencial o aproveitamento adequado desses óleos.

Esta dissertação utiliza assim a metodologia de análise de ciclo de vida, reconhecida internacionalmente pela sua abordagem sistemática na avaliação dos impactos ambientais de sistemas e produtos. No caso desta dissertação, será aplicada aos impactos associados ao óleo de cozinha usado doméstico desde a sua eliminação em casa, até ao seu destino final de tratamento/utilização, excluindo transporte e infraestruturas. Esta abordagem metodológica tem fases distintas, começando com a definição do objetivo e âmbito do estudo, fornecendo uma clareza inequívoca sobre os objetivos do estudo, fronteiras estabelecidas e público-alvo pretendido. Posteriormente, a fase dos inventários é executada para reunir dados abrangentes sobre o consumo de recursos e emissões atmosféricas de gases com efeito de estufa (CO_2e).

Na fase de utilização foram feitos ensaios experimentais de comparação de desempenho (tempo de combustão e emissões diretas de CO_2) com seis velas fabricadas com óleo doméstico recolhido por alunos e seis velas comerciais à base de parafina. Estes ensaios serviram para confirmar valores típicos da literatura de densidade de óleo doméstico usado, para ter um fator de emissão de CO_2 da queima de velas à base de parafina comparável ao existente na literatura para 100% parafina, e para padronizar as quantidades dos componentes típicos de uma vela: pavio, corpo e cera. A diferença entre massas de vela gasta para o mesmo tempo de queima é usada para definir uma equivalência entre quantidade de velas de óleo e quantidade de velas à base de parafina que podem evitar.

Foram estabelecidos três cenários distintos para avaliar as suas implicações ambientais de forma objetiva. O Cenário I, que é o cenário base, replica as práticas de gestão de resíduos existentes na União Europeia, relativamente ao óleo de cozinha doméstico usado. Atualmente é gerado a nível europeu cerca de 854 000 toneladas de óleo de cozinha usado doméstico por ano, que é a unidade funcional da nossa análise de ciclo de vida (FU). Neste cenário, o óleo de cozinha usado doméstico é encaminhado maioritariamente para os esgotos e apenas uma pequena fração (5,6%) é reciclada em biodiesel. A produção de biodiesel evita emissões devido à produção e utilização de gasóleo, que é por sua vez creditado como emissões mitigadas. O encaminhamento para os esgotos gera problemas na manutenção dos sistemas de tratamento de águas residuais, com um aumento nos custos associados. Além disso, o acréscimo no consumo de eletricidade para o tratamento das águas devido à presença de óleo de cozinha usado doméstico é um contribuinte significativo para as emissões de gases com efeito estufa. É também adicionado ao sistema as emissões relativas à produção e ao consumo de velas de parafina, para manter as fronteiras do mesmo, uma vez que no cenário final é feita a comparação com velas à base de óleo usado. O Cenário II direciona todo o óleo para a produção exclusiva de biocombustível (biodiesel) evitando uma quantidade maior de gasóleo fóssil produzido e aliviando o custo de tratamento em águas residuais. Neste cenário, o óleo é recolhido e convertido em biodiesel, como uma alternativa sustentável ao gasóleo convencional fóssil. O Cenário III introduz para consideração a produção de velas à base de óleo de cozinha usado doméstico, mantendo a fração do Cenário I para biodiesel e evitando uma certa quantidade de produção de velas à base de parafina. Neste cenário, o óleo é transformado em bioprodutos além de biocombustível, especificamente cera e velas, com o objetivo de substituir as velas mais comuns de parafina, subproduto do petróleo, a quantidade considerada no cenário base.

Para avaliar as emissões totais de cada cenário, foram consideradas todas as componentes do sistema. Isso incluiu emissões associadas a todos os elementos contabilizados no estudo, como as decorrentes do tratamento de águas devido à presença de óleo de cozinha usado doméstico, bem como as provenientes da produção e utilização de biodiesel. Além disso, a análise incorporou créditos, tanto positivos quanto negativos, relacionados às emissões associadas ao consumo e produção de gasóleo, à fabricação e utilização de velas de parafina, e à produção e uso de velas de óleo usado. De notar que as emisões de CO_2 produzidas na queima dos produtos obtidos de óleo usado foram consideradas biogénicas, isto é, não foram contabilizadas.

Durante toda a análise foi utilizada a geração de eletricidade média europeia dos últimos três anos disponíveis (2019-2021), cujo fator de emissão é de 253 gCO_2e/kWh.

O Cenário I é o único com um total de emissões positivas, com cerca de 826 $ktonCO_2e/FU$. Os restantes cenários diminuem substâncialmente as emissões de gases com efeito de estufa para a atmosfera devido ao reaproveitamento do óleo usado para a produção de bioprodutos. O Cenário II reduz as emissões em 2 624 $ktonCO_2e/FU$, com o reaproveitamento do óleo para produção de biodiesel, e o Cenário III reduz cerca de 1 090 $ktonCO_2e/FU$, com a produção de bioprodutos como a cera e velas. Estas reduções são de grande relevância para a mitigação das emissões de gases com efeito estufa e indicam a viabilidade de estratégias de reaproveitamento de óleo usado para reduzir o impacto ambiental.

Uma análise de sensibilidade é feita considerando diferentes fatores de emissão de gases com efeito estufa para a geração de eletricidade e gás natural, bem como um processo diferente de produção de biocombustível. Notavelmente, quando a eletricidade é produzida de forma mais sustentável, com emissões quase zero até 2050, os resultados demonstram uma alteração significativa nas emissões, nomeadamente nos cenários I e III, pese embora haja uma diminuição no primeiro e um aumento no segundo continuando a ser preferivel, do ponto de vista do aquecimento global, não encaminhar o óleo para as estações de tratamento de águas residuais, aproveitando o para bioprodutos.

Palavras-chave: Fluxo de óleo usado Europeu, tratamento de águas residuais, produção de biodiesel, produção de velas de parafina, potencial de aquecimento global.

Acronyms and Abbreviations

BAU	Business As Usual
CO_2e/ CO_2eq	Carbon Dioxide Equivalent
EU	European Union
EU27	European Union of 27 Countries since 2020
FAME	Fatty Acid Methyl Ester
FOG	Fat, Oils and Grease
FU	Functional Unit
GHG	Greenhouse Gases
GWP	Global Warming Potential
JRC	Joint Research Centre of the European Commission
LCA	Life Cycle Assessment
LHV	Lower Heating Value
RED II	Renewable Energy Directive 2nd Version
UCO	Used Cooking Oil
UN	United Nations
UK	United Kingdom
WTW	Well-to-Wheels
WWTP	Wastewater Treatment Plant

ρ	Density
m	Mass
V	Volume

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1 Introduction

1.1 Framework

On 2015, the Member States of the United Nations (UN) adopted the 2030 Agenda for Sustainable Development[1]with goals interlinked and indivisible to ensure the end of poverty, the protection of the environment and prosperity for all. The Agenda consists of 17 Sustainable Development Goals (SDGs), each with a specific target to be achieved during a 15-year period, **Figure 1.1**.

Figure 1.1 The Sustainable Development Goals. [2]

This work is a life cycle assessment of domestic waste oils, therefore is encompassed by the scope of two of the SDGs, goal 12 – Responsible Consumption and Production, which urges the reduction of our ecological footprint by efficient management of resources while encouraging re-use, recycling and reduce waste at all levels of consumption, and goal 13 – Climate Action, which intends to reduce greenhouse gas emissions in order to limit the increase in global mean temperature to 1.5 degrees Celsius, **Figure 1.2**.

(**a**) (**b**)

Figure 1.2 The Sustainable Development Goals. a) SDG 12; b) SDG 13. [2]

1.2 Goals and Research Questions

In the context of a circular economy and sustainable communities, the waste management is crucial, regarding a responsible consumption, being domestic waste of important consideration. During this work we will focus on domestic waste oils which represent a problem regarding the contamination of ecosystems and the water management cycle [3], while having feasible treatment capacity, with the re-refining as well as fuel preparation, because of that, the European Commission has established a waste framework directive for waste oils for Member States [4].

This work focuses on a life cycle assessment (LCA) of recycling waste oils from domestic usage, studying the environmental aspects and potential impacts throughout its lifespan, using the International Standard principles and framework (ISO 14040 and ISO 14044) [5,6]. The objective is to understand the business-as-usual destination of domestic used cooking oils (UCO) in Europe and estimate their environmental impacts in terms of greenhouse gas (GHG) emissions.

This dissertation intends to answer the following research questions: which are the impacts of the disposal of domestic used cooking oils on the water management cycle? Is the recycling of domestic used cooking oils better than their disposal to wastewater treatment services? How to assess the recycling of domestic used cooking oils to produce different bioproducts, using global warming potential environmental indicators?

2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a standardized methodology that studies the environmental aspects and potential impacts associated with a product or service, throughout its lifespan. A LCA approach can assist in identifying opportunities, selecting relevant indicators, in the overall decision making of industries, governmental or non-governmental organizations in terms of environmental aspects and performance of products/services at different points of their life cycle. LCA is one of several environmental management techniques and does not encompass the economic or social aspects of a product. The International Standard (**ISO 14040** and **ISO 14044**) [5,6] provides principles and frameworks as some methodological requirements when conducting a LCA study.

LCA methodology consists of definition of goal and scope, inventory establishment and analysis, impact assessment and interpretation of the results of each phase, represented in **Figure 2.1**. This framework is detailed in the following chapters.

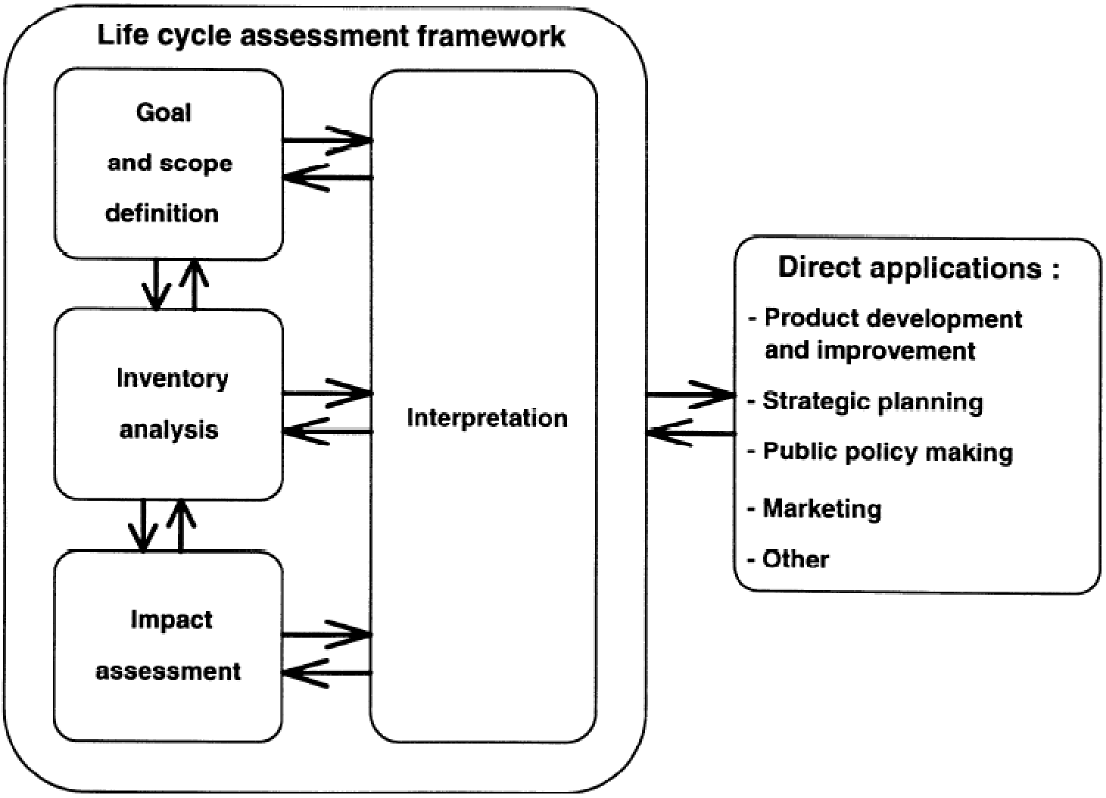

Figure 2.1 Phases and applications of an LCA. [6]

2.1 Goal and Scope Definition

The goal of an LCA must be clearly identified and consistent with the intended application, reason for the study and the target audience to whom the results are to be communicated.

