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Productive and Sustainability Approach to Biodiesel Production Chain: A Systematic Literature Review

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Abstract: This article presents a taxonomy supported by a systematic literature review on the productive and sustainability approach to biodiesel production chain. The purpose of this research is to determine the competitive and productive contexts of the biodiesel production chain identified in the literature. The results of the investigation provide answers to the following questions: How is the biodiesel market and what raw materials are used for its production? What are the raw material treatment methods and production processes for oil extraction? What is the energy balance required to produce biodiesel from different raw materials? What are the carbon and hydraulic footprints of the raw materials? The most significant developments impacting the biodiesel market are the scarcity of raw materials for biodiesel production and the global decline in crude oil prices, which could hinder the market's growth. The primary raw materials used in biodiesel production are vegetable oils, with palm oil accounting for 32%, soybean oil for 26%, and rapeseed oil for 15%. The remaining 27% comprises other raw materials, including used cooking oil, animal fats, and other virgin vegetable oils.

Keywords: biodiesel production chain, production of biofuels, raw materials, systematic literature review, taxonomy.

生物柴油生产链的生产性和可持续性方法：系统文献综述

摘要：本文提出了一个分类法，该分类法得到了关于生物柴油生产链的生产性和可持续性方法的系统文献综述的支持。本研究的目的是确定文献中确定的生物柴油生产链的竞争和生产环境。调查结果回答了以下问题：生物柴油市场状况如何以及其生产使用哪些原材料？榨油的原料处理方法和生产工艺有哪些？从不同原料生产生物柴油所需的能量平衡是多少？原材料的碳足迹和水力足迹是多少？影响生物柴油市场的最重要的发展是生物柴油生产原材料的稀缺和全球原油价格的下跌，这可能会阻碍市场的增长。生物柴油生产所用的主要原料是植物油，其中棕榈油占 32%，大豆油占 26%，菜籽油占 15%。其余 27%由其他原材料组成，包括废食用油、动物脂肪和其他初榨植物油。

关键词：生物柴油生产链、生物燃料生产、原材料、系统文献综述、分类学。

1. Introduction

The rapid growth of the world population and industrial growth have promoted the use of fossil resources as energy sources for centuries; however, their limited nature and environmental impact have promoted an effort for research and use of more sustainable and environmentally friendly ones. One of these alternatives is biofuels such as biodiesel [1]. Biodiesel offers a renewable option to address fuel and socioeconomic issues [2]. Biodiesel is mixed with diesel in different proportions as fuel for all types of vehicles.

Fossil fuels represent 80% of energy consumption worldwide, whereas the share of renewable energies is close to 18% [3], [4], and the biomass (combustion of wood, forest material, and agricultural biomass) represents 9% [3], [5]. Palm oil represents almost 25% of the production of vegetable oils in the world, being, after soy bean, the second most produced vegetable oil [4]. Most of the biomass produced is exported, providing an important source of foreign exchange revenue for exporting countries [6]. In countries exporting energy production biomass, the sector employs millions of people directly and indirectly, and it is responsible for millions of downstream jobs in importing countries [6]. Statistics place energy biomass commodities among the most important agricultural commodities in the world.

Biodiesel can be a result of a process using different feedstocks, such as animal fats, oils, algae, microbial sources of oil, and vegetable oils [7]. Biodiesel is produced from diverse sources with different compositions, purities, and energy potentials. The choice of raw materials depends on the chemistry of the process, the chemical and physical characteristics of the virgin oils used, and the economy, feasibility, and efficiency of the productive processes that develop them [8].

A challenge facing the world is energy reconversion; new unpolluted energy sources can be used as a replacement for fossil fuels [9]. Currently, the essential problems with biodiesel are its relatively high final price compared with that of conventional diesel and the doubts and concerns about its environmental impact [10]. For biodiesel to be competitive and sustainable, research and innovation have been focused on the development of biodiesel production technologies that increase efficiency, reduce costs, reduce water footprint, and abolish monoculture [11]. In short, the challenges of biodiesel are related to competitiveness, which involves aspects of productivity and sustainability. The systematic review of the literature presented in this article focuses on determining the competitive and productive contexts of the biodiesel production chain.

