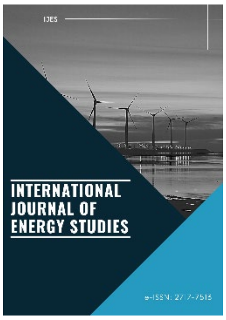
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Research Article

Int J Energy Studies 2025; 10(2): 523-548

DOI: 10.58559/ijes.1659318

Received	:	17 Mar 2025
Revised	:	04 May 2025
Accepted	:	10 Jun 2025

Life cycle assessment of biodiesel produced from cottonseed oil in Türkiye

Aliaa Saleh[a], Hidayet Oğuz[b], Atıf Emre Demet[c*]

[a]Necmettin Erbakan University, 0000-0002-3389-2207

[b]Necmettin Erbakan University, 0000-0002-0988-1516

[c]Necmettin Erbakan University, 0000-0002-7401-9455

*(*Corresponding Author: aedemet@erbakan.edu.tr)*

Highlights

A thorough LCA of biodiesel production from cottonseed oil in Türkiye using OpenLCA.

CML-IA baseline method is used to determine the environmental impact categories.

The approach of “from cradle to grave” is adopted to describe the system boundary.

An area of 1 ha of cotton field has been adopted as a functional unit in the study.

Biodiesel production cycle gives 60541 kg CO_2-eq for GWP and 703 kg SO_2-eq for ACP.

You can cite this article as: Saleh A, Oğuz H, Demet AE. Life Cycle Assessment of Biodiesel Produced from Cottonseed Oil in Türkiye. Int J Energy Studies 2025; 10(2): 523-548.

ABSTRACT

Environmental sustainability to produce biodiesel requires a comprehensive assessment of the effects associated with the production process. This study aims to conduct a life cycle assessment (LCA) of biodiesel production from cottonseed oil in Türkiye to analyze the environmental impacts of biodiesel from cottonseed oil. The system boundary was carried out over cotton cultivation, cotton ginning, oil extraction, oil refinement, and transesterification. CML-IA baseline was the impact assessment method to quantify the environmental impact categories. The functional unit is 1 hectare of cotton field which produces 577 kg of biodiesel. The results demonstrated that the production chain produces 60,541 kg CO_2-eq for global warming potential, 703 kg SO_2-eq for acidification potential, 0.03 kg sb-eq for abiotic depletion potential, and 3964 kg PO_4^{3-}-eq for eutrophication potential. Cotton ginning, oil extraction, and oil refinement stages have the highest shares of environmental impact, and the effect of the transesterification process has the lowest impact.

Keywords: Biofuel, Cottonseed oil, Environmental impact, LCA, Sustainability.

1. INTRODUCTION

Energy is a prerequisite for any kind of development. The prosperity and growth of a country is associated with energy security and sufficiency [1]. Sustainable development aims not only to maintain this sufficiency but also to gain access to secure and affordable energy which enhances quality of life and increases the country's living standards [2]. The transformation to renewable energy resources is one of the main changes that need to be addressed to achieve sustainable energy development. Meanwhile, environmental awareness of global warming, climate change, and the reduction of greenhouse gas emissions are the principal drivers for developing renewable energy (RE) technologies [3]. Among these, biofuel production provides an alternative fuel to be used in the transportation sector. The global consumption of fuel in this sector grows annually at a rate of 1.4% [4]. In 2019, around 3% of transportation fuels were provided from ethanol and biodiesel, while the global production of biofuels increased by 5% [5]. In Türkiye, the biofuel share of total energy consumption in the transportation sector in 2018 was 0.5% with 40% of the biofuel coming from biodiesel. Moreover, the government requires only a 0.5% blend of biodiesel with petro-diesel [6].

Biodiesel is a fatty acid alkyl ester that is produced from vegetable oil and animal fats. The characteristics of being non-toxic, biodegradable, and its ease of production make it a viable preposition to blend with petroleum diesel [7]. The resulting blend reduces the amount of CO_2, SO_x, and particulate matter emitted [8]. Cotton is one of the essential crops that has great commercial significance due to its widespread use, added value, and employment opportunities for the producing countries. Cotton is employed in many industries including the ginning industry, its fiber is utilized in the textile industry, its linter is used in the paper industry, and its seed is used in the oil and feed industry [9]. There are more than 350 different oil crops in the world that can be utilized to produce biodiesel [10]. Cottonseed oil is considered one of the leading oil groups along with soybean, rapeseed, peanut, and sunflower [9]. Cottonseed contains on average 14-25% oil with predominantly triglycerides and an amount of free fatty acids including 18–25% palmitic acid, 1–25% stearic acid, 17–38% oleic acid, 45–55% linoleic acid, and 1.2% myristic acid as well as trace materials like phospholipids, sterols, and hydrocarbons [11][12]. Besides, cottonseed oil shows a great conversion ratio to biodiesel along with sunflower oil under different types of base catalysts [13]. In Türkiye, the consumption of cottonseed oil ranks second among other vegetable oils, and, in 2021, represented 30.29% of total vegetable oils produced at 228 thousand metric tonnes [14]. Cottonseed oil is utilized in vegetable oil mixtures, and the preparation of margarine, shortening, and mayonnaise, it is also used in canned fish and smoked meat [15].

Up to now, the state-of-the-art technology in biodiesel production is transesterification which can be achieved using a variety of methods including catalysis (both homogeneous and heterogeneous), microwave and ultrasound-based processes, enzymatic techniques, and supercritical conditions [16]. Other processes such as pyrolysis, thermal cracking, dilution, reactive distillation technology, and micro-emulsion can also be utilized in biodiesel production [17]. In general, catalysis methods produce considerable amounts of wastewater and soaps as well as being costly due to the requirement of separation, neutralization, and purification steps [18]. The most commonly used catalysts have been evaluated in terms of their appropriateness and limitations [19]. Concerning microwave and ultrasound techniques, even though they consume higher energy, the biodiesel yield is higher and is achieved in a shorter period as well as being a more environmentally friendly approach [16]. The technology of supercritical conditions offers several advantages such as not using catalysts, not generating wastewater, a high reaction rate, and easy separation. However, the difficulty of heat recovery is one of the technology's challenges to be utilized commercially [20] although the technology has been employed using cottonseed oil [21].

The applicability of biodiesel to diesel engines without any modifications is an important consideration. The engine's performance and the characteristics of the emissions are related significantly to the type of feedstock used. The performance of the engine can be described based on three parameters, brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and exhaust gas temperature (EGT). The majority of biodiesel blends decrease the engine's BTE because of the lower calorific value and the higher viscosity of biodiesel containing petro-diesel. For the same reason, its BSFC value is higher and BTE decreases more with a higher blend ratio. As regards EGT, the higher content of oxygen and cetane lowers EGT which means better atomization. Zhang et al. [22] analyzed the emission characteristics of diesel engines under various generations of biodiesel, it has been shown that the emissions of CO, HC, and smoke emissions decreased by approximately 30%, 50%, and 70% while NO_x and CO_2 emissions were higher by 13% and 26% comparing with petro-diesel. In this context, Jamshaid et al. [23] investigated experimentally the characteristics of engine performance and emissions of a B20 blend with cottonseed oil and concluded that the physiochemical features comply with the specifications of both ASTM D6745 and EN14214. As for engine performance, brake power and brake thermal efficiency were slightly lower than with petro-diesel whereas brake-specific fuel consumption was higher. Meanwhile, the emissions of hydrocarbons and carbon monoxide, except NO_x were less. Shankar et al. [24] studied the transesterification of cottonseed oil using an alkali catalyst and walled carbon nanotube method with the results showing that the calorific values of the biodiesel were 36.18 MJ/kg, and 3.78 MJ/kg, respectively.

Life Cycle Assessment (LCA) is a systematic and objective method for measuring the potential environmental impacts of a product, service, or process by determining the quantities of the inputs and outputs from the extraction of the raw materials to the entire life cycle. LCA has four main stages that are required to evaluate the environmental aspects of a product systematically: definition of goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation [25], [26]. LCA makes a comprehensive comparison between alternative products in terms of an environmental sustainability perspective and determines the invisible positive and negative impacts of products [27]. In addition, LCA assists decision-makers in detecting the consequences of current and future plans for biodiesel production and could thereby lead to different recommendations to enhance agriculture practices, and production technologies [28].

The sort of feedstock used to produce biodiesel not only has a positive impact on the environment due to the reduction of CO_2 emissions but also has economic and social impacts [29]. From the perspective of a circular economy, the economics of the biodiesel industry limits its large-scale production and can only be addressed by implementing a process that enables biodiesel to be priced competitively compared to petro-diesel [30]. Life cycle-based approaches are centered on three pillars: Environmental Life Cycle Assessment (E-LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) [31]. The biodiesel industry reinforces sustainability at every stage of the supply chain forming a carbon-neutral bioeconomy [32]. The contribution of biodiesel is critical in Türkiye as it relies largely on imports of fossil fuels while at the same time energy demand is increasing due to economic growth and urbanization. Utilizing biodiesel in the transportation sector reduces vulnerability by enhancing energy security and increasing accessibility to energy which has concomitant benefits for various sectors of the economy without requiring any wide-ranging development of the existing infrastructure [33].