The scope of an LCA study is defined clearly describing the functions of the products systems, the functional unit, the systems to consider and their boundaries, allocation procedures, types of impacts and respective interpretations, data requirements and quality, assumptions and limitations. LCA is an iterative environmental management technique, therefore, the scope of the study can be modified while its being conducted as more information is gathered.

The function of the products systems has to be well defined. If products are to be compared, it is mandatory to describe the different functionalities of each one.

The functional unit is a reference flow to which inputs and outputs are related and ensure the comparability of the LCA results, which is particularly critical when different systems are being assessed guaranteeing that the comparisons are made on common ground.

The system boundaries determine which unit processes are taken into account within the LCA. Several factors influence the systems boundaries, such as the intended application of the study, assumptions made, cut-off criteria, data constraints, and the target audience. Such criteria have to be identified and justified in the scope of the study. The systems should be modelled so that the inputs and outputs at its boundaries are elementary flows.

Allocation procedures is the segmentation and relation of inputs and outputs of a process to the relevant products and by-products and can be done using different rules such as mass, energy, and economic allocations, or any other type of rule when needed. However, since none of these methods are a general solution, ISO standards states that allocations should be avoided whenever possible.

It is required to identify the environmental impact categories our study will consider. There are impacts that are input-related, such as resource depletion and land use, and impacts that are output focused, such as global warming, ozone depletion, terrestrial and aquatic toxicity, photo-oxidant formation, acidification, and eutrophication.

2.2 Inventory

Inventory analysis comprehends data collection and calculation procedures to identify relevant inputs and outputs of a system. This information may include the use of resources and emissions to air, water and land. Different interpretations can be drawn from the same data, depending on the goals and scope of the LCA study and since conducing an inventory analysis is an iterative process, new data requirements or limitations can be identified, changing the information collection procedure so that the goals of the study are still met. The qualitative and quantitative data must be obtained for each process that is included within the system boundaries.

There are some significant calculation procedures when considering:

- Allocations needed when working with different systems involving multiple products. The materials and energy flow as well as environmental emissions must be allocated to the different by-products, according to a documented and justified procedure.
- Energy flow should consider the different fuels and energy sources used, the efficiency of conversion and distribution of energy flow, identifying the inputs and outputs associated with the generation and use of energy.

2.3 Impact Assessment

The impact assessment phase of LCA is meant for evaluating the relevance of potential environmental impacts using the results of the previous inventory analysis. This process involves associating inventory data with specific environmental impacts, where transparency is crucial to ensure that assumptions are clearly described and reported. This phase should include the assigning of inventory data to the impact categories (classification), modelling of the inventory information within impact categories (characterization), and aggregation of results when meaningful (weighting).

2.4 Interpretation

The interpretation phase of the LCA is where we combine the deductions taken from the inventory analysis and the impact assessment to take form of conclusions and recommendations to decision-makers, that is consistent with the goal and scope of the study. The interpretation may involve reviewing and revising the scope of the LCA, as well as the nature and information quality of the data collected with the defined goal.

3 Used Cooking Oil

3.1 Generation

Used Cooking Oil (UCO), also referred to as fat, oil, and grease (FOG), is a widespread by-product originating from diverse food processing sites, food service establishments, and domestic kitchens. FOG encompasses a range of compounds, primarily comprising fatty acids, triacylglycerols, and lipid-soluble hydrocarbons. This waste stream is not limited to the oil used in fryers but includes a wide array of food-related sources, from salad dressings to dairy products [7].

The generation of UCO varies across dietary regimes as global diets shift towards a more westernized pattern, UCO consumption has been increasing globally. This increase in UCO generation has significant implications for waste management and sustainability efforts, as detailed below.

At the domestic scale within the EU27 and the UK, an estimated annual production of approximately 0.8 million tons of UCO are reported. However, a mere 5.6% of this substantial UCO output undergoes systematic collection and subjected to proper disposal or recycling, with the majority primarily directed toward biofuel production [8]. This low collection rate of domestic UCO presents environmental challenges and hampers the circular economy of waste materials, despite its high energetic value.

There are some efforts regarding the collection of UCO at all levels of generation, the most famous one being HORECA, which focuses on responsible UCO disposal and collection at an industrial level, utilizing the substantial quantities of UCO from restaurants, hotels and cafes, primarily generated from frying activities. At the household level there are a few European projects, such as a European initiative (RecOil Project) involving Belgium, Denmark, Greece, Italy, Portugal and Spain, estimated that it was possible to collect up to 2.5 L of UCO per household per month [7].

Governmental regulations and incentives have played a crucial role in driving UCO collection, while several countries have enforced regulations related to UCO disposal, or incentives, such as tax breaks and subsidies, they mainly focus on the industrial sector of UCO generation. This focus aligns with the fact that industrial sources tend to produce larger quantities of UCO, leading to more significant environmental impacts.

While these initiatives and regulations have made substantial progress, there is still room for improvement, especially concerning the enhancement of efficient UCO collection systems at the household level. Achieving comprehensive UCO recycling and responsible disposal remains a global challenge, carrying significant environmental and economic implications.

3.2 Challenges

Improper UCO disposal raises substantial environmental and waste management challenges, as it can contaminate ecosystems, particularly harming aquatic life and water bodies. Additionally, when UCO enters sewer systems, it disrupts the water management cycle.

Accumulations of FOG waste, including UCO, within sewer systems present substantial challenges. When UCO combines with other sewage components, it forms obstructions within sewer networks, resulting in reduced sewer diameters and frequent blockages. These issues are particularly pronounced in combined sewer systems, often leading to floods and overflows. Clearing such blockages necessitates mechanical sewage maintenance and carries the risk of releasing pathogens into ecosystems. In the UK, for instance, there are over 25 000 sewer blockage events annually, with approximately 50 to 75% attributed to FOG and UCO deposition[9,10].

Moreover, the disposal of substantial quantities of UCO into sewer systems exacerbates the problem. Separating UCO from wastewater at Wastewater Treatment Plants (WWTP) introduces added energy and economic costs. WWTPs are vital components of infrastructure, requiring efficiency and financial sustainability. Approximately 1 to 2% of a country's total energy consumption is allocated to the WWTPs, with energy costs forming a significant part of their operational expenses. In Europe, WWTP consume around 24 747 GWh/year, equivalent to roughly 0.8% of the EU27 and UK total electricity generation in 2015 [11].

Furthermore, the operational costs of WWTP surge, with inappropriate UCO disposal incurring energy and economic costs of approximately 3 kWh/kg of UCO and 0.45 €/kg of UCO [12]. Underlying the importance of responsible UCO disposal practises, not only for environmental reasons but also for economic efficiency.

UCO is characterized by its high energetic value, making it a valuable energy resource. This high energetic content offers an opportunity for reducing waste and fostering a circular economy but can also serve as a foundation for sustainable energy solutions.

3.3 Potential

UCO represents a valuable resource with a multitude of applications. Primarily, it finds use in biodiesel production, serves as a nutritious supplement in animal feed, plays a role in the oleochemical industry, and can be utilized for heat and energy generation.

In the face of increasing global dependence on petroleum due to rising living standards and greater demand for transportation and petrochemicals, there is a growing need for alternative and sustainable fuel sources. Biofuels, such as biodiesel, offer a promising solution to enhance energy security while mitigating greenhouse gas (GHG) emissions and reducing urban air pollutants.

Biodiesel, comprised of methyl and ethyl esters of fatty acids (FAME), can be synthesized from various lipid sources, including vegetable oils and animal fats, through the process of transesterification. This chemical reaction involves lipids reacting with alcohol in the presence of a catalyst, yielding biodiesel and glycerol as a byproduct. Typically, two types of oils are utilized: edible, such as coconut oil, soybean, and rapeseed, and non-edible, like algae and waste oils, as raw materials for biodiesel production.

Nevertheless, biodiesel production faces substantial challenges, including competition between food and fuel resources, as well as environmental concerns related to land use and deforestation. To address these issues, the European Commission introduced the Renewable Energy Directive II (RED II), which seeks to promote advanced biofuels and restrict the use of biofuels derived from food and feed crops.

Biodiesel stands as a sustainable alternative to traditional fossil fuels, characterized by high biodegradability and minimal ecotoxicity. It generates lower carbon emissions when burned and when sourced from renewable material, contributes positively to climate change mitigation as part of the short carbon cycle. UCO, despite variations in chemical compositions and physical properties based on collection sources, can typically be processed through heating and filtration to remove suspended matter, yielding the raw material for biodiesel production. To qualify as a fuel, biodiesel must meet strict criteria outlined by the European Standard (EN14214), ensuring its purity exceeds 96.5%.

UCO also serves as a cost-effective substitute for virgin oil in animal feed due to its high nutritional value. However, strict safety protocols are essential due to the potential presence of harmful substances and prior exposure to food. In response to the mad cow disease outbreak in the 90's, the EU has imposed a complete ban on using UCO in animal feed. This ban was enacted because the disease was linked to the practice of feeding cattle remains to other cattle, creating a similar cycle. In contrast, countries like China and the United States have continued to employ UCO for this purpose.

Furthermore, UCO can be utilized in various biological and chemical processes. It can undergo chemical transformation to produce bio lubricants, greases, resins, polymers, and soap. Additionally, it can be employed to generate hydrogen gas, biogas, or be burned directly for energy generation.

Only a few companies have actively promoted the utilization of UCO in scented candle production. Notable examples include The Greatest Candle™, OilRight™, and OiLilin™, who initiated the practice of upcycling UCO for candle manufacturing in the early 2010s.

4 Literature Review

The purpose of this literature review is to search scientific works within the scope of this dissertation that will be related, compared, and somehow discussed with to the results obtained in section 6.

With that goal, it is resorted to a systematic search using a search engine, Web of Science^{TM}, which is a platform that allows consultation of research literature by applying different queries, in order to refine results to get closer to this dissertation goals. On the **Table 4.1** we represent the queries used, as well as the number of results for each one, which allows us to understand that with a more specific query we identify the scientific research truly relevant to our work.

Table 4.1 Search queries on Web of Science and respective results.

	Query	Results
I	(LCA or “Life cycle a*” or “carbon footprint”) and (UCO or “cooking oil”)	255
II	(LCA or “Life cycle a*” or “carbon footprint”) and “candle”	8
III	(LCA or “Life cycle a*” or “carbon footprint”) and (UCO or “cooking oil”) and “candle”	2

The **Figure 4.1** illustrates the publication years of each article for the **Query I**, **II**, and **III**, which allows us to conclude that the research area for the Life Cycle Assessment of Used Cooking Oil has been progressively increasing during the last 10 years, while its usage for bioproducts, such as wax and candles is a relatively recent topic. The **Figure 4.2** represents the country/region of the world where such research is being done.

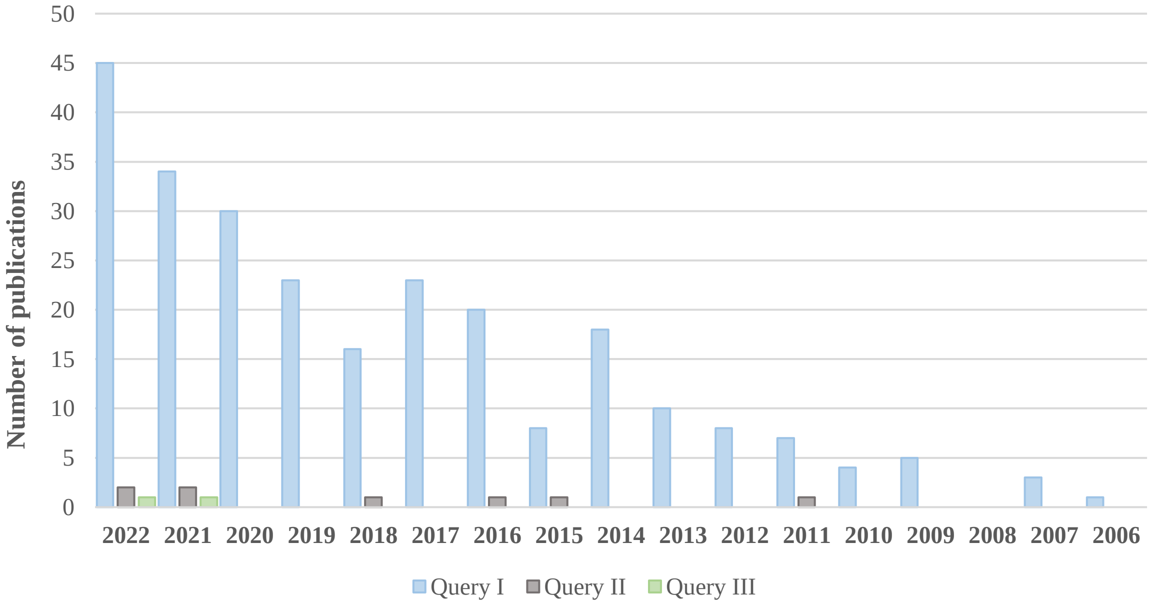

Figure 4.1 Publication years for the queries. [13]

