ASSESSMENT OF GHG EMISSIONS FROM BIOFUEL PRODUCTION BY LIFE CYCLE APPROACH

BİYOYAKIT ÜRETİM AŞAMASINDA AÇIĞA ÇIKAN SERA GAZI EMİSYONLARININ YAŞAM DÖNGÜSÜ YAKLAŞIMI İLE DEĞERLENDİRİLMESİ

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ABSTRACT

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The decreasing stocks of petroleum-based fuels, increasing energy security problems, and the problems related to climate change and air pollution problems encourage the growing interest in biofuels. Biofuels are among low-carbon alternatives for road transport, as they have a much better CO_2 emission performance and lesser air pollution impacts than traditional fossil transport fuels. However, it is significant to examine whether the GHG emissions from biofuels' lifecycle are lower than those from fossil fuels. In addition, biofuel production from crops should not compete with food production and should be economically and environmentally sustainable. According to Turkey's National Greenhouse Gas Inventory, in 2020, the transport sector's share in total GHG emissions was 15.4%, corresponding to 80.7 million tons of CO_2eq. Road transportation accounts for 94.9% of the country's transport sector's GHG emissions. In addition, Turkey's domestic oil source is also limited, making her dependent on imported liquid fuels. Turkey has recently created a road map for 2053, which includes essential principles and important actions to decrease GHG emissions and climate change. In addition, the transposition and implementation of the current and future EU Directives on climate change are critical for Turkey to implement its road map for 2053. For these reasons, Turkey's biofuel potential and emission effects were analyzed in this study. As a method, BioGrace Calculation Tool is used to calculate the life cycle GHG emission reduction potentials of biodiesel from rapeseed and waste oil and bioethanol from sugar beet and corn. According to the results of each biofuel production pathway's life cycle GHG emissions, biodiesel production from waste oil has the lowest life cycle GHG emission, 21.9 g CO_2eq/MJ. Bioethanol production from corn (44.9 g CO_2eq/MJ) and sugar beet (46.1 g CO_2eq/MJ) follows biodiesel from waste oil. Biodiesel from rapeseed has the highest life cycle GHG emission, which is 53.2 g CO_2eq/MJ. Secondly, various biodiesel and bioethanol blending scenarios were implemented to estimate the GHG emissions of biofuel-blended passenger cars. This is accomplished by assuming a 5% annual rise in the proportion of biofuel-blended passenger cars will reach up to 50% of all non-blended passenger cars in 2030, starting from 2020, which is selected as the base year. Finally, crop demand analyses were conducted for rapeseed, sugar beet, and corn cultivation area to estimate Turkey’s capacity to meet biodiesel and bioethanol demands in 2030 according to various biofuel blending rates. According to projection results, blending the biofuels at 0.5% and 2% can easily meet the demand for biodiesel production from rapeseed. Consequently, bioethanol production from sugar beet and corn can be easily achieved with all blending rates by the end of 2030. However, sugar beet and corn production for food demand should also be considered since biofuel production should not compete with food production.

Keywords: Transport Sector, Greenhouse Gas Emission, Biodiesel, Bioethanol, BioGrace, Life Cycle Assessment