There have been several studies of biodiesel production from edible and non-edible oils using LCA [34] [35]. A study on biodiesel production from palm oil in Indonesia demonstrated that while the cultivation phase had adverse global warming potential, the transesterification process was the major contributor to photochemical oxidation [36]. There is limited LCA literature on the use of cottonseed in the production of biodiesel. However, a study conducted in Bahia, Brazil has identified and quantified the potential environmental impacts on global warming, abiotic depletion, acidification, and eutrophication. It was found that the agricultural phase has the highest impact due to the use of pesticides and fertilizers [37]. Human impact on forests has grown primarily due to rising demand for agricultural land, forest products, and services, driven in part by population growth [38]. LCA studies on biodiesel production in Türkiye are limited. One study was conducted on sunflower oil and sugar beet molasses in the production of biofuels with carbon intensity evaluated using the IPCC method and compared with the fossil-based fuels and identifying their potential impacts [39].

Since there is limited LCA research for cottonseed biodiesel production, particularly from cottonseed oil in Türkiye, this study aims to evaluate the environmental impact potentials associated with all the stages of producing biodiesel from cottonseed oil. Moreover, it strives to provide reliable sources of scientific information to increase the environmental performance of biodiesel production for the concerned stakeholders including the owners of cotton plantations, biodiesel companies, and decision-makers of energy policies in Türkiye.

2. LCA METHODOLOGY

According to ISO 14040, standard LCA comprises goal and scope, data inventory, impact assessment, and interpretation. This analysis has been performed using the software OpenLCA 1.11.0. One obstacle that was encountered was the availability of data since many of the databases do not include data for Türkiye. Hence, the majority of the data was obtained from existing literature whilst other data was obtained from secondary sources such as Turkish reports, formal agriculture websites, and journal articles. Databases have also been imported into the software including agribalyse-v301 and Ecoinvent. The CML-IA baseline is the impact assessment method that has been adopted to perform the analysis. CML-IA stands for Centrum voor Milieukunde Leiden - Impact Assessment. It is a widely used Life Cycle Impact Assessment (LCIA) methodology developed by Leiden University. The following subsections describe the process of LCA.

2.1. Goal and Scope

The main purpose of the study is to conduct an attributional life cycle assessment (ALCA) of biodiesel production from cottonseed oil in Türkiye. The main objectives are to analyze the stages that the production of cottonseed biodiesel undergoes including cotton agriculture, cotton ginning, cotton crushing, cottonseed oil refining, and transesterification to produce biodiesel using a “from cradle to gate” approach to identify and quantify the related environmental impact potentials. Post-production stages and transportation between stages have been excluded from the study. The functional unit of a one-hectare field of cotton has been adopted and all the flows in the other stages are based on this functional unit. The system boundary consists of 5 total stages and each stage has several sub-stages. Figure 1 summarizes the production chain of biodiesel production from cotton seed. The five main phases, agriculture, ginning, crushing, refining, and transesterification, and the related sub-stages are described in detail below.

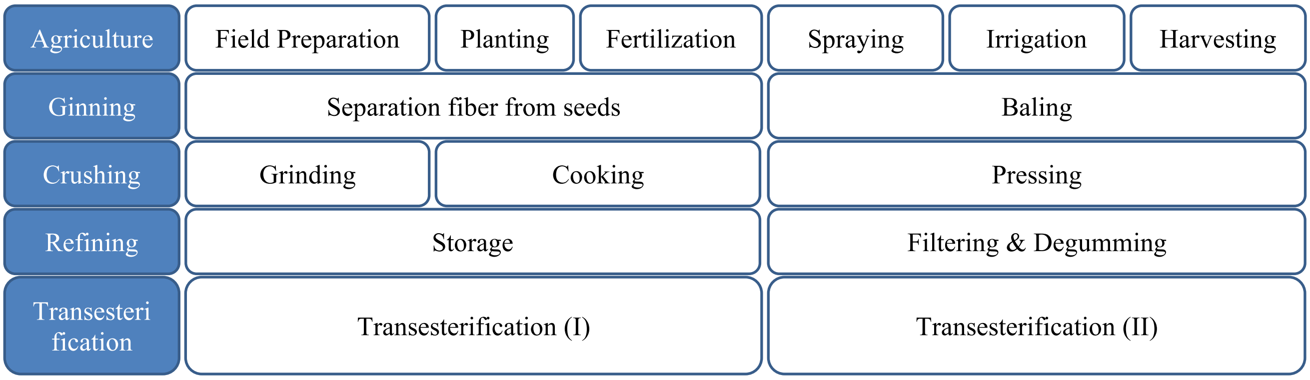


Figure 1. The system boundary of the production of biodiesel from cottonseed oil.

2.1.1. Cotton cultivation and harvesting

Gossypium hirsutum, belonging to the Malvaceae family, is the scientific name for cotton. It is a tropical/subtropical plant but can also be grown outside the Tropics in suitable geographical regions [40]. Its efficient cultivation and the quality of the yield are determined by temperature, soil, sunlight, supplementary nutrients, irrigation or rainfall, and crop care [41]. The cultivation of cotton is the first phase of the production cycle and comprises a number of steps, namely field preparation, planting, fertilization, spraying, irrigation, and harvesting [42] which are described in the following subsections. Figure 2 outlines the inputs and outputs of the agriculture phase.

Field preparation

Soil preparation is a vital step before sowing the seeds as it can affect the final yield. It includes deep plowing to a depth between 25-30 cm to aerate the seedbed ensuring the propagation of microorganisms in the soil and the conversion of plant residue into organic matter [40], [43]. In the initial preparations of the land, tractors are used for plowing [42]. Moreover, a special kind of soil regulator, “Rekor Gelişim®”, is used to improve the structure of the soil by preventing the soil from becoming slippery in the rainy season after planting [43]. According to local soil conditions, 300-400 kg of soil regulator or the base fertilizer is applied per hectare[44], [45].

Crop planting

The sowing of seeds starts when the growing circumstances become appropriate in the prepared field. The soil temperature of the seedbed should reach 15°C in the morning whilst the soil should have been dry for 5-6 days. Seeds are planted at a depth of 3-4 cm [46]. In Türkiye, the planting period starts from mid-March till mid-May [46] using a seeder. An area of one hectare requires 20 kg of cotton seeds [46].

Fertilization

Deficiency of required nutrients affects the growth and development of the plant and, consequently, reduces the yield. Therefore, fertilization is a critical process, which has to be done correctly with the requisite quantity of fertilizer [42]. Fertilizers contain nitrogen to maximize yield, phosphorous to stimulate the splitting of cotton bolls and improve the quality of fibers and potassium which has a role in respiration, and protein synthesis. Its application is based on the particular soil's requirement [40]. There are various fertilizers used in cotton cultivation [44]. The base fertilizer (N, P, and K) is added before planting with around 300-400 kg per hectare and is generally applied once every two years [44], [45].

Spraying

This step includes weed control as well as pest control. Cotton productivity can be decreased by 30% due to the presence of weeds [49]. Weed control can be achieved using crop rotation and herbicides while pest control requires the use of insecticides [40], [49]. To overcome the problems of both weeds and insects, "Rekor Liquid leaf fertilizer ®" is applied in Türkiye mid-season when the flowers start to grow and 10-12 days before the first irrigation. One liter is combined with 400-500 L of water for an area around 1-1.5 hectares and is applied at least twice [44], [50].

Irrigation

The timing of irrigation is a sensitive issue in cotton production. Although it varies according to region, the first irrigation must be between 35-40 days after planting after which the amount of water required increases rapidly until the opening of the top flower [51]. Cotton's average water requirement ranges between 6-7 million liters per hectare [52].

Harvesting

The harvesting period in Türkiye begins in mid-August and continues until November [47]. Cotton is harvested using harvesting machines. The opening of cotton bolls indicates the beginning of harvesting [40]. In 2019, the average yield was 1883 kg/ha of cotton lint [53]. As a rule of thumb, the harvested yield or unginned yield consists of about 32-33% fibers, 52-54% cottonseeds, and 15% leaves and other detritus [54].