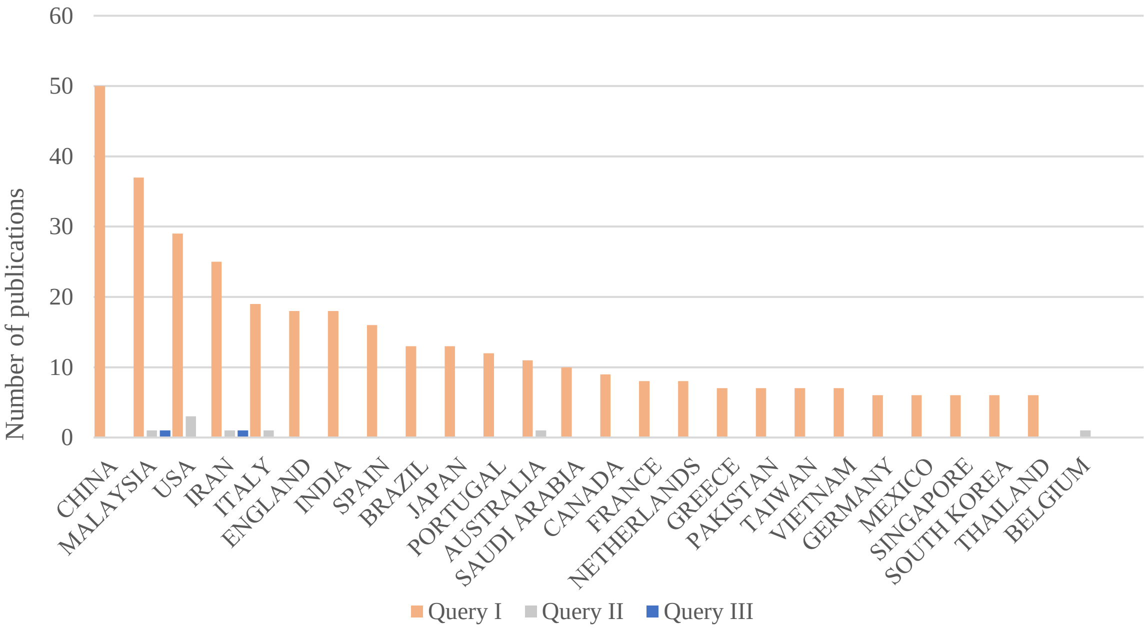

Figure 4.2 Country/region of research for the queries. [13]

From **Query I**, two articles were selected to obtain biodiesel inventories, processes, and flowcharts to later compare to this dissertation results.

The article regarding the LCA of biodiesel production [14], simulates different processes for biodiesel production from vegetable oils and UCO. Focusing on the biodiesel from UCO, the main difference for the two methods of production is on the catalyst used, one using CaO, while the other using NaOH. The inventory for both methods are listed below, on **Table 4.2** and **Table 4.3**.

Table 4.2 Inventory of energy/materials for biodiesel production - NaOH process. [14]

Feed	Products [kg/h]	Waste [kg/h]
UCO = 849.270 [kg/h]	Biodiesel = 859.489	Water + methanol = 32.873
Methanol = 176.232 [kg/h]	Glycerol = 87.400	Na_3PO_4 = 3.835
H_2SO_4 = 7.846 [kg/h]		H_2SO_4 + glycerol + methanol = 73.783
Glycerol = 13.881 [kg/h]		
NaOH = 2.800 [kg/h]		
H_3PO_4 = 2.293 [kg/h]		
Steam = 864.20 [kJ/s]		
Electricity = 2.283 [kW]		

Table 4.3 Inventory of energy/materials for biodiesel production - CaO process. [14]

Feed	Products [kg/h]	Waste [kg/h]
UCO = 885.449 [kg/h]	Biodiesel = 897.969	Water + methanol = 92.640
Methanol = 192.253 [kg/h]	Glycerol = 92.200	$CaSO_42H_2O$ = 137.696
H_2SO_4 = 78.464 [kg/h]		
CaO = 44.862 [kg/h]		
Steam = 2105.620 [kJ/s]		
Electricity = 2.138 [kW]		

The other article selected from the systematic search compares two possibilities for UCO energy reusage, for cogeneration and to generate biodiesel, in terms of Global Warming Potential and Cumulative Exergy Consumption [15]. The article inventories energy/materials due to container washing and characterizes the transportation of the raw materials, **Table 4.4**, however for the processes they only quantify the materials needed to generate biodiesel from 1000 kg of UCO, **Table 4.5**.

Table 4.4 Inventory of container washing and transportation phase. [15]

Feed	Products	Transportation
UCO = 1000.0 [kg] Water = 48.8 [l] Electricity – containers washing = 6.3 [kWh]	UCO = 1000.0 [kg] Wastewater = 48.8 [l]	Transport = 200 [tkm]

Table 4.5 Inventory of materials for biodiesel production in acid-catalyzed process. [15]

Feed	Products	Waste
UCO = 1000.0 [kg]	Biodiesel (99% purity) = 1014.7 [kg]	Water + methanol = 103.7 [kg]
Methanol = 210.6 [kg]	Glycerol (96% purity) = 108.3 [kg]	$CaSO_4 + H_2O$ = 220.0 [kg]
H_2SO_4 = 150.0 [kg] CaO = 85.7 [kg]		

Since the more specific results of the systematic search don’t lead to articles useful for the other bioproduct, candle wax there was a need to use the Google^{TM} search engine to find more research studies in the area.

From this research, it was selected a thesis regarding the LCA of different types of candles[16] and only consider the ones made from wax, to later compare with the dissertation results. It were identified the inventories for the characteristics of each candle, such as weight and burning time, **Table 4.6**, as well as the resources consumption and emissions per burning hour, **Table 4.7**.

Table 4.6 Characteristics of each candle. [16]

	Candle 1	Candle 2	Candle 3	Candle 4	Candle 5
Burning time [h]	165	98	72	120	72
Wax [kg/100 units]	57.633	43.724	28.901	21.489	14.2

Table 4.7 Inventory results per burning hours for each candle. [16]

Input flows	Candle 1	Candle 2	Candle 3	Candle 4	Candle 5
Energy resources [MJ]	1.3863E-10	1.0970-14	8.6645E-15	1.37E-16	3.7719E-15
Material resources [kg]	4.9627E-21	7.4233E-18	4.9627E-18	3.30E-27	1.0847E-17
Output flows					
Emissions to air [kg]	1.2441E-14	1.6292E-14	1.2441E-14	2.4357E-15	9.5240E-15

It was also selected an article concerning the synthesis and properties of wax based on UCO[17]. The UCO was epoxidized them mixed with stearic acid (SA) or cocoa butter substitute (CBS), with the following synthesis recipes, **Table 4.8**. Characteristics such as melting point and burning time were also characterized and represented, **Table 4.9**.

Table 4.8 Synthesis recipe of wax based on UCO. [17]

Sample	E-UCO [g]	SA [g]	CBS [g]
UCO	-	-	-
E-UCO	160	-	-
A1	120	40	-
A2	80	80	-
A3	40	120	-
SA	-	160	-
B1	120	-	40
B2	80	-	80
B3	40	-	120
CBS	-	-	160

Table 4.9 Characteristics of wax based on UCO. [17]

Sample	Initial melting [°C]	Complete melting [°C]	Burning Time [min]
UCO	34	37	-
E-UCO	38	41	42±4
A1	41	44	169±5
A2	46	49	227±8
A3	54	56	335±10
SA	57	58	615±13
B1	35	40	90±4
B2	33	38	49±5
B3	34	39	83±6
CBS	46	50	103±7

A technical report from Joint Research Centre of the European Commission (JRC) that evaluates the Well-to-Wheels (WTW) energy use and GHG emissions for different energy sources and fuels, namely electricity, natural gas and biodiesel [18], was also selected to retrieve values for production and combustion. For natural gas, the emission factor from combustion is 56,1 gCO_2e/MJ, while biodiesel from UCO, using glycerine to internal biogas generation and consumption is represented in **Table 4.10**.

Table 4.10 Emission factors for natural gas combustion and biodiesel production [18].

		Emission Factor (gCO_2e/MJ)
Natural Gas	Combustion	56.1
Biodiesel from UCO	Biodiesel Production	7.2

5 Materials and Methods

For this dissertation it was available THE GREATEST CANDLE^{TM} do-it-yourself (DIY) kit [19], offered by the company; and energy consumption meter, 2 domes equipped with Arduino temperature, humidity, pressure and carbon dioxide sensors and paraffin conventional candles, for the experimental procedure of testing the performance of each wax.

The LCA approach described in section 3 was followed to the business as usual (BAU) European flow of UCO, Scenario I, and this BAU compared with alternative UCO destinations as represented in **Figure 5.1**. In this LCA we want to compare different scenarios for the domestic UCO destination, since the products have different functionalities, our functional unit (FU) will relate to input instead of the more typical approach of the systems output. The FU of our system is 854 000 tons of UCO. The LCA quantifies all materials and energy used and their environmental footprint during manufacturing, utilization and use of each pathway, focusing only on its global warming potential. During this LCA, it wasn't accounted the transportation phase or any construction materials e.g., related to pipelines, biodiesel factory, etc.

The goal of this study is to compare different destinations for the domestic UCO in the European context: wastewater treatment plants, biofuel or waxes and candles, for that we use different scenarios that will be further explained.

For domestic EU27+UK UCO consumption, both collected quantities and potential resources, we followed the GREENEA estimations, from the European Waste-to-Advanced Biofuels Association [8], being the total collectable resource of 854 000 metric tons, while the collected domestic UCO represents no more than 5.6%, with 47 736 metric tons, of those being mainly used being used for biodiesel production. This data is in accordance with another source used that estimates in 2019, the EU27+UK had the domestic UCO collection potential of around 700 000 to 1 200 000 metric tons [20].

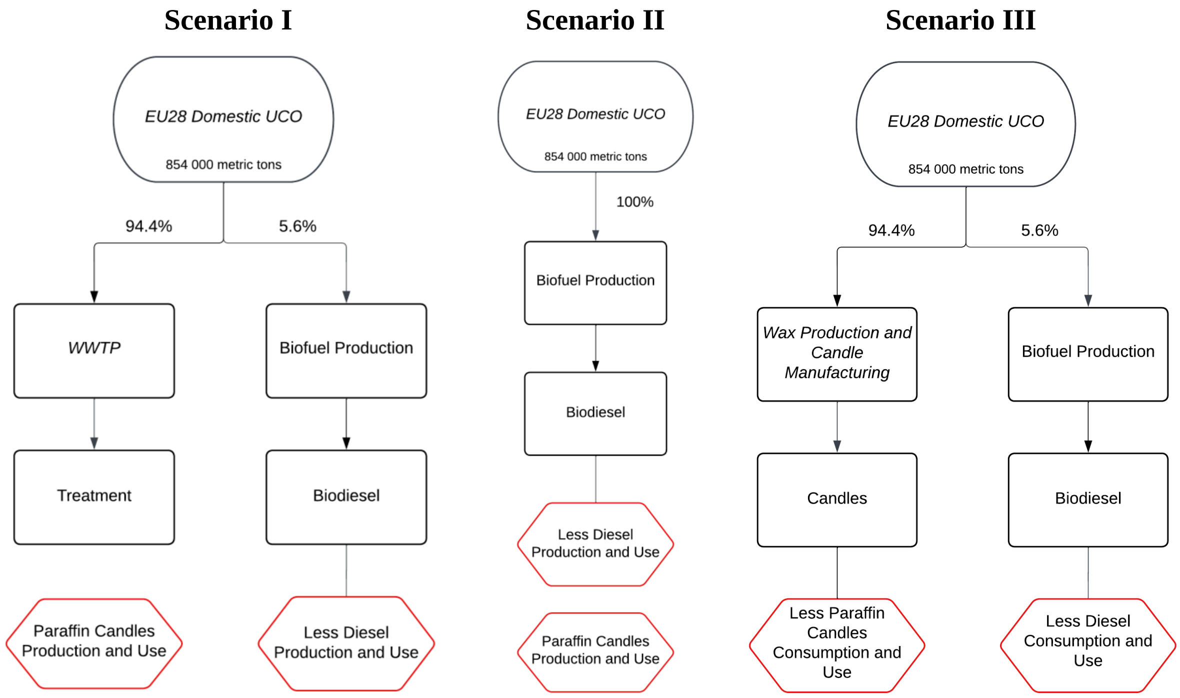

Figure 5.1 LCA scenarios flowcharts.