2. Systematic Literature Review (SLR) Development

Next, the deployment of the methodology is carried out.

2.1. Stage 1 - Planning the Review

2.1.1. Step 1: Formulation of the Problem

The formulation of the problem was partly exposed in the introduction of this article. In summary, the object of this study is the production chain of biodiesel studied from the production and sustainability approach, as detailed below.

Productive approach: This approach seeks to determine the market, raw materials, processes for the extraction or purification of oils, and energy balance in the production of biodiesel.

Sustainability approach: It determines the carbon and hydraulic footprints of the production processes derived from different raw materials.

2.1.2. Step 2: Development and Validation of the Review Protocol

The review protocol is a pre-established plan that specifies the methods used that are crucial in the development of the systematic review [12] because it reduces the possibility of investigator bias in the selection and analysis of the data [13]. For the specific case of this study, the review is divided into two established approaches: productive and sustainability.

The following research questions guide the review:

Q1: How is the biodiesel market and what raw materials are used for its production?

Q2: What are the raw material treatment methods and production processes for oil extraction?

Q3: What is the energy balance required to produce biodiesel from different raw materials?

Q4: What are the carbon and hydraulic footprints of the raw materials?

For the development of the SLR, inclusion and exclusion criteria were defined so that the research articles were considered within the review only if they contained relevant information about our research problem. For this purpose, the titles of these articles were validated, discarding those that did not fit within the scope of the study.

To ensure its scientific relevance, the literature was restricted to articles published in journals classified Q1, Q2, and Q3 in WoS and Scopus. Technical reports and electronic submissions that lacked peer review were not included. The research papers that passed the pertinence and relevance filters were individually validated in their content: methodology deployed, results, and conclusions.

Specifically, the following topics were investigated: biodiesel market, raw materials for biodiesel production, raw material treatment methods, biodiesel production methods, energy balance of biodiesel production, and carbon and water footprints of raw materials.

2.2. Stage 2 - Performing the Review

2.2.1. Step 3: Literature Search

The research linked 34,003 articles, 12,247 in WoS and 21,756 in Scopus.

Table 1 Search of the literature (The authors)

Approaches	**Search subtopics**	**Search keys**	**Sources**	**Results**
Productive approach	Biodiesel market	Global biofuel market	WoS	353
			Scopus	860
		International biofuel trade	WoS	87
			Scopus	223
	Raw materials for biodiesel production	Biodiesel production feedstocks	WoS	2,445
			Scopus	4888
	Raw material treatment methods	Acid treatment: FFA biodiesel	WoS	98
			Scopus	114
		Glycerolysis treatment: FFA biodiesel	WoS	6
			Scopus	10
		Crude glycerol purification	WoS	4
		Glycerolysis reaction	Scopus	6
	Biodiesel production methods	Base catalyst transesterification	WoS	1214
			Scopus	987
		Acid catalyst transesterification	WoS	1599
			Scopus	2799
		Heterogeneous catalyst transesterification	WoS	1067
			Scopus	1415
		Supercritical methanol transesterification	WoS	165
			Scopus	247
	Energy balance of biodiesel production	Biofuel energy balance	WoS	576
			Scopus	1983
Sustainability approach	Carbon and hydraulic footprints of the raw materials	GHG carbon footprint Biodiesel feedstocks	WoS	1569
			Scopus	3026
		Water footprint biodiesel feedstocks	WoS	3064
			Scopus	5201
			Total	34003

2.2.2. Step 4: Screening for Inclusion

In this step, each article is examined to decide whether to include it in the data extraction and analysis phase.

A two-stage procedure was followed as an efficient search mechanism: first, coarse screening was performed based on the review of the abstracts of the articles, followed by a more refined evaluation based on a full text review.

Information on the two approaches was extracted from each study:

(1) *Productive focus:* market, raw materials, and related production processes for the extraction or purification of oils and energy balance of biodiesel production.