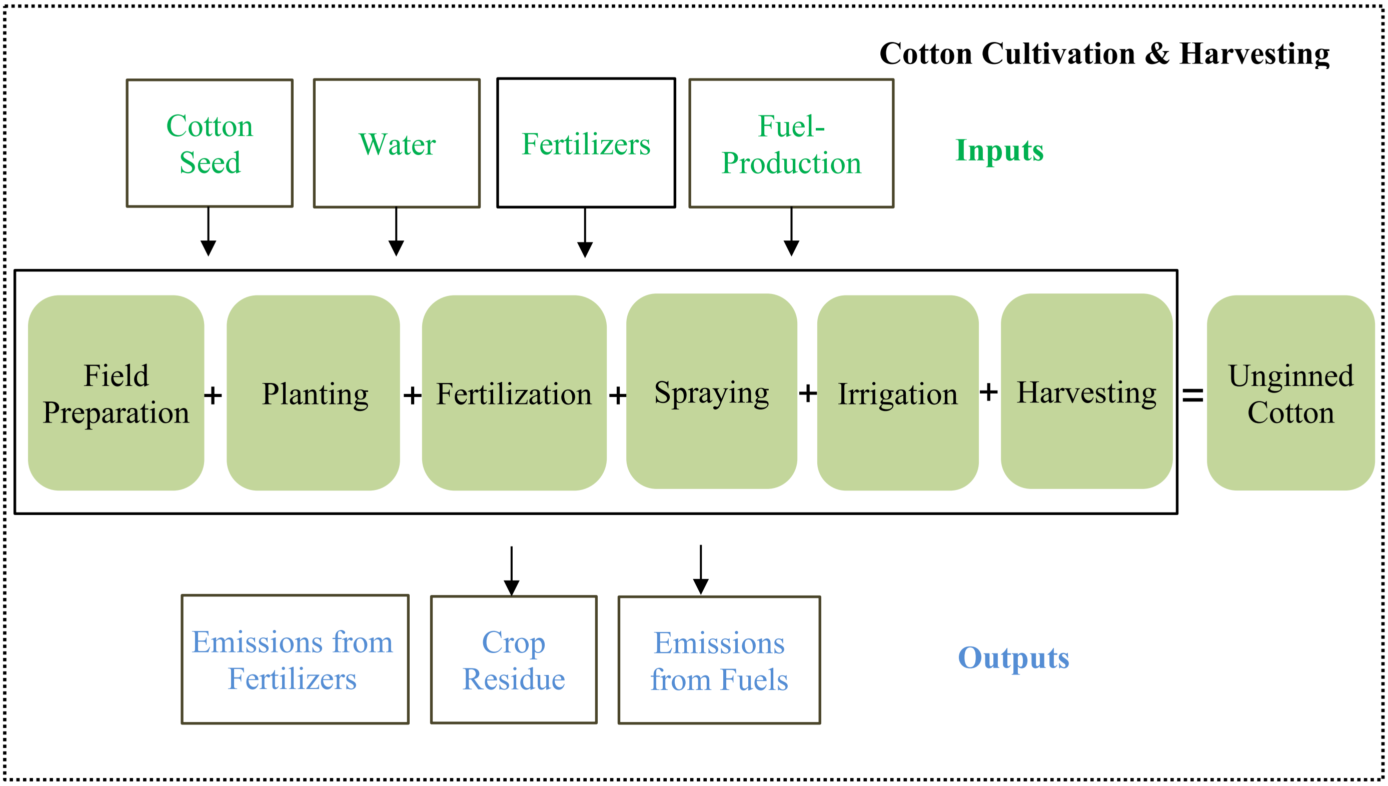


Figure 2. System boundary for cultivation phase.

2.1.2. Cotton ginning

The separation of cotton lint fiber from the cottonseed occurs in this phase by removing the wastes attached to the cottonseed and bridges both the textile industry and agriculture [41]. The process involves many sub-stages including opening the cotton bales, cleaning, blending, combing, and spinning [55]. Figure 3 summarizes the flows of the cotton ginning phase.

2.1.3. Cottonseed oil extraction

Oil from cottonseed is extracted either mechanically (mechanical extraction method) or chemically (solvent extraction method) [56]. For mechanical extraction, after storage, the seeds are sieved to get rid of impurities and are then crushed into small bits using hammer mills or discs before being cooked in pots using steam. Finally, the resulting mixture is pressed from which the crude cottonseed oil is extracted with the remnants forming cottonseed meal which is sold as an organic fertilizer. The oil is decanted and stored at room temperature [37]. The content of oil in cottonseeds ranges between 12-25% [15], while cottonseed meal accounts for about 42% [57]. Figure 4 describes the system boundary for the oil extraction stage:

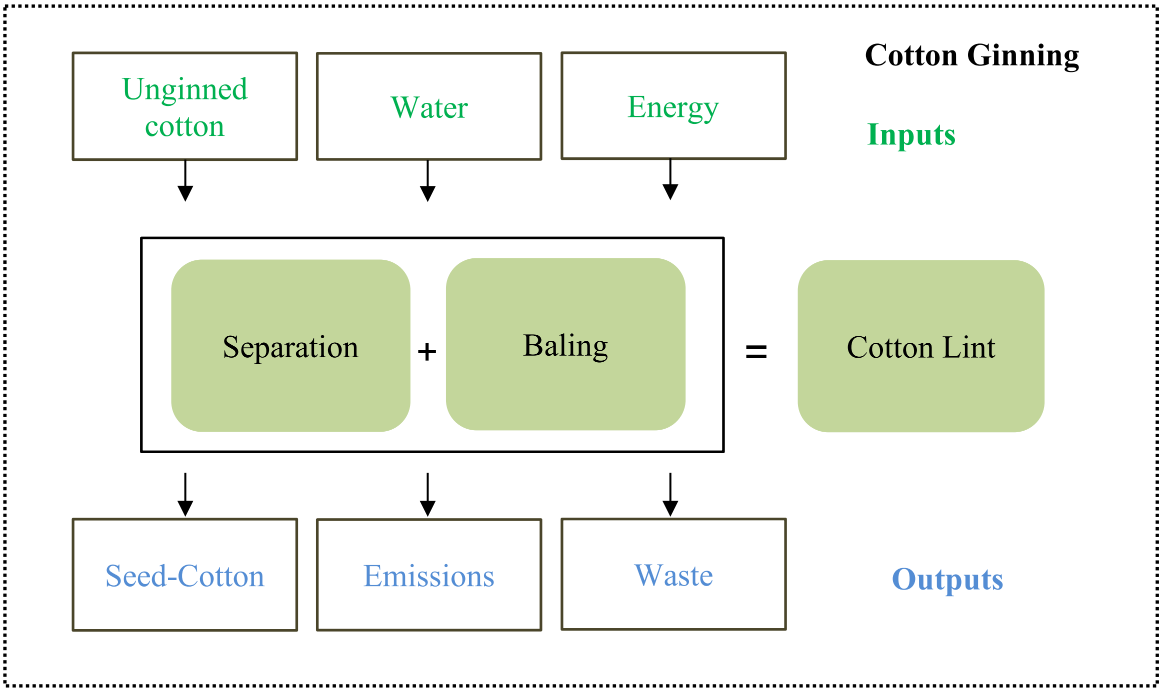


Figure 3. System boundary for cotton ginning phase.

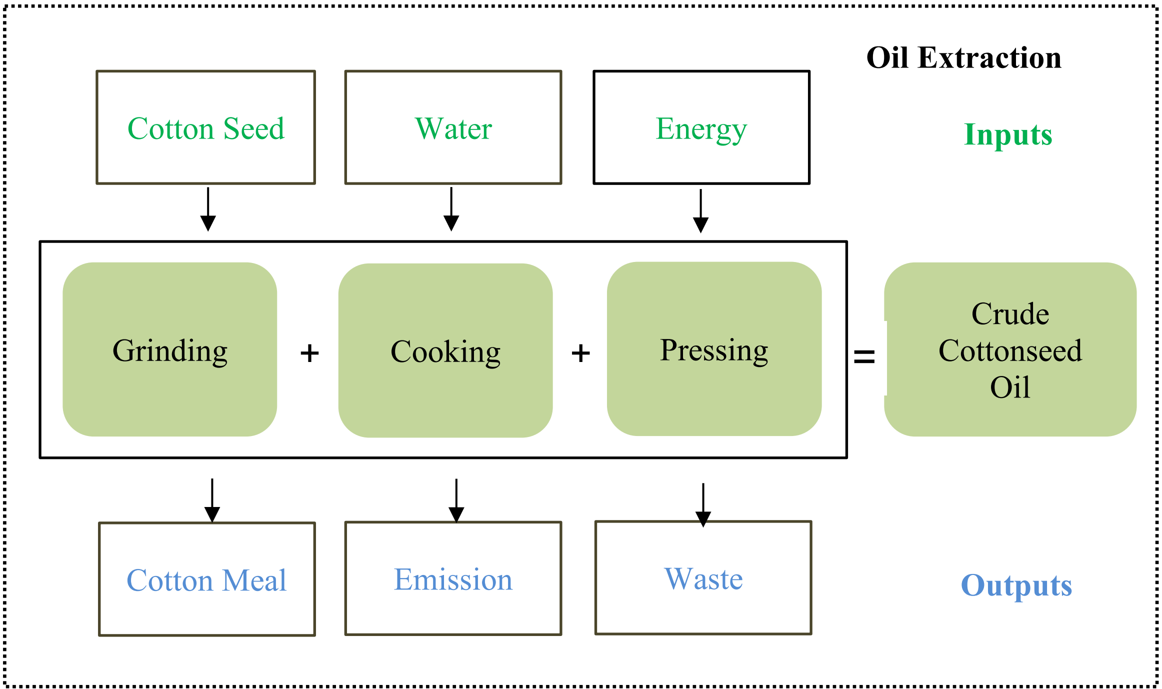


Figure 4. System boundary for seed oil extraction phase.