The amount of paraffin candles that can be replaced by UCO candles needs to perform equally, i.e., if a candle is expected to burn a certain amount of time this amount has to be kept for candle alternatives even if it implies burning more quantity. To evaluate differences in combustion time and CO_2 emissions derived from burning an experimental analysis of paraffin and UCO candles was undertaken (see Annex B). The same reasoning is applied to diesel fuel, the alternative biodiesel has to provide the same amount of energy even if it implies burning more quantity.

During this LCA, we employed various types of emission factors, each contributing to a comprehensive assessment of the environmental impact across different scenarios. The emission factors for electricity consumption were based on the average from all electricity production in the EU27 for the three most recent available years of data (2019-2021) [21], resulting in 253 gCO_2e/kWh. Additionally, for natural gas, we utilized the emission factor from direct combustion, amounting to 56.1 gCO_2e/MJ [18].

Furthermore, emission factors for materials used in biodiesel production and production of candles were obtained from a common source [22], ensuring accurate accounting of their environmental implications. The emissions from direct combustion for conventional diesel were measured at 73.2 gCO_2e/MJ [18]. We considered emissions from the refining process of crude oil diesel, referencing the JRC WTW report [18], which yielded and emission factor of 7.2 gCO_2e/MJ.

For the paraffin candles, according to a study [23], the emissions associated with the production of paraffin wax amount to 60 gCO_2e per 100 g of paraffin. This factor reflects the carbon footprint generated during the manufacturing process of paraffin wax. For the cotton wick, the emissions generated for the production of cotton was 1000 gCO_2e/kg of cotton [24].

Considering the combustion of paraffin wax, which is a subproduct of crude oil, we can derive its chemical equation as C_nH_{2n+2}, with n greater than 20. From this equation, we deduce the massic relation between CO_2 and paraffin, which is approximately 3.14 gCO_2e per gram of paraffin wax. The combustion of bioproducts derived from UCO are considered biogenic, therefore not accounting their emissions. This emission factors are summarized in **Table 5.1**.

Table 5.1 Emission factors for biodiesel production, diesel refining and usage, and candles production and use.

Emission Factors	**Energy**	Electricity (gCO_2e/kWh)	253
		Natural Gas (gCO_2e/MJ)	56.1
	Materials (gCO_2e/kg)	Methanol	300
		Sulphuric Acid	140
		NaOH	1120
		H_3PO_4	1450
		Aluminium	8140
		Cotton	1000
		Paraffin Wax	600
	Direct Combustion	Diesel (gCO_2e/MJ)	73.2
		Paraffin Wax (gCO_2e/g)	3.14
	Refining (gCO_2e/MJ)	Diesel	7.2

5.1 Experimental Analysis of Candles

To understand and better characterize the performance of a UCO-based wax versus a conventional paraffin-based one, it was determined experimentally, according to the procedure indicated in Annex B. This experimental procedure it was useful to validate UCO density from literature data, to validate CO_2 emissions from burning the paraffin-based candles, and to have a comparison of burning quantity of both types of wax. For the experiment the components were assembled to characterize a standard candle: wax, body and wick.

The density of the UCO was determined using UCO from three different households with each having a separate usage pattern, using the following equation and was compared with the literature, to valid the literature value of 0.91 kg/L [20].

$$\rho = \frac{m}{V}\ [kg/m^3] \tag{1}$$

To compare the characteristics of a paraffin-based and UCO-based waxes, we conducted a detailed analysis using various sensors to measure temporal trends of properties like temperature, pressure, humidity, and CO_2 concentration within a controlled environment. Additionally, it was assessed combustion performance by measuring the weight of each candle before and after one hour of burning in the same environment.

To ensure consistency in the experiment, it was standardized the amounts of each material used to produce each candle. Regular candles with paraffin wax, aluminium bodies, and cotton wicks were employed as a baseline. For UCO-based wax production, we utilized a brennenstuhl^{TM} power monitor to measure instant power values and determine electricity consumption during wax production.

During the experiment, we estimated the composition of a standard candle by characterizing the quantities of wax, wick, and body for all types of candle, along with the energy required to produce a homemade UCO candle. For the UCO wax, we found that using 100 mL of UCO with THE GREATEST CANDLE^{TM} do-it-yourself (DIY) mix of 20 g yields approximately 110 g of wax. Additionally, for every 110 g of wax, we used 6 g of 100% cotton wick, and for every 45 g of wax, a standard aluminium base weighting 1.3 g was assumed.

For the analysis, it’s important to note that the DIY kit used for the UCO-based wax, Clove and Cinnamon Scented Kit, contains additional components with scents and potential unknown chemicals in the formulation. Due to the lack of information regarding these specific chemicals, we have not accounted for them in the LCA emissions factor.

The energy consumption from the UCO wax production, was measured using the previously mentioned power monitor, resulting in 0.2 kWh for the process of making 110 g of wax. These values have been standardized and summarized per 100 g of wax in **Table 5.2**, as represented below.

Table 5.2 Characterization of each candle components.

Component	Material	Ratio	Unit (/100 g of wax)
Raw Material*	UCO	90.91	mL
Wick	100% Cotton	5.45	g
Body	Aluminium	2.89	g
Energy*	Electricity	0.18	kWh

(* Only for UCO candles.)

Based on the measurements of UCO density and a thorough comparison with conventional wax, we estimated the quantities of UCO-based wax available for production and its associated energy consumption. Additionally, by understanding the conversion rate to paraffin wax, we calculated the precise quantity being replaced by this more sustainable alternative.

With a comprehensive understanding of the quantities of both types of wax, we can utilize the standardized measurements mentioned earlier, **Table 5.2** , to calculate the precise amounts of aluminium and cotton required for candle production.

5.2 LCA Inventory

The increase energy consumption from the wastewater treatment due to the presence of UCO is estimated to be 3 kWh/kg of UCO according to a recent European study [12].

For the biodiesel production, it was considered the inventory in **Table 4.2**, which accounts for the current most common process of biodiesel generation from UCO, using the NaOH process. The feedstock, products and wastes of this process are represented in **Figure 5.2**.

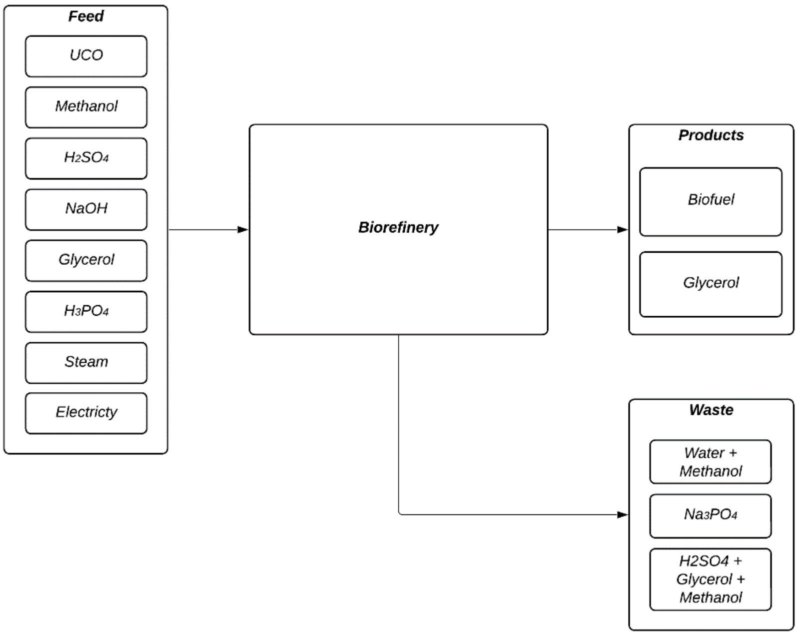

Figure 5.2 Inventory for refining biodiesel using the NaOH process.

This study assesses different paths for recycling domestic UCO using alternative scenarios of waste management and final product utility. There are three different scenarios established for this work, represented graphically using flowcharts.

Scenario I: This is the base scenario where we assess the current level of wastewater treatment of the domestic European UCO, accounting the energy expenditure surplus due to the presence of UCO in wastewaters, and assessing UCO present usage as feedstock to produce biodiesel, accounting the raw materials and energy consumption of the refining process, as well as the combustion emissions savings during its usage, from replacing a portion of the conventional crude oil as depicted in **Figure 5.3**. The production of paraffin candles and usage is also accounted, having an incremental value of the GHG emissions of our system. The inventory for this scenario is available in the Annex, **Table A.1**.

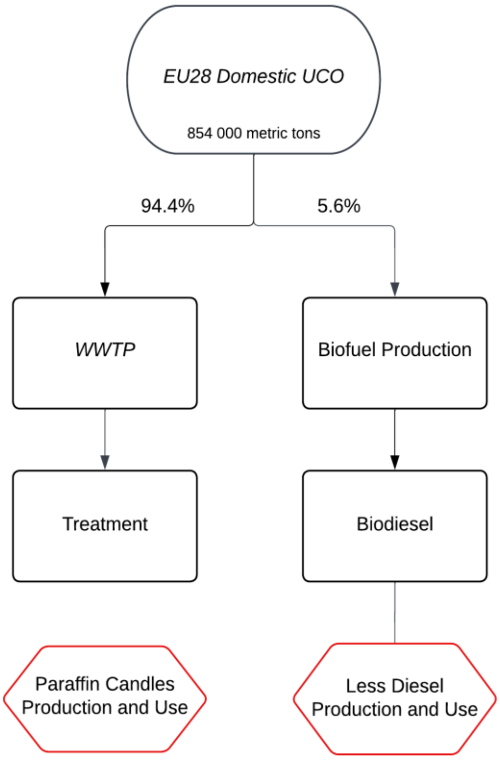

Figure 5.3 Scenario I flowchart.

Scenario II: Is an extension of the previous one, where we assume complete collection of the European domestic UCO, saving the WWTP energy consumption regarding the treatment of the UCO present in wastewaters, to only produce biodiesel, accounting raw materials, energy consumption of the refining process and the combustion emissions savings during its usage, **Figure 5.4**. The inventory is represented in **Table A.6**.

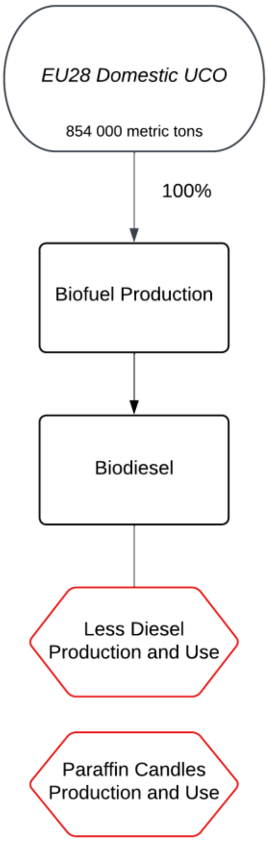

Figure 5.4 Scenario II flowchart.

Scenario III: In this scenario we assume that quantity of UCO disposed to WWTP in **Scenario I** is used to produce other bioproducts of incremented value, such as wax and candles, replacing the fossil-based conventional product that uses paraffin, yet still accounting raw materials needed to produce a standardized candle, such as cotton and aluminium. This scenario considers the fraction of UCO used to produce biodiesel mentioned in **Scenario I** and takes into account the replacement of products from conventional crude oil, such as paraffin candles and diesel, as well as the mitigation of UCO on the wastewater, represented in **Figure 5.5**. The inventory for this scenario is represented in **Table 5.3**.

Table 5.3 Material/energy inventory for Scenario III.