(2) *Sustainability approach:* carbon and hydraulic footprints of the raw materials.

The inclusion and exclusion criteria were expressed through research questions, so that any study unrelated to them was excluded. Fig. 1 illustrates the details of the systematic bibliographic search, whose screening led to the detailed analysis of 83 scientific articles whose results allowed the taxonomy presented here to be carried out.

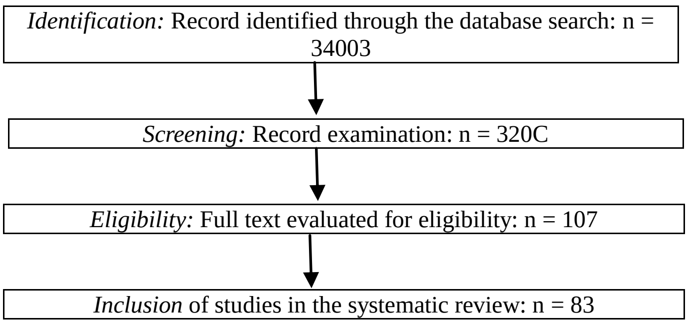

Fig. 1 Systematic review flowchart (The authors)

2.2.3. Step 5: Quality Assessment

After selecting the papers based on the inclusion-exclusion criteria selection procedure, we proceeded to collect and carefully read the full text of all the articles studied that proved to be quality research, and therefore, were included. The quality assessment was entrusted to the three review authors in parallel. Discrepancies in the findings were discussed and resolved. Table 2 lists the studies used in the literature review.

Table 2 Studies in the systematic review (The authors)

Search subtopics	**References**
Biodiesel market	[14-25]
Raw materials for biodiesel production	[21, 26-41]

Continuation of Table 2

Raw materialtreatment methods	Acid treatment: FFA biodiesel	[42-45]
	Glycerolysis treatment: FFA biodiesel	[46-48]
Biodiesel Production Methods	Base catalyst transesterification	[49-52]
	Acid catalyst transesterification	[53-56]
	Heterogeneous catalyst transesterification	[57-59]
	Supercritical methanol transesterification	[60-63]
Energy balance of biodiesel production		[64-69]
Carbon and hydraulic footprints of raw materials	GHG carbon footprint biodiesel feedstocks	[70-76]
	Water footprint biodiesel feedstocks	[77-84]

2.2.4. Step 6. Data Extraction

Data extraction often involves coding. In this article, the data extraction and coding was carried out with the help of the NVivo 11 software. Fig. 2 shows, through a word cloud, the most used vocabulary in the articles used for the bibliographic review. It is necessary to mention the importance of reviewing the whole research and not just relying on the main result of the software.

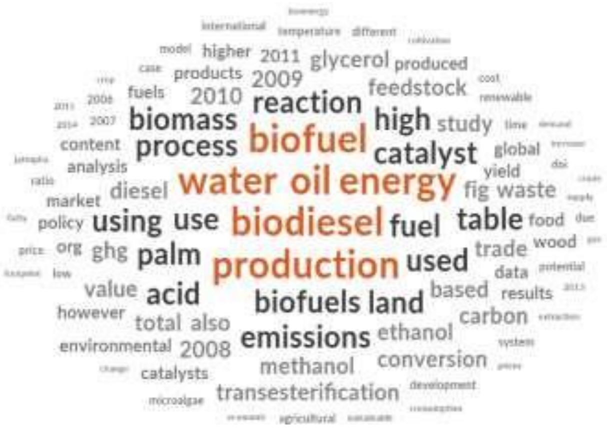

Fig. 2 Word cloud (Using NVivo 11)

Table 3 shows the count of the 8 most used words in the review articles.

Table 3 Word count (The authors' using NVivo 11)

#	Word	Count
1	Biodiesel	7593
2	Oil	6669
3	Production	6418
4	Energy	5962
5	Water	3050
6	Biofuel	2791
7	Fuel	2741
8	Biofuels	2697

2.2.5. Step 7: Analysis and Synthesis of the Data

This stage seeks to answer the questions that characterize the taxonomy developed here.