2.1.4. Cottonseed oil refinement

Crude oils contain several impurities like free fatty acids, non-fatty substances that are called gums, and color pigments. The main purpose of the refining process is to eliminate these impurities through several steps [58] including degumming, neutralization, bleaching, and deodorization [59]. The storage of crude oil is also important to reduce losses related to starts and shutdowns and to convey the oil to the refining operations [58]. The degumming step involves the addition of water, and diluted acids such as phosphoric acid after the oil has been heated to 60-70°C after which the subsequent reaction is maintained for 30 minutes at 70°C to facilitate full gum hydration. Thereafter, a specific quantity of caustic soda is added to equalize the free fatty acid [59], [60]. From that point on, the degummed oil undergoes centrifugal separation, the addition of bleaching earth, and so on. [59]. Figure 5 presents the system boundary for this stage.

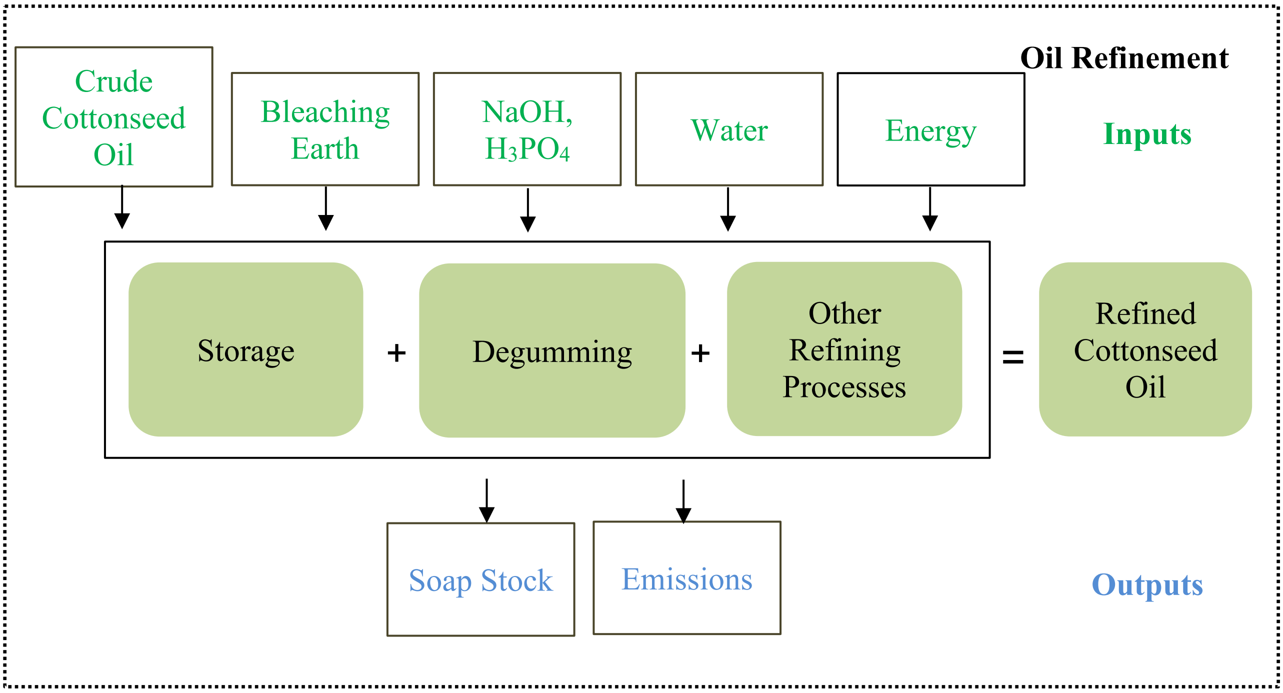


Figure 5. System boundary for oil refinement phase.

2.1.5. Transesterification

Transesterification is a chemical reaction of triglycerides and alcohol in the presence of a base, either an acid or an enzyme catalyst based on the type of raw material, to produce fatty acid methyl ester (FAME) and glycerol [61][62]. The choice of transesterification route is highly related to the cost of the production [63]. Right now, biodiesel through alkaline-catalyzed transesterification is still the most adopted and widely used in biodiesel production because it has a high energy yield, less deterioration of equipment, and a high rate of reaction. Furthermore, the reaction takes place at low temperatures and pressure, with low catalyst concentrations, and it is suitable for pure vegetable oils [64]. Base catalysts like sodium hydroxide and potassium hydroxide are the most commonly used in transesterification and the ease of solubility of methanol in NaOH as well as its rapid reaction with triglycerides, makes it preferable to ethanol [65]. The typical ratio of methanol to triglyceride is 3:1 to have a complete transesterification reaction. However, since the reaction is in equilibrium, an additional quantity of methanol is required to shift the reaction toward the outputs of the equation and enhance the productivity of the reaction. According to Hoda. N [66], the 6:1 molar ratio shows good results in terms of the conversion yield of cottonseed oil, and 0.3% NaOH is enough to produce biodiesel FAME from cottonseed oil. Hanh et al. [67] reported that 0.3 to 1% concentration of alkali catalysts has accomplished effective conversion based on the oil used. After the transesterification reaction, the product passes through the purification process to refine the biodiesel by removing any excess contaminants and impurities such as methanol, NaOH, soap, wax, etc. to comply with international standards [68]. Wet washing is one of the methods that is used in this process. It ivolves adding water to neutralize the effect of the unreacted alkaline catalyst. Although any excess methanol can be removed before or after washing, it is preferable to flush it out before [69].

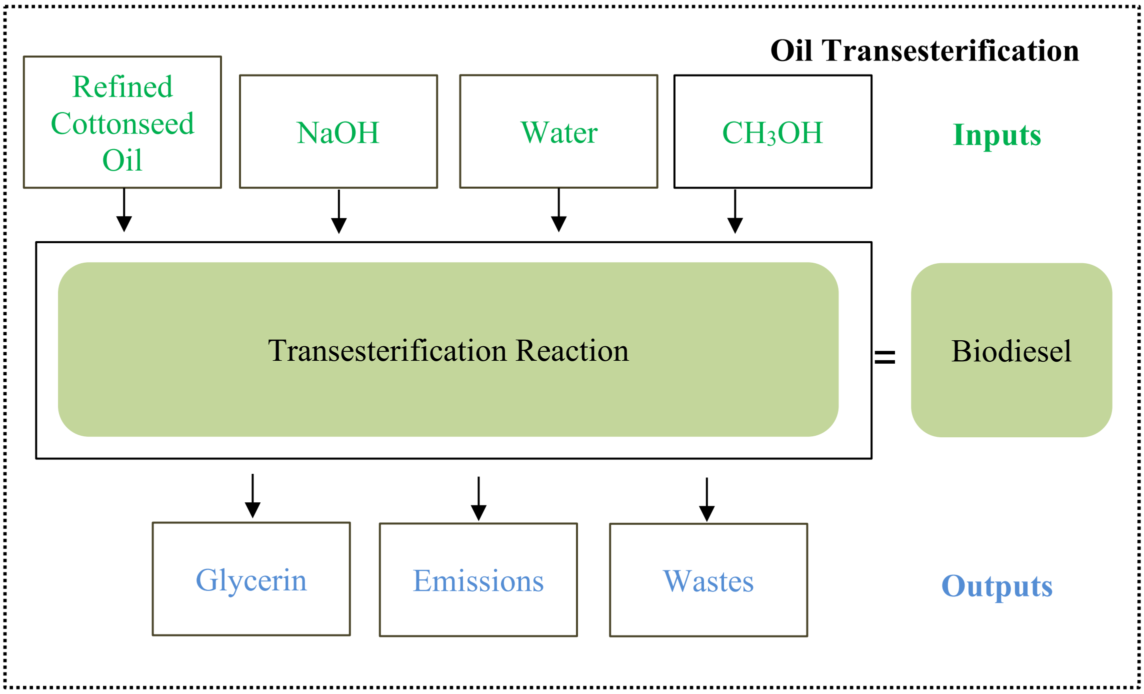


Figure 6. System boundary of oil transesterification phase.