Biodiesel Production	**Feed**	Material (kg)	UCO	4.78E+07
			Methanol	9.92E+06
			H_2SO_4	4.42E+05
			NaOH	1.58E+05
			Glycerol	7.82E+05
			H_3PO_4	1.29E+05
		Energy	Electricity (kWh)	1.29E+05
			Steam (MJ)	1.75E+08
	Products	Material (kg)	Biodiesel	4.84E+07
			Glycerol	4.92E+06
	Waste	Material (kg)	Water + Methanol	1.85E+06
			Na_3PO_4	2.16E+05
			H_2SO_4 + Glycerol + Methanol	4.15E+06

Paraffin Candle Production	**Feed**	Material (kg)	Wax	4.94E+08
			Cotton	2.69E+07
			Aluminium	1.30E+05
UCO Candle Production	**Feed**	Material (kg)	UCO	8.06E+08
			Wax	6.37E+08
			Cotton	3.68E+07
			Aluminium	2.15E+06
		Energy (kWh)	Electricity	1.75E+05

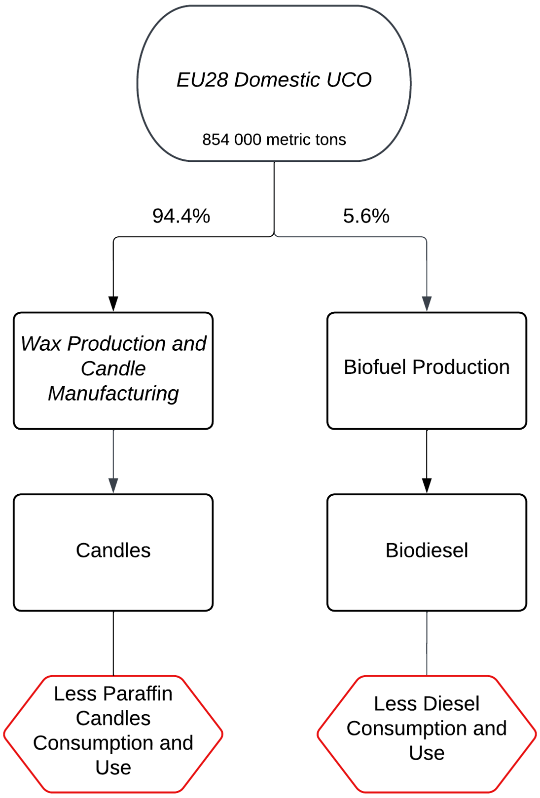

Figure 5.5 Scenario III flowchart.

The utilization of UCO presents various pathways with distinct products and functions, necessitating a comprehensive assessment of their environmental impacts. The primary products derived from UCO include wastewater treatment, aimed at cleaning domestic wastewater to mitigate the environmental challenges previously discussed, biodiesel production, serving as a fuel for combustion in motor vehicles, and wax/candles, primarily valued for their aesthetics and scent or for emergency lighting purposes. In this LCA, the functional unit chosen is the amount of UCO generated at a European scale, allowing for a standardized measurement across these diverse pathways.

The boundary of this LCA only focuses on direct emissions from the processes regarding the WWTP, biodiesel production and use, candle manufacturing and usage, as well as indirect emissions prevented from producing and consuming fossil-based products, such as paraffin and diesel. This LCA doesn’t account the transportation phase or any construction materials e.g., related to pipelines, factories, etc. This work focuses on the environmental impact category which is output-related, global warming, using the metric GWP 100 years from IPCC.

In this study, an energy allocation, which uses the lower heating values (LHV) of products, is adopted, following the guidelines endorsed by the European Commission, to allocate CO_2e emissions for each pathway within the process. For biodiesel produced from UCO, the LHV value of 37.2 was obtained from the JRC WTW report [18] while conventional diesel is assigned an LHV value of 43.1. Furthermore, the LHV value of glycerol obtained from fat residue is set at 14.82 MJ/kg [25]. These LHV values serve as critical benchmarks for evaluating the environmental impacts of the various products in our investigation.

5.3 Sensitivity Analysis

To ensure the reliability and comprehensiveness of the study, a sensitivity analysis was conducted to evaluate the impact of various inputs and parameters. Significant factors, such as the biodiesel production process with a different catalyst (CaO), alternative emissions factors, and boundaries for energy sources (electricity and natural gas), were systematically examined.

For the biodiesel production, we utilize the inventory in **Table 4.3**, which accounts for the process of biodiesel generation from UCO, using the alternative CaO process. **Figure 5.6** depicts the feedstock, products and waste streams involved in this process, while the comprehensive inventory for each scenario, regarding the biodiesel production, can be found in the Annex, in **Table A.9** and **Table A.10**.

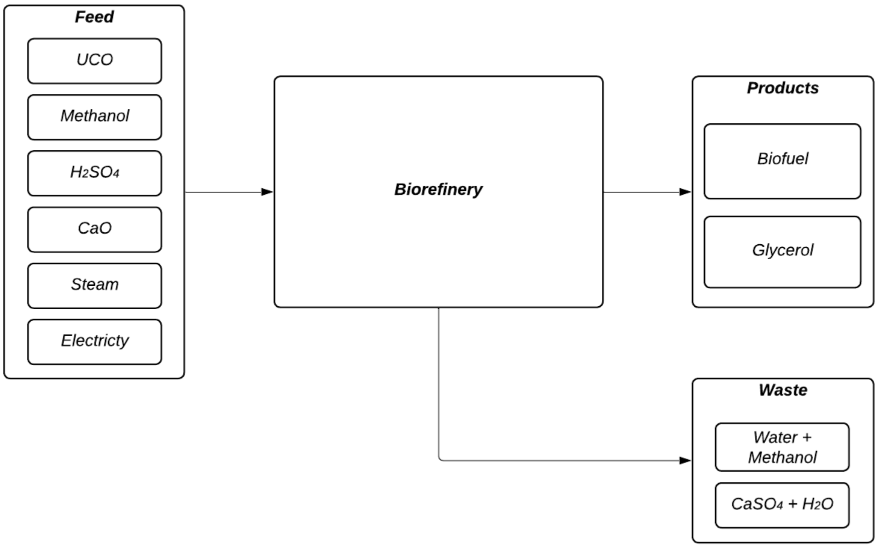

Figure 5.6 Inventory for refining biodiesel using the CaO process.

The sensitivity analysis also considered the utilization of various emission factors for different energy sources, such as electricity and natural gas.

For electricity, we incorporated JRC emission factors [18] for a medium voltage power plant in both 2016 and projected figures for 2030 of 106.3 gCO_2e/MJ and 73.0 gCO_2e/MJ, respectively (382.7 gCO_2e/kWh and 259.2 gCO_2e/kWh, respectively). This facilitated an assessment of potential changes in electricity generation practices and their implications on the environmental outcomes. Additionally, the study accounted for the EU27 goals for GHG emissions for electricity generation, set for the year 2050 of 0.0 gCO_2e/kWh. This evaluation provided insights into the pathways' alignment with long-term sustainability targets and their potential contributions to future energy policies.

For natural gas, we expanded our analysis by incorporating the JRC emission factors [18]. Rather than solely considering emissions from direct combustion, we took a thorough approach and included emissions associated with the entire lifecycle of natural gas, encompassing production, distribution, compression, and transportation, with a value of 67.6 gCO_2e/MJ.

A summary table was compiled, **Table 5.4**, summarizing the new emission factors used in this sensitivity analysis.

Table 5.4 Emission factors of energy sources for the sensitivity analysis.

Emission Factors	**Electricity** (gCO_2e/kWh)	JRC 2016	382.7
		JRC 2030 Projection	259.2
		EU27 2050 Goal	0.0
	Natural Gas (gCO_2e/MJ)	JRC 2016	67.6

By objectively analysing these variables, the study enhanced the robustness and credibility of the findings. The sensitivity analysis shed light on potential uncertainties, allowing for informed decision-making and recommendations for sustainable waste management and resource utilization.

6 Results

6.1 Experimental Analysis of Candles

Figure 6.1 represents the variability of the different measured UCO densities in kg/L, where we observed values from the range of 0.91 kg/L to 0.94 kg/L. The results are in agreement with existing literature, that refer to a typical UCO density of 0.91 kg/L [20]. For the following results we used the mean value of density obtained, of 0.922 kg/L.

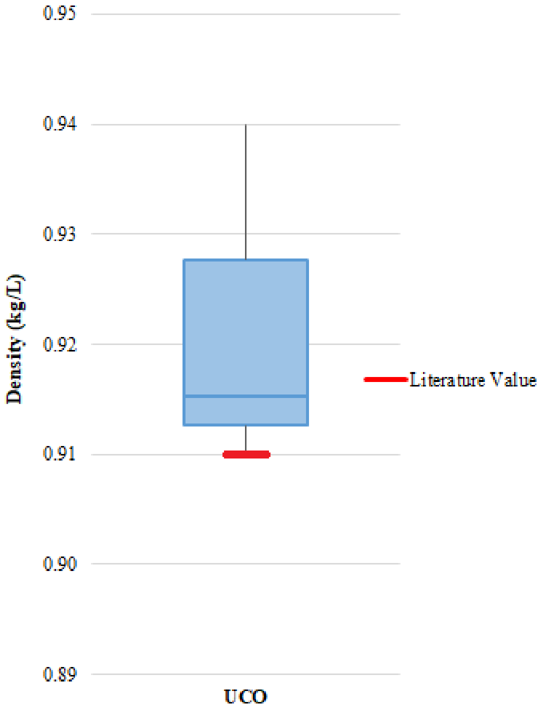

Figure 6.1 Household UCO density.

Figure 6.2 denotes the consumption of wax during its burning time using values in grams of wax per burning hour (g/h). For the UCO-based wax the results have a significantly higher fluctuation than the paraffin one, as shown below, the median being, 4.94 g/h and 3.83 g/h, respectively, which means that we will need more UCO wax to fulfil the paraffin wax demand by burning hour, the equivalence factor to use in LCA would be the substitution of 3.83 g of paraffin wax by 4.94 g of UCO wax.

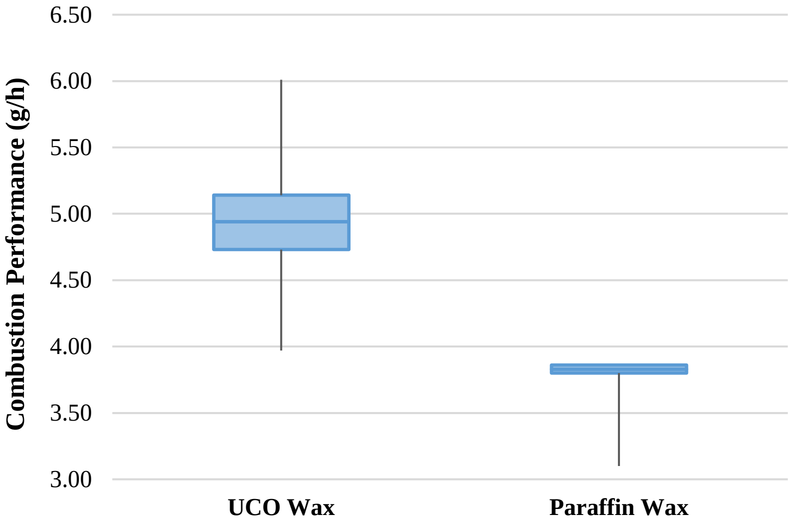

Figure 6.2 Combustion performance of each type of wax.

Figure 6.3 represents the experimental emission factor, kilogram of CO_2e per kilogram of burned paraffin wax, using infrared sensors of CO_2.The median value for the experimental emission factor being 1.82 $kgCO_2e$/kgparaffin with a standard deviation of 0.31 $kgCO_2e$/kgparaffin. The results differ from the literature value of 3.14 $kgCO_2e$/kgparaffin and can be explained by not using a 100% paraffin candle, since it was used commercial candles which are often times a mixture of paraffin and palm oil.

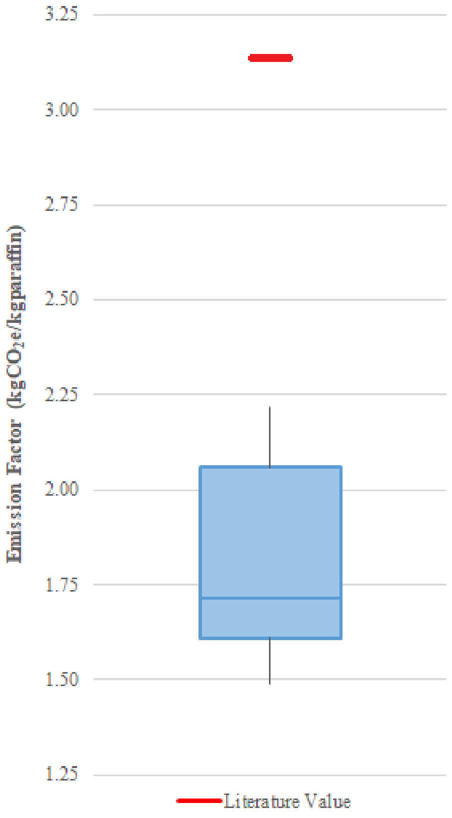

Figure 6.3 Experimental emission factor of paraffin wax.

6.2 GWP 100 Years Analysis

The results for the GWP 100 years emissions from **Scenario I**, **II**, and **III**, are represented in tonCO$_2$e for each portion taken into consideration for this LCA system, such as oil to WWTP and biodiesel production and use emissions, initially, then adding credits, both negative and positive, regarding emissions from diesel production, diesel use, paraffin candle production and usage, and UCO candle production and usage.