ÖZET

BİYOYAKIT ÜRETİM AŞAMASINDA AÇIĞA ÇIKAN SERA GAZI EMİSYONLARININ YAŞAM DÖNGÜSÜ YAKLAŞIMI İLE DEĞERLENDİRİLMESİ

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Petrol bazlı yakıt stoklarının azalması, artan enerji güvenliği sorunları, iklim değişikliğine bağlı sorunlar ve hava kirliliği sorunları biyoyakıtlara olan ilginin artmasına neden olmuştur. Biyoyakıtlar, geleneksel fosil kaynaklı ulaşım yakıtlarından çok daha düşük CO_2 emisyon performansına ve daha az hava kirliliği etkilerine sahip olduklarından, karayolu taşımacılığı için düşük karbonlu alternatifler arasında yer almaktadır. Ancak, biyoyakıtların yaşam döngüleri boyunca açığa çıkan sera gazı emisyonlarının fosil yakıtlarınkinden daha düşük olup olmadığının araştırılması önemlidir. Bunun yanında, tarımsal kaynaklı biyoyakıt üretimi, gıda üretimi ile rekabet etmemeli ve ekonomik ve çevresel olarak sürdürülebilir olmalıdır. Türkiye Ulusal Sera Gazı Envanteri 'ne göre 2020 yılında ulaştırma sektörünün toplam sera gazı emisyonlarındaki payı %15,4; 80,7 milyon ton CO_2 eşdeğeridir ve karayolu taşımacılığı da sektörün sera gazı emisyonlarının %94,9'unu oluşturmaktadır. Ayrıca, Türkiye'nin yerli petrol kaynağının da sınırlı olması, onu ithal sıvı yakıtlara bağımlı kılmaktadır. Türkiye yakın zamanda 2053 yılı için, sera gazı emisyonlarını ve iklim değişikliğini azaltmak için temel ilkeleri ve önemli eylemleri içeren bir yol haritası oluşturmuştur. Ayrıca, iklim değişikliğine ilişkin mevcut ve gelecekteki AB Direktiflerinin iç hukuka aktarılması ve uygulanması, Türkiye'nin 2053 yol haritasını uygulaması açısından kritik öneme sahiptir. Bu nedenlerden dolayı bu çalışmada Türkiye'nin biyoyakıt potansiyeli ve emisyon etkileri analiz edilmiştir. Yöntem olarak BioGrace Hesaplama Aracı kullanılarak, kanola ve atık yağdan elde edilen biyodizel ile şeker pancarı ve mısırdan elde edilen biyoetanolün yaşam döngüsü sera gazı emisyonlarını azaltma potansiyelleri hesaplanmıştır. Her bir biyoyakıt üretim yolunun yaşam döngüsü sera gazı emisyonlarının sonuçlarına göre, atık yağdan biyodizel üretimi, 21,9 g CO_2eşdeğer/MJ ile en düşük yaşam döngüsü sera gazı emisyonuna sahiptir. Mısır (44,9 g CO_2eşd/MJ) ve şeker pancarından (46,1 g CO_2eşd/MJ) biyoetanol üretimi emisyonları, sırasıyla atık yağdan üretilen biyodizel emisyonunu takip etmektedir. Kanoladan elde edilen biyodizel, 53,2 g CO_2eq/MJ ile en yüksek yaşam döngüsü sera gazı emisyonuna sahiptir. Buna ek olarak, bu çalışmada, biyoyakıt karışımlı binek otomobillerin sera gazı emisyonlarını tahmin etmek için çeşitli biyodizel ve biyoetanol harmanlama senaryoları uygulanmıştır. Hesaplamalar referans yıl olarak seçilen 2020'den başlayarak, biyoyakıt karışımlı binek otomobillerin oranında yıllık %5'lik bir artışın yapılarak, 2030'da tüm harmanlanmamış binek otomobillerin %50'sine ulaşacağı varsayılarak yapılmıştır. Son olarak, çeşitli biyoyakıt harmanlama oranlarına göre Türkiye'nin 2030 yılında biyodizel ve biyoetanol taleplerini karşılama kapasitesini tahmin etmek için kanola, şeker pancarı ve mısır ekim alanları için ürün talep analizleri yapılmıştır. Projeksiyon sonuçlarına göre %0,5 ve %2 oranındaki biyoyakıtların harmanlanması kanoladan biyodizel üretimi talebini rahatlıkla karşılayabilecektir. Buna ek olarak, şeker pancarı ve mısırdan biyoetanol üretimi, 2030 yılı sonuna kadar tüm harmanlama oranlarıyla kolaylıkla sağlanabilir. Ancak biyoyakıt üretiminin gıda üretimi ile rekabet etmemesi gerektiğinden, gıda talebine yönelik şeker pancarı ve mısır üretimi de dikkate alınmalıdır.