2.2. Life cycle inventory

The production of cottonseed-based biodiesel is a multi-output process which means that materials should be allocated not only to the major product but also to co-products and by-products throughout the life cycle inventory. Mass-based allocation is one of the approaches to assign the inputs and outputs of the phases due to its straightforwardness. Table 1 depicts the allocation percentages that are used in the inventory data for each stage.

Table 1. The used allocation percentages for the stages.

Type	Allocation Percentage (%)	Phase	Reference
Seed-cotton	53	Cotton harvesting and ginning	[54]
Cotton	32	Cotton harvesting and ginning	[54]
Crude cottonseed oil	22	Oil extraction	[15]
Cotton meal	42	Oil extraction	[57]
Refined cottonseed oil	94	Oil refinement	[70]
Soapstock	6	Oil refinement	[70]
Biodiesel	89	Transesterification	[71]
Glycerin	11	Transesterification	[71]

Tables 2, Table 3, Table 4, Table 5, and Table 6 present the inventory data for cotton cultivation, cotton ginning, cottonseed oil extraction, cottonseed oil refinement, and oil transesterification, respectively.

Table 2. The inventory data for cultivation for 1 ha as a functional unit.

Inputs	*Quantity*	*Unit*	*Reference*
Cotton seed	20	kg	calculated using [46]
Soil preparation & tillage [1]	1	ha	OpenLCA
K_2O fertilizer	87.5	kg	calculated using [43], [44], [45]
Phosphate fertilizer	87.5	kg	calculated using [43], [44], [45]
Nitrogen fertilizer	175	kg	calculated using [43], [44], [45]
Water	6500	m^3	[52]
Sprayer	0.8	L	calculated using [44], [50]
Broadcast seeder [2]	1	ha	OpenLCA
Broadcast sprayer [3]	1	ha	OpenLCA
Cotton stripper-harvesting [4]	1	ha	OpenLCA

Outputs	Quantity	Unit	Reference
Unginned cotton	5800	kg	calculated

1: The type of tillage is unspecified. **2:** The specifications are assumed 75HP tractor and 20 ft wide.
3: 125 HP tractor and 60 ft wide. **4:** 150 HP and R5-8.

Table 3. The Inventory data for cotton ginning for 1 ha as a functional unit.

Inputs	*Quantity*	*Unit*	*Reference*
Unginned cotton	5800	kg	calculated
Water	0.038	m^3	calculated using [72]
Electricity	23.68	MWh	calculated using [73]
Outputs	***Quantity***	***Unit***	***Reference***
Cotton lint	1883	kg	[52]
Seed cotton	3070	kg	calculated
Cotton residue	847	kg	calculated

Table 4. The Inventory data for the cottonseed oil extraction for 1 ha as a functional unit.

Inputs	*Quantity*	*Unit*	*Reference*
Seed cotton	3070	kg	calculated
Water	1.10	m^3	calculated using [37]
Energy	381	kWh	calculated using [57]
Outputs	***Quantity***	***Unit***	***Reference***
Crude cottonseed oil	675.4	kg	calculated
Cotton Meal	1289	kg	calculated

Table 5. The Inventory data for the cottonseed oil refinement phase for 1 ha as a functional unit.

Inputs	*Quantity*	*Unit*	*Reference*
Crude cottonseed oil	675.4	kg	calculated
Phosphoric acid	0.84	kg	calculated using [74]
Sodium hydroxide	13.5	kg	calculated using [74]
Water	62	kg	[58]
Outputs	***Quantity***	***Unit***	***Reference***
Refined cottonseed oil	648.36	kg	calculated using [70]
Soap stock	41.38	kg	calculated using [70]

Table 6. The Inventory data for the oil transesterification phase for 1 ha as a functional unit.

Inputs	***Quantity***	***Unit***	***Reference***
Refined cottonseed oil	648.36	kg	calculated
Methanol	146.93	kg	calculated by 6:1 ratio [75]
NaOH	2.5	kg	calculated using [76]
Water	518.69	kg	calculated using [77]
Electricity	90.05	MJ	calculated using [78]
Heat	294.05	MJ	calculated using [78]
Outputs	***Quantity***	***Unit***	***Reference***
Biodiesel	577	kg	calculated using [71]
Glycerin	71.32	kg	calculated using [71]
Wastewater	274.1	kg	calculated using [79]

3. RESULTS & DISCUSSION

The impact assessment method was performed using the CML-IA baseline available in the OpenLCA 1.11.0 software to better understand the environmental impact categories. This analysis determines the environmental loads of each phase of the production chain of biodiesel, which in turn provides researchers and decision-makers with valuable information about agricultural development, the textile industry, and oil extraction and refinement. The functional unit of 1 hectare of the cotton field has been adopted for many reasons. This type of functional unit falls under agricultural land use-oriented functional units, which have been rarely adopted in the literature. It is appropriate for first-generation feedstocks; it also drives helpful results at the policy level. Finally, it shows the efficiency of agricultural management [80]. The collection of data for any LCA can be challenging, and the availability of all material inputs for each stage was a major challenge in this study. As mentioned previously, there is no published data for LCA of biodiesel from cottonseed oil in Türkiye, so the only practical solution was to use secondary sources for the majority of the data. Because of this, a level of uncertainty may arise for the presented results. The impact categories that have been identified are the potential for global warming, acidification, abiotic depletion, abiotic depletion of fossil fuel, and eutrophication, which are sufficient to give prudent insights to policymakers. The analysis of these impact categories is enabled by the calculation of the equivalent CO_2, SO_2, Sb, MJ, and PO_4^{3-}, respectively. In the cotton agriculture stage, nitrogen fertilizers, cotton strippers, phosphate, and K_2O fertilizers are the main inputs that have the greatest potential impact, respectively. In the cotton ginning and oil extraction stages, electricity seems to be the main influencing input. In the meantime, bleaching material and heat production are the major inputs that affect the potentials significantly in oil refinement and transesterification, respectively. Regardless of the method, feedstock, country, and functional unit, most LCA studies of biodiesel production found that the cultivation phase is the most significant contributor to environmental categories such as sunflower [81], palm oil [82], and cottonseed oil in Brazil [37]. However, this study indicates different results from these studies. The reason for this is the use of local organic fertilizers in Türkiye for cotton cultivation like "Rekor Gelişim®". Nevertheless, N and K fertilizers are the main contributors to the impact categories in the cultivation phase followed by cotton harvesting using heavy machines. Indeed, the shift to modern agricultural practices has led to a rise in environmental pollution globally [83]. The high usage of electricity is the major contributor to the cotton ginning and oil extraction phases. Fossil fuels and their byproducts, widely utilized in global electricity generation, contribute to environmental pollution while also adversely impacting the health of humans, animals, and plants [84]. Figure 7 shows the assessment of the impact categories for each phase of the production chain of biodiesel from cottonseed oil.

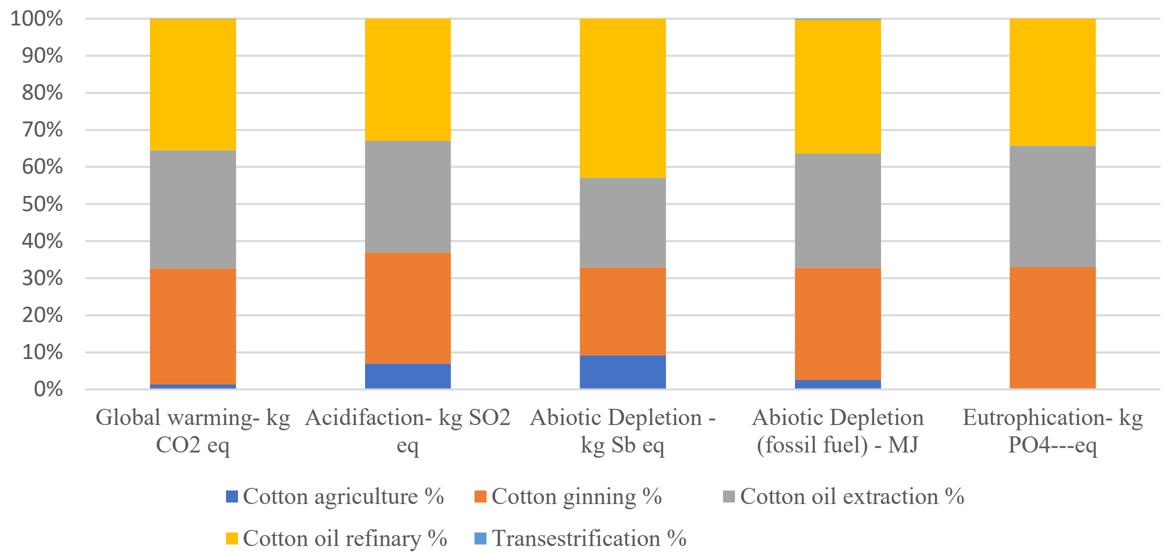


Figure 7. Assessment of impact categories of biodiesel production phases for 1 ha of a cotton field.