For **Scenario I**, since it is considering the disposal of UCO to the WWTP, as well as the biodiesel production, the GWP emissions from energy and material consumption are added, both having positive values for this scenario. The energy consumption due to the treatment of the wastewater with the presence of UCO amounts to 2 418.5 GWh/year, which represents 9.8% of the total energy consumption from the WWTP in the EU27 + UK, of 24 747 GWh/year. When adding to consideration the diesel savings from both, production and use, these take negative values, once they are emissions avoided indirectly from biodiesel production. The emissions from biodiesel refining from UCO amounts to 7.08 gCO$_2$e/MJ, being 7.2 gCO$_2$e/MJ, the standardized value as mentioned in **Table 4.10**. Finally, factoring the emissions from paraffin candles manufacturing and usage, these take a positive value, adding to the oil to WWTP. These results are summarized below, **Figure 6.4**, and their values represented in the **Annex**, **Table A.5**.

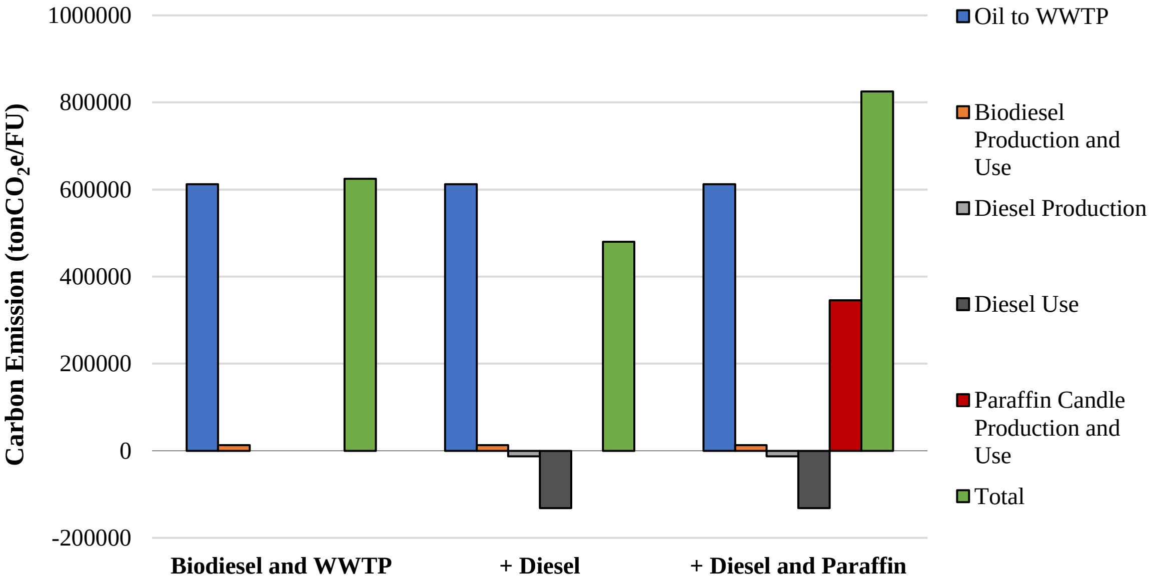

Figure 6.4 Net GWP emissions from each phase (**Scenario I**).

For **Scenario II**, the disposal of UCO to the WWTP is totally mitigated by using it entirely for biodiesel production, meaning the emissions portion of oil to WWTP is now being saved, justifying the negative value it now has. The emissions portion from biodiesel production and use, now accounts for a greater value, since we are producing more biofuel, as well as the emissions mitigated from diesel combustion and use. The paraffin candles manufacturing and usage stay unchanged in this scenario. These results are summarized below, **Figure 6.5** and their values in **Table A.6**.

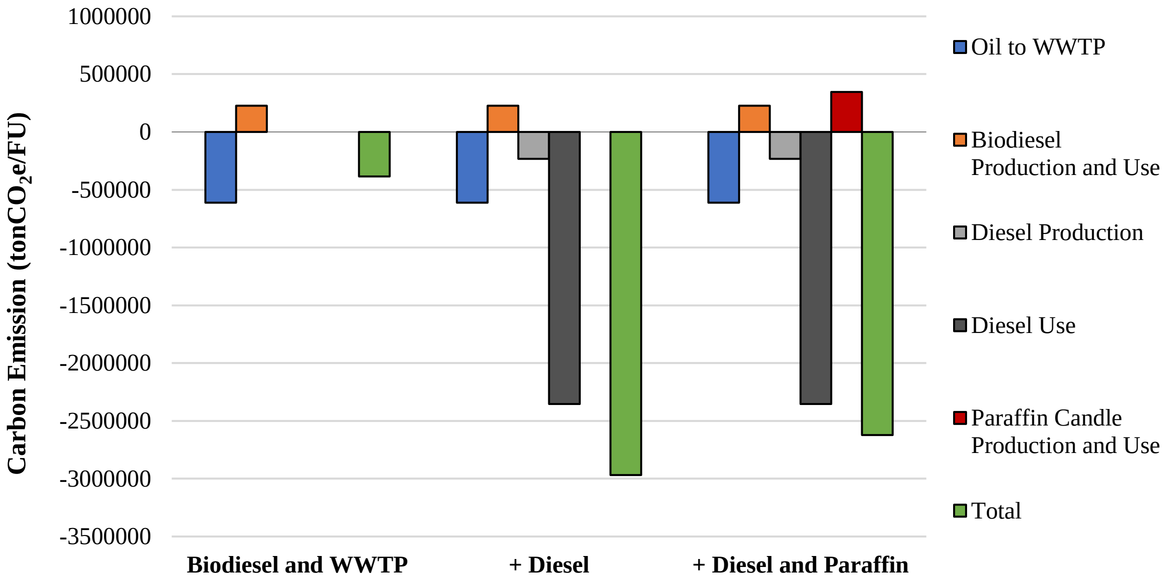

Figure 6.5 Net GWP emissions from each phase (**Scenario II**).

For **Scenario III**, the disposal of UCO to the WWTP is still mitigated like on the previous scenario. Regarding the biodiesel and diesel production and use phase, the values are the same as in **Scenario I**. This scenario adds the production of other bioproducts with the UCO, namely the production of wax and candles. Since we are replacing paraffin-based candles with UCO-based ones, the manufacturing and usage from paraffin candles are now deducted from our system, having a negative value, while the addition of UCO candles results in the increment of more emissions from energy and material consumption. The results are summed up in **Figure 6.6**, and their values in **Table A.7**.

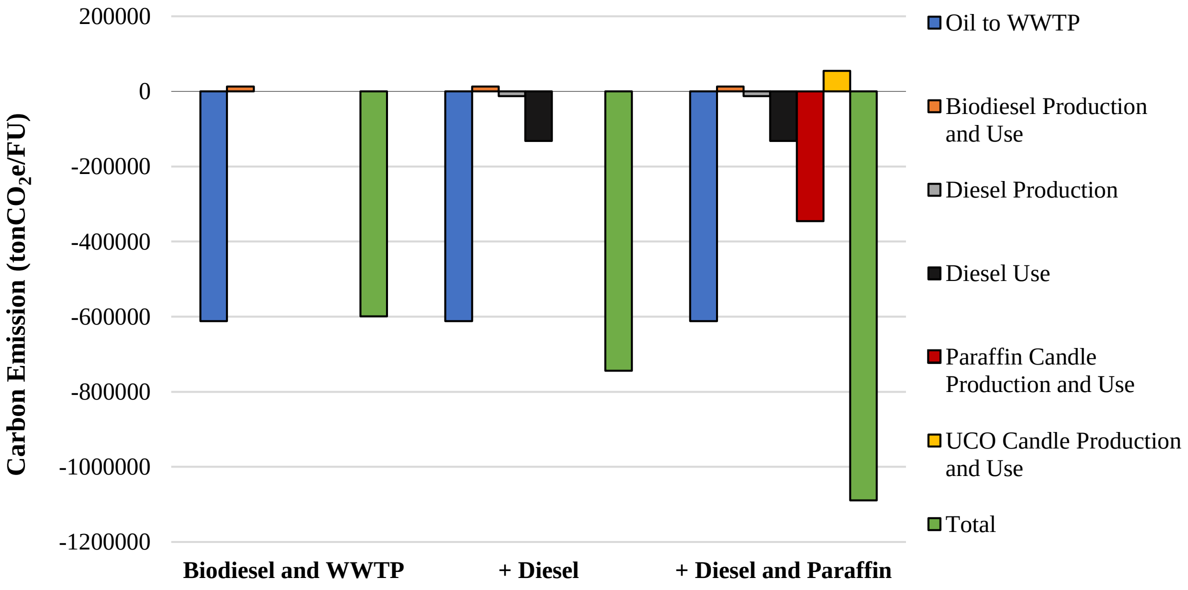

Figure 6.6 Net GWP emissions from each phase (**Scenario III**).

Finally, we compare the results from each scenario to understand which one is best at saving GWP 100 years emissions, on **Figure 6.7**.

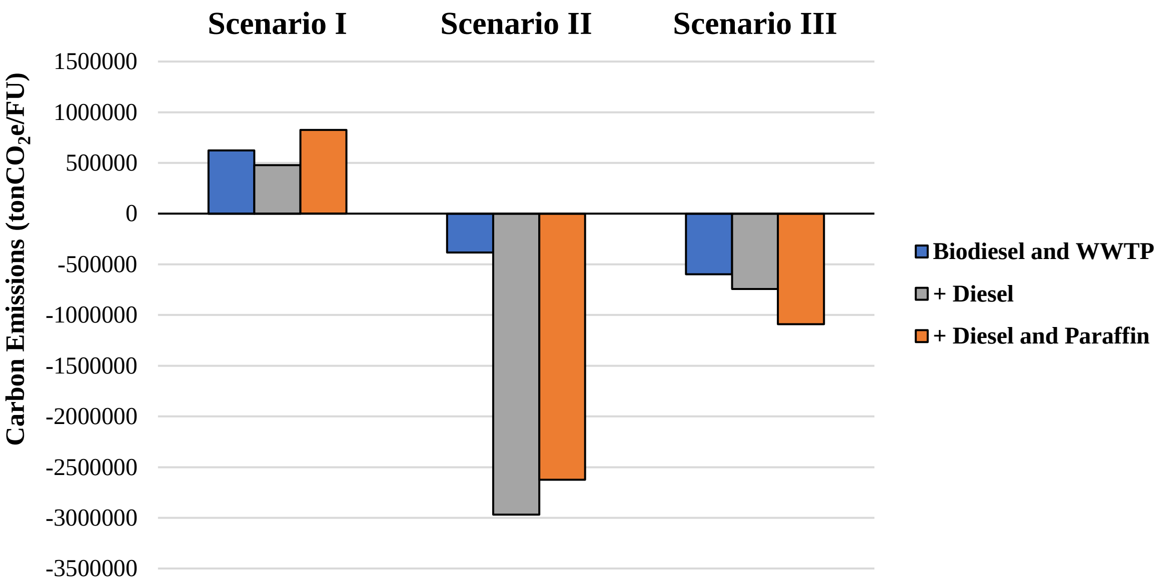

Figure 6.7 Net GWP emissions for different scenarios.

Since **Scenario I** is the current level of waste management in the EU, it's the only one with positive net GWP emissions. Even when considering emissions saved from producing and using biodiesel from UCO instead of the conventional diesel or increasing emissions by adding the paraffin candles consumption emissions to the scenario.

When considering the emissions from biodiesel refining and from the WWTP, **Scenario III** reduces them by 96% when compared it to the base scenario, while **Scenario II** only reduces 62%, because as previously explained, in this scenario we have a higher production of biodiesel resulting in higher emission from its production and not considering the diesel production and use.

When adding accountability from emissions saved from diesel refining and use, **Scenario II** has better results, decreasing emissions by 719% in comparison to the base scenario, by producing more biofuel, we mitigate more diesel consumption, while **Scenario III** reduces 255%.

Finally, considering all portions of this LCA, biodiesel production and use, WWTP, diesel production and use and paraffin candles production and use, **Scenario II** has the most reduction in GWP emissions, 418%, when compared to the base scenario, followed by **Scenario III** with a reduction of 232%.

6.3 Sensitivity Analysis

To understand and identify possible reliabilities from our work, a sensitivity analysis was produced, by changing significant inputs, such as the process of biodiesel production, using a different catalyst (CaO), applying different emission factors and respective boundaries for the energy sources (electricity and natural gas), working with the JRC emission factors[18] for a medium voltage power plant, in 2016 and 2030, and finally the EU 27 goals of GHG emissions for electricity generation for 2050.