Q1: How is the biodiesel market and what raw materials are used for its production?

Market:

The increase in demand for biofuels is protected by various public policies [20], [24], [38]. In some countries, the growth of mandatory regulations and tax and subsidy systems has supported the demand for biofuels [19], [23]. Driven by blending targets, the consumption of global biofuel is expected to continue to rise highly in developing countries; however, in developed countries, this expansion might be limited due to declining total fuel demand and reduced political incentives [17].

Currently, the demand for ecological fuels that manage to reduce greenhouse gas (GHG) emissions is a determining factor that promotes the market [16]. It is estimated that the growing demand for biodiesel to substitute common fossil fuels in power generation and automotive applications drives market growth [14]. While biofuels are expected to continue on agricultural raw materials, a substantial increase in advanced biofuel technology is not expected in the medium term. Vegetable oil is the preferred feedstock in biodiesel production, and biodiesel production based on waste cooking oils continues to play an essential role in the European Union, Canada, China, India, and the United States [15], [18]. One negative aspect to note is the large-scale production of biofuels from different types of plants and crops, which can result in a shortage of food products and alter food prices, thus raising concerns about food security. This factor will stifle the expansion of the biofuel market [22], [25].

The manufacture and consumption of liquid biofuels decreased significantly in 2020 because of the COVID-19 pandemic. However, the data for the first half of 2021 show a remarkable recovery [14].

Fig. 3 reveals the market value of biofuels worldwide in 2020 and 2021, with a forecast for 2030 that shows an expected continuous linear growth.

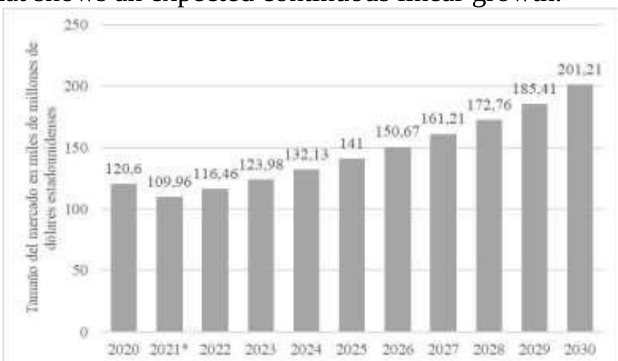

Fig. 3 The market value of biofuels worldwide in 2020 and 2021, with a forecast for 2030 that shows an expected continuous linear growth [14]

Raw materials:

The raw material characterizes the biodiesel industry, so the cost of biodiesel is affected by the raw material used. Today, the raw material is equivalent to at least 80% of the costs associated with biodiesel production [18]. The raw materials most used in the production of biodiesel are vegetable oils, including palm (32%), soybean (26%), and rapeseed (15%), and the remaining 27% correspond to other raw materials, such as used vegetable oils, animal fats, and other virgin vegetable oils, including sunflower oil. In 2021, the vegetable oil segment accounted for the largest share of the market with more than 97.00% of global revenue [85]. However, the selection of raw materials varies by region, depending on their availability and cost.

According to the raw material, the market has been classified into vegetable oils, used cooking oil [34], [36], and animal fats that are sub-segmented into poultry, tallow, white fat, and others [27]. The segment of vegetable oil raw materials is subdivided into castor oil [29], [39], palm oil [28], [31], algae oil [33], [37], Jatropha oil [21], [32], [40], soybean oil [26], [41], [86], and rapeseed oil [30], [35]; rapeseed, soybean, and palm oils are the most commonly used raw materials for biodiesel.

Although animal fats have shown their benefits due to their calorific value, which is higher than that of vegetable oils, and their use would significantly contribute to reducing soil and water pollution, their use is still very low; therefore, it is desirable that the productive chains for their recycling and purification be developed so that they are considered serious raw materials for the production of biodiesel.

Q2: What are the raw material treatment methods and production processes for oil extraction?