3.1. Global warming potential (GWP)

GWP measures the impact of CO_2 emissions in the atmosphere and is represented by the kg CO_2 -eq. Based on the performed analysis method, the total equivalent quantity of CO_2 for all the stages of biodiesel production is 60,541 kg for the functional unit of 1 ha of a cotton field. The results show that the oil refinement phase has the largest impact on GWP with 35.35%. The impacts of cotton ginning and oil extraction are 31.28% and 31.92%, respectively. Meanwhile, agriculture has a surprisingly low impact at 1.36%. In comparison, an LCA study in Bahia, Brazil estimated GWP at 1,475 kg CO_2 -eq per 1,000 kg of biodiesel, with agriculture identified as the dominant contributor due to high fertilizer dependency [37]. Similarly, a study published by MDPI reported a GWP of 17.247 kg CO_2 -eq per kg of biodiesel, demonstrating significant emissions from the agricultural phase, particularly related to nitrogen fertilizer application and fossil fuel consumption for machinery [23]. While previous LCA studies generally attribute the highest GWP values to agricultural activities, the current study highlights processing stages (cotton ginning and refining) as the predominant contributors. The difference may be attributed to Türkiye's agricultural practices, which integrate organic fertilizers rather than conventional nitrogen-intensive fertilizers, potentially mitigating cultivation-related emissions.

3.2. Acidification Potential (ACP)

ACP refers to the many compounds that cause acid rain. The reference unit of this potential is kg SO_2-eq. According to the results, the total value was about 703 kg SO_2-eq, with cotton ginning, oil extraction, and oil refinement being the main contributors. The emissions of NO_x, SO_x, and ammonia are the compounds that affect this category the most. The cotton ginning phase contributes 30.03%, while oil extraction and refinement contribute 30.16% and 32.81%, respectively. The agriculture phase contributes 1.65%, and the transesterification 0.04%. In contrast, the Bahia, Brazil LCA study recorded 17.5 kg SO_2-eq per 1,000 kg of biodiesel, primarily driven by agricultural practices, including fertilizer use and pesticide applications [37]. Findings from a MDPI study on oil extraction techniques identified sulfuric acid usage in cottonseed oil processing as a significant ACP contributor, aligning with the present study's emphasis on refinement and extraction emissions [23]. In previous studies, agriculture (fertilizer and pesticide application) was responsible for the majority of acidification impacts. In Türkiye's context, the ACP is primarily influenced by industrial processing rather than cultivation. This distinction suggests a strong reliance on electricity-intensive techniques for refining and extraction, necessitating further investigation into potential renewable energy integrations to minimize ACP.

3.3. Abiotic depletion potential (ADP)

This is a measure that demonstrates the exploitation of non-renewable sources to produce energy. It can be divided into the material component, which is measured in kg Sb-eq, and the fossil fuel component in MJ-eq [85], [86]. Based on the analysis, the material component of the ADP represents a total quantity of 0.03 kg Sb-eq with 206,075 MJ for the fossil fuel component. The agriculture phase accounts for 9.18%, cotton ginning, and oil extraction 23.79% and 24.17%, respectively, and oil refinement for 42.84%. and transesterification 0.02%. Oil refining has the greatest impact on this category. The Bahia, Brazil study reported 5.0×10^{-3} kg Sb-eq per 1,000 kg of biodiesel, identifying agriculture as the primary contributor due to high fossil fuel consumption for irrigation and mechanized farming [37]. A study from MDPI reported 89.116 MJ primary energy per kg of biodiesel, emphasizing significant energy consumption during processing and transesterification stages [23]. Unlike Brazilian findings, which emphasize agricultural fossil fuel consumption, Türkiye's results highlight oil refinement as the dominant ADP contributor. This underscores the need for energy efficiency improvements in processing plants, possibly through renewable electricity adoption to reduce fossil fuel dependency.

3.4. Eutrophication potential (EP)

EP refers to the excess supply of nutrients in water bodies and soils and kg PO_4^{3-}-eq is the reference unit for EP potential [87]. The results of this category are 0.28%, 32.73%, 32.75%, and 34.24% for agriculture, cotton ginning, oil extraction, and oil refinement, respectively, from a total of 3964 kg PO_4^{3-}-eq. Transesterification does not affect this category. Bahia, Brazil's cottonseed biodiesel LCA recorded 10 kg PO_4^{3-} eq per 1,000 kg of biodiesel, identifying agriculture as the most critical contributor due to fertilizer runoff [37]. A European biodiesel study concluded that fertilization runoff significantly impacts EP, highlighting nitrogen leaching as a major concern [68]. While previous studies emphasize agriculture's role in eutrophication, Türkiye's findings indicate processing stages (oil refinement and extraction) as major EP contributors. This discrepancy may arise due to reduced fertilizer runoff in Türkiye's cotton farming, shifting the eutrophication burden to chemical-intensive oil processing.

According to the data in this study, cotton ginning, oil extraction, and oil refinement stages have the biggest impacts on these potentials. The greatest impact of biodiesel production was on the global warming potential category. Cotton cultivation has the least impact on all the potentials, although the application of fertilizers (N, P, and K), agrochemicals, and the type of tillage have a significant impact. The conversion to organic farming presents an opportunity to minimize environmental impacts in the cultivation and harvesting phase [88]. The high use of electricity and equipment is largely responsible for the impacts of the other phases. As regards transesterification, the treatment of wastewater is critical as its contents include chemical oxygen demand, oil, alcohol, and glycerin, which have environmental impacts [89]. As previously mentioned, there are no similar LCA studies of biodiesel production using cottonseed oil and there are few studies that deal with the textile side of cotton in Türkiye.

4. CONCLUSION

Progress in the biodiesel industry can occur through enacting energy policies that regulate sustainability with reference to its triple pillars (environment, economy, and society). The deployment of biodiesel blends in the transportation sector in Türkiye is slow and remains insignificant. The impact of biodiesel is linked to both the feedstock and its life cycle and thus life cycle assessment is a necessary procedure that should be taken into consideration when planning new policies. Our study assesses the environmental impacts related to cotton cultivation, cotton ginning, oil extraction, refinement, and finally biodiesel production using a transesterification reaction. The global warming potential, acidification, abiotic depletion of fossil fuel, and eutrophication are the impact categories that have been studied for all the phases based on the functional unit of 1 hectare of cotton cultivation using the CML-IA baseline method with OpenLCA software. The results of the analysis show that the stages of cotton ginning and oil refining have the biggest impacts on the defined environmental potentials.

The results should be interpreted bearing in mind that they exclude the post-production use of biodiesel as well as the transportation occurring between stages and the allocation percentages of co-products. Furthermore, due to the lack of current data, much of the data has been generated from secondary sources.

For future studies, researchers should focus on conducting a comprehensive life cycle assessment using primary data sources to reduce uncertainty and enhance accuracy, particularly for cottonseed biodiesel production in Türkiye. Expanding the study to include post-production emissions, transportation impacts, and economic feasibility would provide a more holistic perspective. Additionally, investigating state-of-the-art biodiesel production techniques, such as supercritical transesterification, and evaluating their environmental benefits compared to conventional methods could further optimize sustainability. Finally, assessing the engine performance and air emissions of cottonseed-based biodiesel blends in Türkiye would help validate its practical viability and support future policy decisions.

In summary, this study highlights the environmental impact of biodiesel production from cottonseed oil in Türkiye, identifying key contributors and areas for improvement. Here are the main concluding remarks:

- Cottonseed biodiesel production in Türkiye has significant environmental impacts, with cotton ginning, oil extraction, and refinement being the most influential stages.
- Global Warming Potential: 60,541 kg CO_2-eq per hectare, with cotton oil refinement (35.35%) and cotton ginning (31.28%) being the largest contributors.
- Acidification Potential: 703 kg SO_2-eq, where cotton refinement (32.81%) and oil extraction (30.16%) have the highest impacts.
- Abiotic Depletion Potential: 206,075 MJ fossil fuel depletion and 0.03 kg Sb-eq material depletion, with oil refinement responsible for 42.84% of fossil depletion impacts.
- Eutrophication Potential: 3964 kg PO_4^{3-}-eq, primarily driven by oil refinement (34.24%) and cotton oil extraction (32.75%).
- Electricity consumption in processing stages contributes heavily to acidification potential and abiotic depletion, emphasizing the role of renewable energy integration in production.
- Cotton cultivation has a lower environmental impact, largely due to the use of organic fertilizers, but improvements in sustainable farming techniques can further enhance eco-efficiency.
- The transesterification process has the smallest environmental impact, but requires optimized waste treatment and purification methods to improve sustainability.
- Future research should conduct a full cradle-to-grave LCA, including post-production emissions, transportation effects, and economic feasibility, to present a comprehensive environmental outlook.
- Policymakers and industry leaders should use LCA insights to promote sustainable biodiesel practices, ensuring long-term environmental and energy security benefits for Türkiye.