The main contributors for the emissions (positive and negative) from our system boundaries were identified in **Scenario III** to recognize the impact of each source on the obtained results and because this scenario considers, WWTP, biodiesel, diesel, paraffin, and UCO based candles. For example, the total electricity (consumed and the absolute value of the credited consumption) was considered. The conclusions are represented on **Figure 6.8** and **Table A.8**.

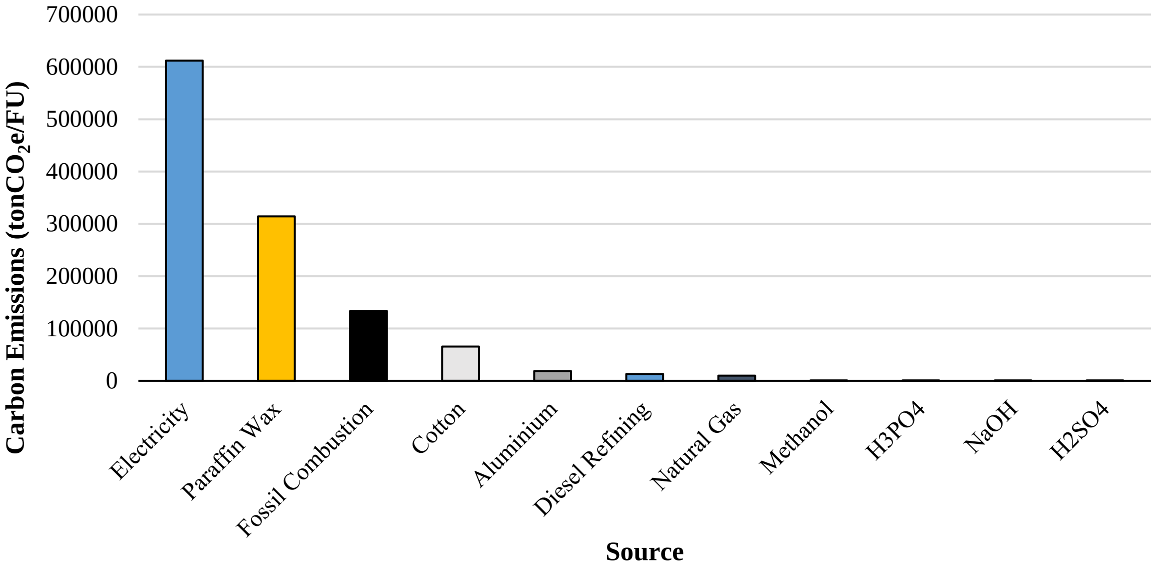

Figure 6.8 Identification of main sources that impact GWP.

We identify the main contributors from electricity consumption, mainly from the WWTP's, followed by paraffin wax production, fossil-based combustion, cotton, aluminium, diesel refining and natural gas. The remaining materials represent emissions below 0.1% of the total.

We start by changing parameters that influence the biodiesel production and use, by using CaO as the catalyst in the transesterification and changing the emission factor of natural gas, now considering the JRC results for EU piped natural gas supply [18] (67.6 gCO_2e/MJ), instead of only direct combustion emissions (51.6 gCO_2e/MJ), by doing so we understand their impact on our base framework. Following the same procedure from the previous NaOH process and emission factor for natural gas, we compare the obtained results for each scenario, taking into account all portions of our LCA, WWTP, biodiesel, diesel and paraffin production and use, represented in **Figure 6.9** and **Figure 6.10**.

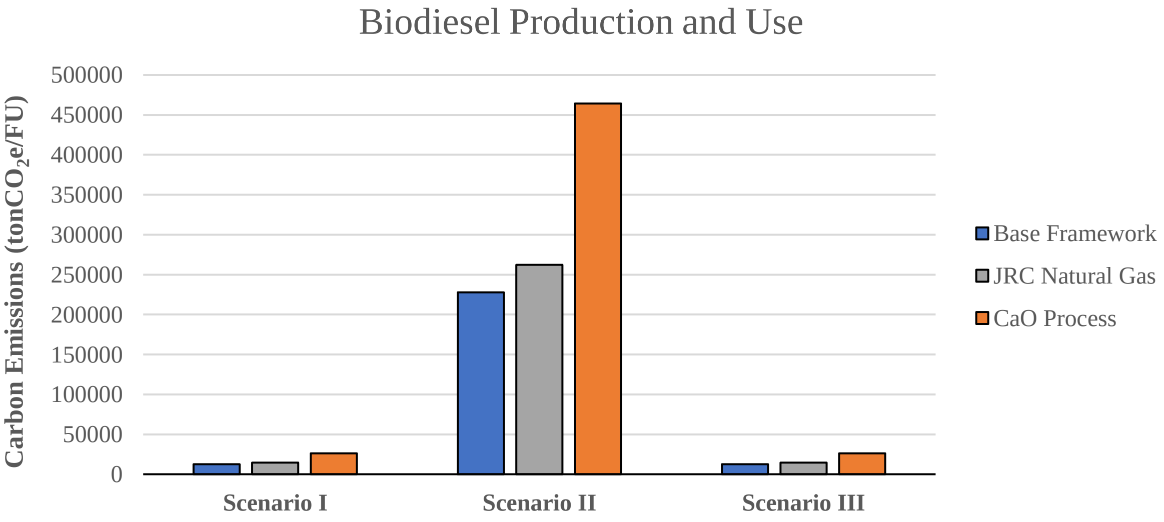

Figure 6.9 Sensitivity analysis of net GWP emissions from biodiesel production and use.

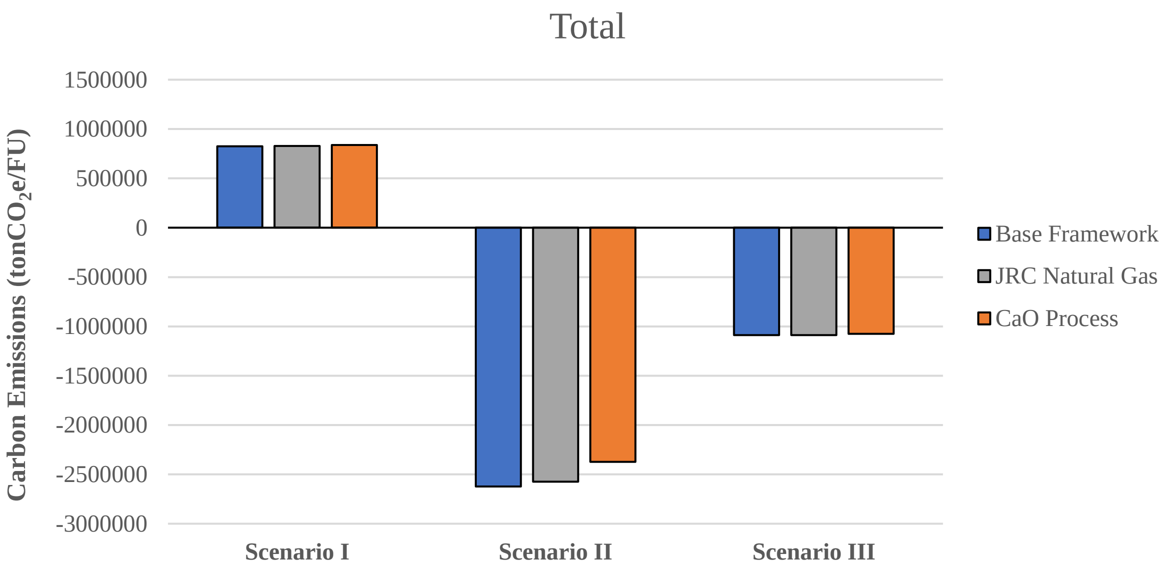

Figure 6.10 Sensitivity analysis of the total net GWP emissions for each scenario.

For the biodiesel production and use, the difference between the base framework and the changes from the emission factor of the natural gas and the biodiesel production process are, +13% and +51%, respectively, these differences being more visible in **Scenario II,** where we are using all of the available UCO for biodiesel production. For the total emissions of each scenario, they are all very similar, except in **Scenario II**, mainly because the biodiesel production and use emissions don't represent a significant portion of our systems emissions. The results are represented in **Table A.9**.

Now focusing on the main portion of emissions, that are from electricity consumption, comparing our base framework results to different emission factors for a medium voltage, for the years 2016 and 2030, 382.7 gCO_2e/kWh and 259.2 gCO_2e/kWh, respectively, and the EU goal of a net neutral emission factor for electricity generation, 0 gCO_2e/kWh.

Our in-depth analysis of the impact of varying electricity emission factors on our system has yielded significant insights. When we consider the primary source of emissions, electricity consumption, and apply the JRC 2016 emission factor, we observe a substantial 38% increase in overall system emissions within **Scenario I**. However, in **Scenario II** and **III**, where we replace the electricity consumption of the WWTP by producing different bioproducts which exhibits an increase in net emissions, of 11% and 29%, respectively.

The results under the JRC 2030 emission factor closely mirror those of the base scenario, as the emission factor remains in close proximity. Conversely, in the scenario representing the EU ambitious goal of achieving a net-neutral electricity generation by 2050, the system demonstrates an increase in net GHG emissions. When comparing different scenarios and emission factors, we can conclude that it is always better to use UCO to produce bioproducts, reducing the net emissions of the system. These results are characterized in **Table A.10**.

7 Conclusions

The primary aim of this dissertation is to investigate, at the European context, which is the best option for dealing with UCO, in terms of GWP. Addressing the following research questions: what are the impacts of the disposal of domestic used cooking oils on the water management cycle? Is the reutilization of domestic waste cooking oils a more viable alternative compared to their disposal to wastewater treatment services? How can the recycling of domestic waste cooking oils be effectively assessed for the production of different bioproducts, using environmental indicators?

The disposal of domestic UCO negatively impacts the water management cycle worldwide. It causes blockages in sewage systems, increases energy consumption, and raises costs for WWTP. Proper UCO handling and disposal practices are essential to mitigate their environment and economic consequences and ensure efficient wastewater treatment processes.

The reutilization of UCO proves to be a more viable alternative compared to their disposal to wastewater treatment services. This approach conserves energy, reduces GHG emissions, and mitigates water pollution, making it an environmentally beneficial choice that also leads to reduced costs of operation for WWTP and lowers the maintenance required for the sewage systems. Prioritizing UCO reutilization for bioproducts promotes sustainable management practices with multiple economic and environmental benefits.

Using a LCA methodology and system expansion crediting avoided products (biodiesel and paraffin) allows to compare different scenarios and a sensitivity analysis allowed to estimate GWP and to prove that is always better to use UCO to produce bioproducts in a circular economy context.

The document offers significant insights into the effective management and utilization of domestic UCO. Appropriate handling of UCO, such as refraining from its disposal into the sewage systems, leads to substantial reduction in GHG emissions alone, by minimizing the energy consumption for its treatment that was found in the literature to be 3 kWh/kg of UCO.

The complexity of domestic UCO collection on a wider scale poses a limitation. The logistics and infrastructure required for widespread UCO collection can vary significantly and may impact the overall feasibility and environmental benefits of UCO utilization. This LCA doesn’t account for the transportation phase or any construction materials, such as those related to pipelines and factories, which can influence the overall environmental impact. A simplified approach to manufacturing materials for candles was used for comparability between both paraffin-based and UCO-based candles, however limited disclosure of the chemical composition of the materials needed to produce candles hinders accountability for emission factors.

The developed methodology for LCA assessments has broader applicability for assessing various products with different functions. These findings highlight the potential for sustainable UCO utilization and offer insights for future research and decision-making in waste management and resource utilization. By addressing these limitations and building upon the strengths, future studies can further enhance the understanding and practical applications of UCO utilization for sustainable waste management, contributing to a greener and more resource-efficient future.

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Annex

A. Annex A

Table A.1 Material/energy inventory for Scenario I.

WWTP	**Feed**	Material (kg)	UCO	8.06E+08
		Energy (kWh)	Electricity	2.42E+09
Biodiesel Production	**Feed**	Material (kg)	UCO	4.78E+07
			Methanol	9.92E+06
			H_2SO_4	4.42E+05
			NaOH	1.58E+05
			Glycerol	7.82E+05
			H_3PO_4	1.29E+05
		Energy	Electricity (kWh)	1.29E+05
			Steam (MJ)	1.75E+08
	Products	Material (kg)	Biodiesel	4.84E+07
			Glycerol	4.92E+06
	Waste	Material (kg)	Water + Methanol	1.85E+06
			Na_3PO_4	2.16E+05
			H_2SO_4 + Glycerol + Methanol	4.15E+06

Table A.2 Material/energy inventory for Scenario II.