Anahtar Kelimeler: Ulaşım Sektörü, Sera Gazı Emisyonu, Biyodizel, Biyoetanol, BioGrace, Yaşam Döngüsü Değerlendirmesi

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SYMBOLS AND ABBREVIATIONS

SYMBOLS

C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
K_2O	Potassium
m^3	Cubic meter
N	Nitrogen
N_2O	Nitrous oxide
P_2O_5	Phosphorus Pentoxide

ABBREVIATIONS

BAU	Business as usual
CHP	Combined Heat and Power
CONCAWE	European Council for Clean Air and Water in Europe
COVID-19	Coronavirus disease
DDGS	Dried Distillers Grains
EC	European Commission
EMRA	Energy Market Regulatory Authority
EU	European Union
EUCAR	European Council for Automotive Research and Development
FAME	Fatty acid methyl esters
FFA	free fatty acids
FQD	Fuel Quality Directive
g	gram
GHG	Greenhouse gas
GWP	Global Warming Potential
ha	hectare

ISO	The International Organization for Standardization
JEC	Joint European Commission
JRC	Joint Research Center
kg	Kilogram
km	kilometre
LCA	Life Cycle Assessment
MJ	Mega joule
NG	Natural Gas
NPK	nitrogen, phosphorus, and potassium
RED	Renewable Energy Directive
TAMRA	Tobacco and Alcohol Market Regulatory Authority
toe	tons of oil equivalent
TSE	Turkish Standards Institute
TURKSTAT	Turkish Statistical Institute

1. INTRODUCTION

Population and economic growth are the main contributors to climate change. The human contribution to greenhouse gas emissions (GHG) is increasing daily and is now higher than ever. High dependency on fossil fuels is one of the major contributing factors to air pollution and climate change. Yet, they are the primary energy sources for some economic sectors to meet high energy demand. Because of the excessive dependence on fossil fuels, the transport sector is one of the most climate-intensive sectors in the world. Especially road transportation is considered the primary source of GHGs as a part of the total transport emissions.

Due to improvements in fuel efficiency, electrification, and the use of biofuels, transportation emissions increased by less than 0.5% in 2019 globally (compared to 1.9% yearly since 2000). Despite this, transportation is still responsible for 24% of direct carbon dioxide (CO_2) emissions from fuel combustion. Road vehicles, such as cars, buses, trucks, two-wheelers and three-wheelers – account for approximately three-quarters of CO_2 emissions from the transportation sector [1].

Between 2018 and 2019, domestic transportation emissions in the European Union increased by 0.8%. According to preliminary estimates, they dropped by 12.7% in 2020 due to a severe decline in transportation activities during the Covid-19 pandemic [2].

In Turkey, from the beginning of the 2000s, fuel consumption in road transportation has increased dramatically. In 2020, Turkey's overall fuel consumption in road transportation reached 25,284 tons of oil equivalent (toe).[3] Moreover, the increase in road vehicle numbers has reached 66% in the last decade. This rise in vehicle numbers, unfortunately, has caused to increase in the level of GHG (carbon dioxide, methane, and ozone) and air pollutant (carbon monoxide, particulate matter, nitrogen oxides, sulphur dioxide) emissions from the transportations sector, as can be seen in Figure 1[4].

According to Turkey's National Greenhouse Gas Inventory, in 2020, the transport sector's share in total GHG emissions was 15.4%, corresponding to 80.7 million tons of carbon dioxide equivalent (CO_2eq). Road transportation accounts for 94.9% of the country's transport sector's GHG emissions (76.6 million tons of CO_2eq). It is followed by domestic aviation (2.7%), pipeline transport (0.4%), and railway (0.4%), respectively [4]. Figure 1 depicts Turkey's historical trends in GHG emissions from the transportation sector. Emissions from the transport sector were 199.2 % higher than in 1990, and the annual emission increase is more than 6.4%.