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Aliaa Saleh: Software, Investigation, Writing - Original Draft.

Hidayet Oğuz: Conceptualization, Methodology, Validation.

Atıf Emre Demet: Writing - Review & Editing, Supervision, Project Administration.

CONFLICT OF INTEREST

The authors declare that they do not have any financial and personal relationships that might have biased the results of the presented work.

REFERENCES

[1] Amigun B, Musango J K, and Stafford W, Biofuels and sustainability in Africa. Renewable and Sustainable Energy Reviews 2011; 15: 1360–1372.

[2] Yang L, Takase M, Zhang M, Zhao T, and Wu X, Potential non-edible oil feedstock for biodiesel production in Africa: A survey, Renewable and Sustainable Energy Reviews 2014; 38: 461–477.

[3] Al-Shetwi A. Sustainable development of renewable energy integrated power sector: trends, environmental impacts, and recent challenges. Science of the Total Environment 2022; 822: 153645.

[4] Attia A, Nour M, Nada S. Study of Egyptian castor biodiesel-diesel fuel properties and diesel engine performance for a wide range of blending ratios and operating conditions for the sake of the optimal blending ratio. Energy Conversion and Management 2018; 174: 364–377.

[5] Kaya A, Karaosmanoglu F. Life cycle assessment of safflower and sugar beet molasses-based biofuels. Renewable Energy 2022; 201: 1127–1138.

[6] IEA. Turkey 2021. International Energy Agency 2021. Available at: IEA Report.

[7] Dahiya A. Cutting-edge biofuel conversion technologies to integrate into petroleum-based infrastructure and integrated biorefineries. Bioenergy 2015; 467–485.

[8] Sanz Requena J, et al. Life Cycle Assessment (LCA) of the biofuel production process from sunflower oil, rapeseed oil and soybean oil. Fuel Processing Technology 2011; 92(2): 190–199.

[9] Tokel D, Dogan I, Ozyigit I. Cotton agriculture in Turkey and worldwide economic impacts of Turkish cotton. Journal of Natural Fibers 2022; 19(15): 10648–10667.

[10] Atabani A, Mahlia T, Badruddin I, Masjuki H, Chong W, Lee K. Investigation of physical and chemical properties of potential edible and non-edible feedstocks for biodiesel production, a comparative analysis. Renewable and Sustainable Energy Reviews 2013; 21: 749–755.

[11] Fernandes D, Serqueira D, Portela F, Assunção R, Munoz R, Terrones M. Preparation and characterization of methylic and ethylic biodiesel from cottonseed oil and effect of tert-butylhydroquinone on its oxidative stability. Fuel 2012; 97: 658–661.

[12] Salunkhe D, Chavan J, Adsule R, Kadam S. World oilseeds: chemistry, technology, and utilization. Van Nostrand Reinhold 1992. [http://lib.ugent.be/catalog/rug01:000261128].

[13] Patni N, Bhomia C, Dasgupta P, Tripathi N. Use of sunflower and cottonseed oil to prepare biodiesel by catalyst assisted transesterification. 2013. [https://api.semanticscholar.org/CorpusID:55917688].

[14] Turkey Cottonseed Oil Production by Year (1000 MT). IndexMundi 2022. [https://www.indexmundi.com/agriculture/?country=tr&commodity=cottonseed-oil&graph=production].

[15] Bozdoğan Konuşkan D, Yilmaztekin M, Mert M, Gençer O. Physico-chemical characteristic and fatty acids compositions of cottonseed oils. Journal of Agricultural Sciences (Belihuloya) 2017; 23: 253–259.

[16] Andreo-Martínez P, Ortiz-Martínez V, García-Martínez N, de los Ríos A, Hernández-Fernández F, Quesada-Medina J. Production of biodiesel under supercritical conditions: state of the art and bibliometric analysis. Applied Energy 2020; 264: 114753.

[17] Sreeharsha R, Dubey N, Mohan S. Orienting biodiesel production towards sustainability and circularity by tailoring the feedstock and processes. Journal of Cleaner Production 2023; 414: 137526.

[18] Ambat I, Srivastava V, Sillanpää M. Recent advancement in biodiesel production methodologies using various feedstock: a review. Renewable and Sustainable Energy Reviews 2018; 90: 356–369.

[19] Rizwanul Fattah I, Ong H, Mahlia T, Mofijur M, Silitonga A, Rahman S, Ahmad A. State of the art of catalysts for biodiesel production. Frontiers in Energy Research 2020; 8.

[20] Qadeer M, Ayoub M, Komiyama M, Khan Daulatzai M, Mukhtar A, Saqib S, Ullah S, Qyyum M, Asif S, Bokhari A. Review of biodiesel synthesis technologies, current trends, yield influencing factors and economical analysis of supercritical process. Journal of Cleaner Production 2021; 309: 127388.

[21] Anikeev V, Yakovleva E. Biodiesel synthesis from vegetable oils with supercritical methanol. Journal of Supercritical Fluids 2013; 77: 100–102.

[22] Zhang Y, Zhong Y, Lu S, Zhang Z, Tan D. A comprehensive review of the properties, performance, combustion, and emissions of the diesel engine fueled with different generations of biodiesel. Processes 2022; 10(6).

[23] Jamshaid M, Masjuki H, Kalam M, Zulkifli N, Arslan A, Qureshi A. Experimental investigation of performance, emissions and tribological characteristics of B20 blend from cottonseed and palm oil biodiesels. Energy 2022; 239: 121894.

[24] Shankar A, Pentapati P, Prasad R. Biodiesel synthesis from cottonseed oil using homogeneous alkali catalyst and using heterogeneous multi walled carbon nanotubes: characterization and blending studies. Egyptian Journal of Petroleum 2017; 26(1): 125–133.

[25] Lee K, Inaba A. Life Cycle Assessment best practices of ISO 14040 series. Center for Ecodesign and LCA (CEL), Ajou University 2004.

[26] Li N, Guo Y. Life Cycle Assessment of Rapeseed Biodiesel. World Electric Vehicle 2010.

[27] Hosseinzadeh-Bandbafha H, et al. Environmental life cycle assessment of biodiesel production from waste cooking oil: a systematic review. Renewable and Sustainable Energy Reviews 2022; 161: 112411.

[28] Gupta V, Tuohy M. Biodiesel from production to combustion. Springer Cham 2018; 8.

[29] Fernández-Tirado F, Parra-López C, Romero-Gámez M. A multi-criteria sustainability assessment for biodiesel alternatives in Spain: life cycle assessment normalization and weighting. Renewable Energy 2021; 164: 1195–1203.

[30] Waudby H, Zein S. A circular economy approach for industrial scale biodiesel production from palm oil mill effluent using microwave heating: design, simulation, techno-economic analysis and location comparison. Process Safety and Environmental Protection 2021; 148: 1006–1018.

[31] Rebolledo-Leiva R, Moreira M, González-García S. Progress of social assessment in the framework of bioeconomy under a life cycle perspective. Renewable and Sustainable Energy Reviews 2023; 175: 113162.

[32] Sreeharsha R, Dubey N, Mohan S. Orienting biodiesel production towards sustainability and circularity by tailoring the feedstock and processes. Journal of Cleaner Production 2023; 414: 137526.

[33] Cevheribucak G. Energy transition and sustainable road transportation in Turkey: multiple policy challenges for inclusive change. Frontiers in Sustainable Cities 2021; 3.

[34] Prado V, Daystar J, Pires S, Wallace M, Laurin L. Comparative life cycle assessment of edible vegetable frying oils. Transactions of the ASABE 2021; 64(6): 1717–1733.

[35] Gallejones P, Pardo G, Aizpurua A, del Prado A. Life cycle assessment of first-generation biofuels using a nitrogen crop model. Science of The Total Environment 2015; 505: 1191–1201.

[36] Soraya D, Gheewala S, Bonnet S, Tongurai C. Life Cycle Assessment of biodiesel production from palm oil in Indonesia. Journal of Sustainable Energy & Environment 2014; 5: 27–32.

[37] Lima A, Torres E, Kiperstok A, Moreira Santos G. Environmental impacts of the biodiesel production chain of cotton seed in Bahia, Brazil. Clean Technologies and Environmental Policy 2017; 19(5): 1523–1534.