Raw material treatment methods:

In the raw material, free fatty acids (FFA) are undesirable compounds due to the reaction with the base catalyst to generate carboxylic acid (soap) salts and water. There is a huge barrier in the biodiesel industry, which is the soap formation reaction, because soap reduces biodiesel yields, increases the viscosity of products, forms emulsions, and makes it difficult to separate glycerol from biodiesel [42].

In industrial applications, acid esterification is the most common treatment to decrease free fatty acids [42-45], whereas glycerol esterification [46], [47] is effective to reduce free fatty acids, but it is not used on a large scale.

Production processes for oil extraction:

Transesterification is a chemical reaction necessary to produce vegetable oil, biodiesel, or animal fat, where they are transformed in the presence of a catalyst (generally basic) with an alcohol (usually methanol or another low molecular weight alcohol) to obtain the corresponding alkyl esters of the mixture of fatty acids present in the oil, vegetable, or animal fat [51].

There are four types of transesterification reactions: base-catalyzed [49-52], acid-catalyzed [53-56], from heterogeneous catalysts [57-59], and supercritical methanol [60-63]. The most common type is base-catalyzed transesterification because it is the fastest reaction with the highest yield, the smoothest reaction condition, and the lowest cost, corrosion, and toxicity [49].

Q3: What is the energy balance required to produce biodiesel from the different raw materials?

The energy balance expresses the ratio between the energy contained in the biofuel and the fossil energy used in its production. Energy balance of 1.0 means that as much energy is needed to produce a liter of biofuel as the energy contained in it; in other words, the biofuel in question involves neither net energy gains nor losses. Energy balance of 2.0 means that one liter of biofuel contains twice the energy needed to produce it [65], [66], [69].

The main energy consumption in the production of biodiesel occurs in the agricultural stage, where fuel, agrochemicals, and fertilizers are the factors that have the greatest effect on the results [64], [67], [68]. Table 4 shows the performance and energy balance of the main vegetable biofuels led by palm oil.

Table 4 Yield and energy balance of biofuels [64]

Crop	Biofuel yield (liters/ha)	Biofuel energy balance
Sunflower	952	3
Soy	446	1.4–3.3
Rape	1190	1.2–3.7
Palm oil	5950	8.6–9.6

Q4: What are the carbon and water footprints of the raw materials?

Biocultures reduce greenhouse gas (GHG) emissions through the direct removal of carbon dioxide from the air as they grow and store it in biomass and soil. Many of these crops generate complementary products such as proteins for animal feed, thus saving the energy that would be used to produce them in another way [70], [71]. Despite these potential benefits, scientific studies have shown that GHG offsets vary greatly for each biofuel compared to oil. This is due to the methods used to produce the feedstock and make the fuel. Some crops can generate even more GHG than the same fossil fuels [75]. The main indicators of the effect of biofuels on the environment are the carbon and water footprints.

Carbon footprint:

The carbon footprint is the sum of GHG emissions during production [72], [73], [76]. Table 5 shows the reductions in GHG emissions versus fossil fuels.

Table 5 Reductions in greenhouse gas emissions compared with fossil fuels [74]

Raw material	Percentage reduction
Palm oil	50%–80%
Rape	40%-60%
Soy	40%-70%
Second-generation biofuels	70-90%

Water footprint:

The water footprint is created as an analytical tool to address issues related to water security policies and sustainable water use [83], [84]. The calculation of the water footprint makes it possible to quantify the total volume of water consumed and/or polluted per unit of time, used to produce a good or service or consumed by an individual, community, or factory, considering all the water used in the processes involved in the product supply chain [77], [78], [82].

The variation in the water footprint of crops is considerable depending on the characteristics of the species, conditions of agricultural production, climate of the area, and efficiency of irrigation, whether by rain or extracted from rivers, aquifers [80], [81]. Table 6 shows different water footprints and water consumption required to produce one liter of biodiesel.

Table 6 Water footprint and liters of water used for one liter of biodiesel [79]

Raw material	Biodiesel water footprint (m3/GJ)	Liters of water per liter of biodiesel
Coconut oil	4751	157.617
Peanut	200	6.607
Palm oil	156	5.166
Rape	194	6.429
Cotton seed	547	18.134
Soy	343	11.397
Sunflower	477	15.841

Rapeseed and oil palm are the best raw materials from a sustainability viewpoint.