Biodiesel Production	**Feed**	Material (kg)	UCO	8.54E+08
			Methanol	1.77E+08
			H_2SO_4	7.89E+06
			NaOH	2.82E+06
			Glycerol	1.40E+07
			H_3PO_4	2.31E+06
		Energy	Electricity (kWh)	2.30E+06
			Steam (MJ)	3.13E+09
	Products	Material (kg)	Biodiesel	8.64E+08
			Glycerol	8.79E+07
	Waste	Material (kg)	Water + Methanol	3.31E+07
			Na_3PO_4	3.86E+06

Table A.3 Material/energy inventory for biodiesel production using the CaO process (Scenario I and Scenario III).

Biodiesel Production	**Feed**	Material (kg)	UCO	4.78E+07
			Methanol	1.04E+07
			H_2SO_4	4.24E+06
			CaO	2.42E+06
		Energy	Electricity (kWh)	1.15E+05
			Steam (MJ)	4.09E+08
	Products	Material (kg)	Biodiesel	4.85E+07
			Glycerol	4.98E+06
	Waste	Material (kg)	Water + Methanol	5.00E+06
			$CaSO_4$ + Water	7.44E+06

Table A.4 Material/energy inventory for biodiesel production using the CaO process (Scenario II).

Biodiesel Production	**Feed**	Material (kg)	UCO	8.54E+08
			Methanol	1.85E+08
			H_2SO_4	7.57E+07
			CaO	4.33E+07
		Energy	Electricity (kWh)	2.06E+06
			Steam (MJ)	7.31E+09
	Products	Material (kg)	Biodiesel	8.66E+08
			Glycerol	8.89E+07
	Waste	Material (kg)	Water + Methanol	8.93E+07
			$CaSO_4$ + Water	1.33E+08

Table A.5 GWP 100 years emissions (Scenario I).

		Biodiesel and WWTP	**+ Diesel**	**+ Diesel and Paraffin**
GWP 100 Years Emissions (tonCO_2e/FU)	Oil to WWTP	611887.58	611887.58	611887.58
	Biodiesel Production and Use	12747.31	12747.31	12747.31
	Diesel Production	-	-12963.31	-12963.31
	Diesel Use	-	-131793.64	-131793.64
	Paraffin Candle Production and Use	-	-	345584.41
	UCO Candle Production and Use	-	-	-
	Total	624634.89	479877.94	825462.35

Table A.6 GWP 100 years emissions (Scenario II).

		Biodiesel and WWTP	**+ Diesel**	**+ Diesel and Paraffin**
GWP 100 Years Emissions (tonCO$_2$e/FU)	Oil to WWTP	-611887.58	-611887.58	-611887.58
	Biodiesel Production and Use	227630.55	227630.55	227630.55
	Diesel Production	-	-231487.66	-231487.66
	Diesel Use	-	-2353457.89	-2353457.89
	Paraffin Candle Production and Use	-	-	345584.41
	UCO Candle Production and Use	-	-	-
	Total	-384257.04	-2969202.58	-2623618.18

Table A.7 GWP 100 years emissions (Scenario III).

		Biodiesel and WWTP	**+ Diesel**	**+ Diesel and Paraffin**
GWP 100 Years Emissions (tonCO$_2$e/FU)	Oil to WWTP	-611887.58	-611887.58	-611887.58
	Biodiesel Production and Use	12747.31	12747.31	12747.31
	Diesel Production	-	-12963.31	-12963.31
	Diesel Use	-	-131793.64	-131793.64
	Paraffin Candle Production and Use	-	-	-345584.41
	UCO Candle Production and Use	-	-	54366.61
	Total	-599140.27	-743897.22	-1089481.63

Table A.8 GWP emissions by source.

Source	**Emissions (tonCO$_2$e/FU)**	**Fraction (%)**
Electricity	611964.36	52.44%
Paraffin Wax	314251.81	26.93%
Fossil Combustion	133438.23	11.43%
Cotton	65416.29	5.61%
Aluminum	18594.08	1.59%
Diesel Refining	12963.31	1.11%
Natural Gas	9828.33	0.84%
Methanol	297.72	0.03%
H_3PO_4	187.23	0.02%
NaOH	176.59	0.02%
H_2SO_4	61.86	0.01%
TOTAL	1166941.36	100.00%

Table A.9 Sensitivity analysis of the total GWP emissions and biodiesel production and use.

GWP Emissions (tonCO$_2$e/FU)				
		Scenario I	**Scenario II**	**Scenario III**
Base Framework	Biodiesel Production and Use	12747.31	227630.55	12747.31
	Total	825462.35	-2623618.18	-1089481.63
JRC Natural Gas	Biodiesel Production and Use	14683.59	262206.96	14683.59
			+ 13.19%	
	Total	827398.63	-2575144.21	-1087545.35
		+ 0.23%	**+ 1.88%**	**+ 0.18%**
CaO Process	Biodiesel Production and Use	26005.63	464386.27	26005.63
			+ 50.98%	
	Total	838419.29	-2372964.90	-1076524.69
		+ 1.55%	**+ 10.56%**	**+ 1.20%**

Table A.10 Sensitivity analysis of electricity emission factors for each scenario.

		Scenario I	**Scenario II**	**Scenario III**
Total GWP Emissions (tonCO$_2$e/FU)	**Base Framework**	825462.35	-2623618.18	-1089481.63
	JRC 2016 (Medium Voltage)	1139113.08	-2915086.76	-1.40E+06
		38.00%	**-11.11%**	**-28.79%**
	JRC 2030 (Medium Voltage)	840457.99	-2616446.93	-1104475.74
		1.82%	**0.27%**	**-1.38%**
	EU 2050	213543.51	-2009517.94	-456431.67
		-74.13%	**23.41%**	**58.11%**

B. Annex B – Experimental Protocol

Experiment Protocol – Paraffin vs. UCO candle

Purpose

The purpose of this experiment is to compare the characteristics and performance of a paraffin-based wax to a used cooking oil (UCO) based one, by measuring the temporal trends of properties such as temperature, pressure, humidity, and CO_2 concentration of the surrounding air, as well as their combustion performance in a ventilated room. Compare a fossil-based candle to a UCO candle and assess their environmental impacts.

Theoretic Introduction

The process of making wax from UCO is called hydrogenation, which consists of a chemical reaction between hydrogen, H_2, and unsaturated organic compounds, reducing double and triple bonds in hydrocarbons, saturating it. This saturation will affect chemical and physical characteristics of the substrate, the main one is staying solid at room temperatures.

The thermochemical reaction between oxygen, O_2, and wax, $C_n H_{2n+2}$, for $n > 20$, produce condensed water, H_2O, and carbon dioxide, CO_2.

Since twice as much oxygen is burned than carbon dioxide released, the air volume decreases, decreasing the pressure inside of the glass dome.

There's a physical aspect that counteracts this trend. Once the candle heats the air it also expands it, increasing the pressure. Only when the oxygen is fully depleted and the candle goes out, the air cools down reducing its volume and pressure.

These chemical and physical processes tend to cancel each other initially, only when oxygen consumption is significant, it's observed the decrease of the pressure inside of the glass dome.

For a larger value of n, the oxygen and carbon dioxide relation is more 3:1 than the 2:1 previously mentioned. Since around 20% of air is oxygen, we get around 8% of air volume removed, meaning that about 1/11 to 1/12 of the air volume is going to be replaced by water inside of the glass dome.

Materials

- Paraffin Candle
- DIY Greatest Candle™ Candle Kit
- Used Cooking Oil (100mL)
- Scale (± 0.01g)
- Microwave (1000W)
- Power Monitor
- Glass Dome (V= 5.9L)
- Water
- Lighter
- Stirring rod
- Beakers (150mL and 200mL)
- Candle containers
- Filter
- Sensor SCD-30 (NDIR detects and monitors CO_2 in air based on the absorption of infrared light at a given wavelength)
- Sensor BME280 (measures barometric pressure, temperature, and humidity)
- Processor Arduino UNO (Sends information to the cloud every 20s)
- Multiplexer TCA9548A (Connects devices with the same I2C address, gatekeeping the commands.

Scheme and Experiment Set-Up

Figure A.1 UCO, DIY powder (left) and set-up (right).

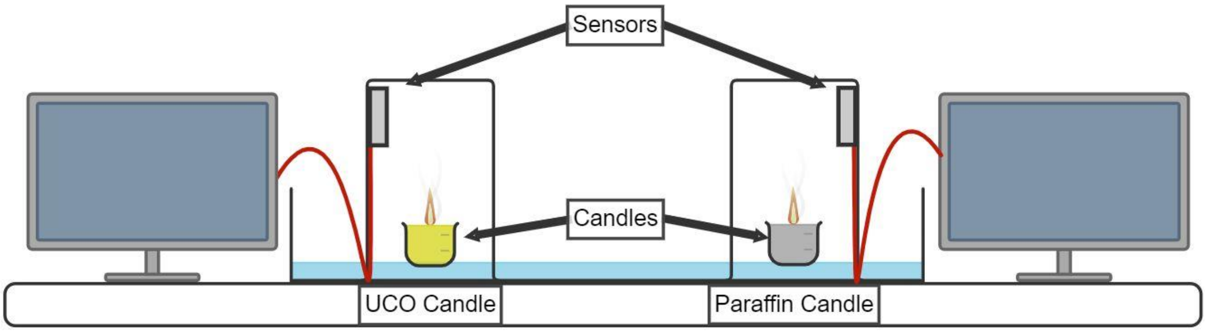

Figure A.2 Experimental set-up.

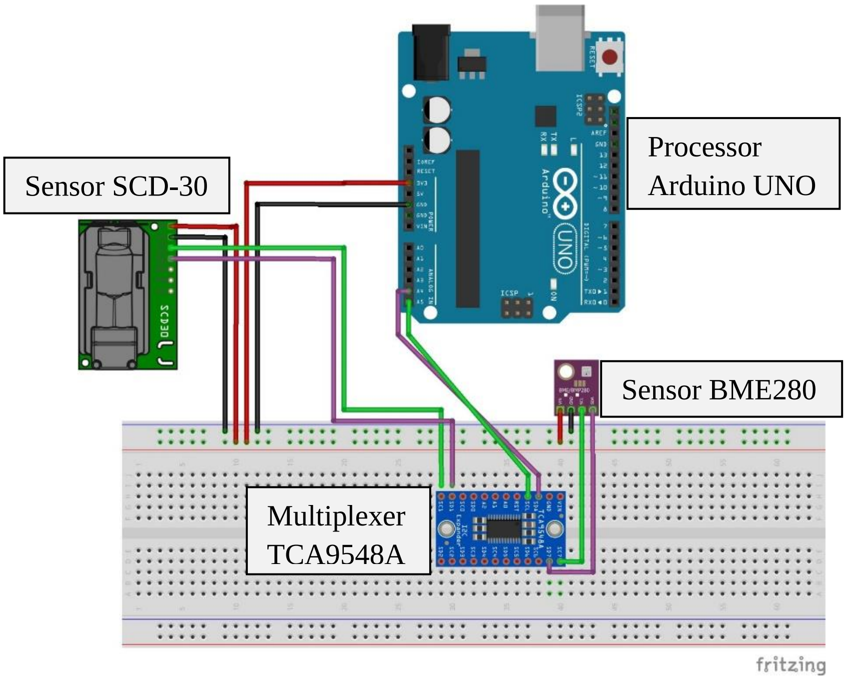

Figure A.3 Sensors set-up.

Procedure

- Before starting the experiment, determine the density of the different UCO collected. To do so simply weight the empty recipient and weight again when its full of UCO. By knowing the recipient predetermined volume we can calculate the UCO density.
- After that we can start by producing the UCO-based candle, checking if the UCO available has any suspended materials that needs to be filtered out.
- Pour 100mL of UCO to the 250mL beaker, in order to heat up the content using the microwave for 1 minute. This device should be connected to a plug using the power monitor as an intermediary, to later register the instantaneous power usage, in order to calculate the energy consumption of the heating process.
- Add the chemical compound to the oil and with the help of a stirring rod, stir until the mix is homogeneous, and let it rest.
- Weight both candles to ensure its comparability for this work and using the set-up, register the ambient air conditions.
- Light the candles and close the previously obtained volume glass dome and add enough water to ensure the non-influence of outside conditions during the experiment until both burn out.
- Collect the data and determine the combustion time and temporal evolution of the concentrations of CO_2 and H_2O of each candle.
- Using another UCO and paraffin candle, first weight each one, then leave them on for one hour.
- After that weight them again and compare.