[38] Worja S. Role of Non-Timber Forest Products to local people livelihoods in Melut Area, Upper Nile State, South Sudan. Eregli Journal of Agricultural Science 2023; 3(1): 1–7.

[39] Isler-Kaya A, Karaosmanoglu F. Life cycle assessment of safflower and sugar beet molasses-based biofuels. Renewable Energy 2022; 201: 1127–1138.

[40] Department of Agriculture, Forestry and Fisheries. Cotton Production guideline. Republic of South Africa 2016.

[41] Baydar G, Ciliz N, Mammadov A. Life cycle assessment of cotton textile products in Turkey. Resources, Conservation and Recycling 2015; 104: 213–223.

[42] Singh R, Agrawak R, Bos U, Kanekar H. Life cycle assessment of cotton cultivation systems. India 2018.

[43] Cotton - Soil Preparation. Pamuk.org.tr.. Accessed Nov. 18, 2022.

[44] Cotton - Cotton Fertilization. Pamuk.org.tr.. Accessed Nov. 20, 2022.

[45] Rekor Gelişim Tarla Gübresi Broşürü. Rekorgubre.com.tr.. Accessed Nov. 20, 2022.

[46] Cotton - Cotton Cultivation. Pamuk.org.tr.. Accessed Nov. 19, 2022.

[47] Caglar E. Cotton and Products Annual. United States Department of Agriculture, Global Agricultural Information Network 2021.

[48] Ahmed N, et al. Role of macronutrients in cotton production. Cotton Production and Uses: Agronomy, Crop Protection, and Postharvest Technologies. Springer Singapore 2020; 81–104.

[49] Khawar J. Weed flora, yield losses and weed control in cotton crop. 2016.

[50] Rekor Gübre Yaprak Gübresi Broşürü. Rekorgubre.com.tr.. Accessed Nov. 20, 2022.

[51] Oğuz I, et al. Türkiye'de sürdürülebilir pamuk değer zincirlerinin desteklenmesi projesi. 2021.

[52] Cotton Australia. Cotton's water use. Accessed Nov. 20, 2022.

[53] Demir M. Turkey Country Report. 78th Plenary Meeting of the International Cotton Advisory Committee (ICAC) 2019.

[54] Cotton Harvest & Yields - Wikifarmer. Accessed Dec. 08, 2022.

[55] Bralla J. Handbook of manufacturing processes: how products, components and materials are made. Industrial Press, Inc. 2007.

[56] Hussein S, Mohammed E, Gasmelseed G. Extraction and Transesterification of cottonseed oil. Multi-Knowledge Electronic Comprehensive Journal for Education and Science Publications 2020.

[57] Jain M, Pal A, Kumar V. Life Cycle Assessment of Cotton Seed Oil. International Journal of Current Engineering and Scientific Research 2015.

[58] Carr R. Refining and Degumming Systems for Edible Fats and Oils. Journal of the American Oil Chemist's Society 1978; 55.

[59] Cottonseed Oil Refinery Plant Process || Cotton Seed Oil Refining Plant. Spectec India. Accessed Dec. 17, 2022. [https://www.spectecindia.com/cotton-seed-oil-refining-process/].

[60] Carr R. Degumming and refining practices in the U.S. Journal of the American Oil Chemists' Society 1976; 53(6): 347–352. [https://link.springer.com/article/10.1007/BF02605721].

[61] Alhassan Y, Kumar N, Bugaje I, Pali H, Kathkar P. Co-solvents transesterification of cotton seed oil into biodiesel: effects of reaction conditions on quality of fatty acids methyl esters. Energy Conversion and Management 2014; 84: 640–648.

[62] Fan X, Wang X, Chen F. Biodiesel production from crude cottonseed oil: an optimization process using response surface methodology. The Open Fuels & Energy Science Journal 2011; 4: 1–8.

[63] Salaheldeen M, Mariod A, Aroua M, Rahman S, Soudagar M, Rizwanul Fattah I. Current state and perspectives on transesterification of triglycerides for biodiesel production. Catalysts 2021; 11(9). [https://www.mdpi.com/2073-4344/11/9/1121].

[64] Babadi A, Rahmati S, Fakhlaei R, Barati B, Wang S, Doherty W, Ostrikov K. Emerging technologies for biodiesel production: processes, challenges, and opportunities. Biomass and Bioenergy 2022; 163: 106521. [https://colab.ws/articles/10.1016%2Fj.biombioe.2022.106521].

[65] Musa I. The effects of alcohol to oil molar ratios and the type of alcohol on biodiesel production using transesterification process. Egyptian Journal of Petroleum 2016; 25(1): 21–31.

[66] Hoda N. Optimization of biodiesel production from cottonseed oil by transesterification using NaOH and methanol. Energy Sources, Part A: Recovery, Utilization and Environmental Effects 2010; 32(5): 434–441.

[67] Hanh H, Dong N, Okitsu K, Maeda Y, Nishimura R. Effects of molar ratio, catalyst concentration and temperature on transesterification of triolein with ethanol under ultrasonic irradiation. Journal of the Japan Petroleum Institute 2007.

[68] Demir G, Soyhan H. Biodiesel production using wet and dry purification methods. European Journal of Engineering and Natural Sciences 2017; 2(1): 137–143.

[69] Atadashi I, Aroua M, Aziz A. Biodiesel separation and purification: a review. Renewable Energy 2011; 36(2): 437–443.

[70] Casali B, Brenna E, Parmeggiani F, Tessaro D, Tentori F. Enzymatic methods for the manipulation and valorization of soapstock from vegetable oil refining processes. Sustainable Chemistry 2021; 2(1): 74–91.

[71] Sinha D, Murugavelh S. Biodiesel production from waste cotton seed oil using low-cost catalyst: engine performance and emission characteristics. Perspectives in Science 2016; 8: 237–240.

[72] Embassy of Ethiopia. Profile on Cotton Ginning Plant Report 2013.

[73] Koç E, Kaplan E. An investigation on energy consumption in yarn production with special reference to ring spinning. Fibers & Textiles in Eastern Europe 2007.

[74] CN102250683A - Alkali refining process of cottonseed oil. Google Patents. Accessed Dec. 26, 2022. [https://patents.google.com/patent/CN102250683A/en]

[75] Hoda N. Optimization of biodiesel production from cottonseed oil by transesterification using NaOH and methanol. Energy Sources, Part A: Recovery, Utilization and Environmental Effects 2010; 32(5): 434–441.

[76] Öğüt H, Oğuz H. The Third Millennium's Fuel: Biodiesel. 2nd ed. Ankara: Nobel Yayın Dağıtım, 2006. ISBN 975-591-730-6.

[77] Limmun W, Sansiribhan S. Water-spray washing technique as a purification process in the production of biodiesel. E3S Web of Conferences 2020.

[78] Ehimen E. Energy balance of microalgal-derived biodiesel. Energy Sources, Part A: Recovery, Utilization and Environmental Effects 2010; 32(12): 1111–1120.

[79] Veljković V, Stamenković O, Tasić M. The wastewater treatment in the biodiesel production with alkali-catalyzed transesterification. Renewable and Sustainable Energy Reviews 2014; 32: 40–60.

[80] Rajaeifar M, Tabatabaei M, Aghbashlo M, Hemayati S, Heijungs R. Biodiesel production and consumption: life cycle assessment (LCA) approach. 2019; 161–192.

[81] De Marco I, Miranda S, Riemma S, Iannone R. Biodiesel production from sunflower: an environmental study. Chemical Engineering Transactions 2016; 49: 331–336.

[82] Castanheira É, Freire F. Environmental life cycle assessment of biodiesel produced with palm oil from Colombia. International Journal of Life Cycle Assessment 2017; 22(4): 587–600.

[83] Ozyigit I. Heavy metals in agricultural soils; origins, distribution and effects. Eregli Journal of Agricultural Science 2021; 1(1): 46–71.

[84] Kıymaz Y, Oğuz H. Assessment of electricity generation using deep learning on solar power plants. Necmettin Erbakan University Journal of Science and Engineering 2024; 6(2): 289–311.

[85] Farinha C, de Brito J, do Veiga M. Life cycle assessment. Eco-Efficient Rendering Mortars 2021; 205–234.

[86] Dincer I, Abu-Rayash A. Sustainability modeling. Energy Sustainability 2020; 119–164.

[87] Definition of environmental impacts. Polymers, the Environment and Sustainable Development 2003; 197–200.
[88] Holka M, Kowalska J, Jakubowska M. Reducing carbon footprint of agriculture—can organic farming help to mitigate climate change? Agriculture (Switzerland) 2022; 12(9).
[89] Daud N, Sheikh Abdullah S, Abu Hasan H, Yaakob Z. Production of biodiesel and its wastewater treatment technologies: a review. Process Safety and Environmental Protection 2015; 94(C): 487–508.