2.3. Stage 3 – Reporting the Review

2.3.1. Step 8: Reporting the Findings

How is the biodiesel market and what raw materials are used for its production?

Currently, the expectation is that with the growing demand for ecological fuels and the support from governments, the biodiesel market will be promoted; however, the lack of raw materials for the generation of biodiesel and global fall in crude oil prices can hamper the growth of the biodiesel market.

The raw materials most used in the production of biodiesel are vegetable oils, including palm (32%), soybean (26%), and rapeseed (15%). The remaining 27% correspond to other raw materials, such as used vegetable oils, animal fats, and other virgin vegetable oils. The raw material determines the success in the production of biodiesel because it is part of 90% of the production costs and is crucial for the quality of biodiesel. Likewise, the main environmental impacts within the biodiesel production chain occur when it is obtained.

The raw material seeks to satisfy three aspects: technical, economic, and environmental. The technical aspect is paramount, because without it will not be possible to place it on the market; the economic aspect can be overcome with subsidies, as in many countries; later, it remains in the regulations and norms of each government how much weight the environmental aspect has. Therefore, there is no ideal raw material, and the situation for each country is different, depending on its geographical reality, energy security strategy, economy, and long-term objectives.

What are the raw material treatment methods and production processes for oil extraction?

There are three raw material treatment methods: acid treatment to decrease FFAs, glycerolysis treatment to decrease FFAs, and crude glycerol purification for glycerolysis reaction. Glycerolysis treatment has many advantages over acid esterification because it is faster, less toxic, and cheaper. Research on glycerolysis treatment is limited, and it requires further investigation and discussion.

Transesterification reactions are divided into four groups: acid-catalyzed, base-catalyzed, enzymatic-catalyzed, and non-catalyzed supercritical methanol. The most common type is base-catalyzed transesterification, which is the fastest reaction with the highest yield, the lowest corrosion, the mildest reaction condition, and the lowest toxicity and cost.

What is the energy balance required to produce biodiesel from different raw materials?

According to the performance and energy balance of the main vegetable biofuels, Table 4 shows palm oil's advantage.

What are the carbon and hydraulic footprints of the raw materials?

With regard to the carbon footprint, Table 6 reveals the reductions in greenhouse gas emissions compared to fossil fuels. On the other hand, Table 6 shows different water footprints and the necessary water consumption to produce one liter of biodiesel, indicating that second-generation biofuels and palm oil are the best options in terms of the water footprint. Despite this, as mentioned before, raw material selection depends on the edaphoclimatic, technological, logistics, productive, and market conditions in each region and country.

3. Conclusions

The work presents a broad perspective on the biofuels sector, which allows different stakeholders, especially state and industrial stakeholders, to propose competitive strategies over time, focused on increasing the sector's competitiveness and sustainability, supported by efficiency and performance of biomasses and production technologies.

This paper responds to key questions about biofuels through a specially designed taxonomy. With the revealed context, important positive aspects of the alternative are evident; however, it is complementary to the current one centrally supported by fossil fuels and other emerging alternatives such as third- and fourth-generation biofuels, batteries, and hydrogen. An energy transition from fossil fuels to hydrogen is expected as technological developments make it possible to exhaust the possibilities of existing alternatives and proceed to the most promising ones. An especially attractive alternative has to do with used oils, especially edible oils, because they require less processing for their use as biofuel, but the investment must be made in the development of efficient supply chains in supply logistics with a high capacity to identify, negotiate, and logistically satisfy suppliers.

Owing to the interrelationships between the agricultural, energy, and food sectors and because both food and biofuels are tradable goods, regulatory policies are now even more fundamental to generate industrial and demand incentives and energy mode transitions within an optimal economic and environmental rationality traceable in reality and projected technological evolution.

Future research should also focus on how the environmental impacts of biodiesel production systems can be reduced by employing innovative techniques.

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