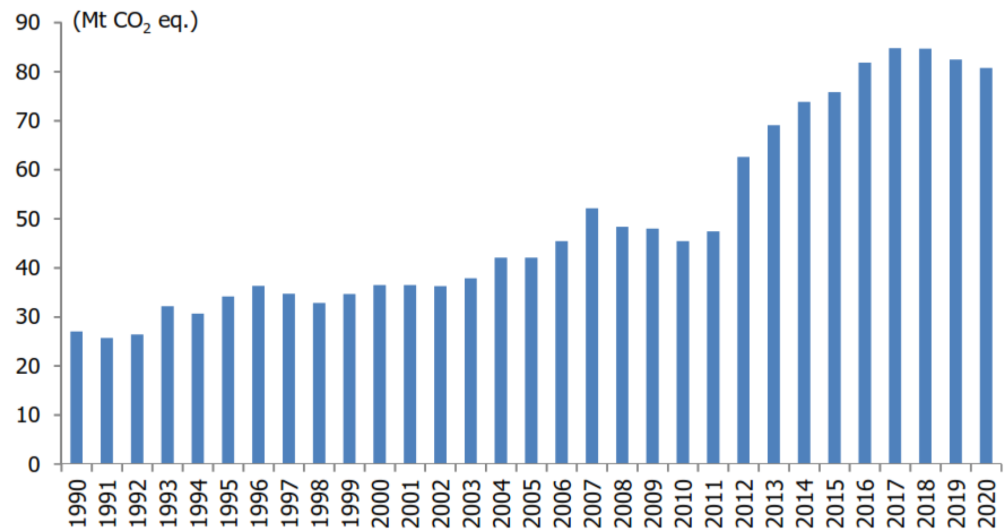


Figure 1. GHG emissions from the transportation sector of Turkey[4]

On the other hand, Turkey's domestic oil source is limited and mostly depends on imported fossil fuels. Turkey's dependency on external sources such as Russia, Iran, or any other country creates energy security problems resulting from various reasons. Due to these reasons, Turkey needs to invest in alternative fuels to increase energy security and deal with the continuous increase in GHG emissions.

Energy insecurity and emissions from the lifecycle of fossil fuels can be reduced by switching from fossil fuels to renewable energy. Biomass-based low-carbon transport fuels (biofuels) are the primary renewable sources of road transportation.

Electric cars and low-carbon fossil fuel (LNG) are also significant alternatives to reducing lifecycle emissions of fossil fuels in road transportation.

Biofuels, as mentioned above, are among low-carbon alternatives for road transport, as they have a much better CO_2 emission performance and lesser air pollution impacts than traditional fossil transport fuels. The European Union (EU) supports biofuel use in road transportation as a renewable alternative to fossil fuels in its Member States and Candidate Countries such as Turkey. However, the EU has also aimed to mitigate the potential negative impacts of biofuel production, such as its life cycle GHG emissions.

1.1. Problem Definition

The decreasing stocks of petroleum-based fuels, increasing energy security problems, the problems related to climate change (including increasing vehicle contributions to GHG emissions in road transportation) and air pollution problems encourage the growing interest in biofuels and other bioliquids from biomasses, which are considered renewable energy alternatives to fossil fuels [5].

Biofuels and other bioliquids are critical in achieving the EU’s 14% use of renewable sources objective in transportation. However, it is significant to examine that GHG emissions from biofuels' lifecycle are lower than those from fossil fuels. In addition, biofuel production should not compete with food production and should be economically and environmentally sustainable. For this purpose, the EU sets out biofuel sustainability standards for all EU-produced or consumed biofuels to ensure that they support sustainability and are produced in an environmental-friendly manner.

Turkey has recently created a road map including essential principles and important actions to decrease GHG emissions and climate change mitigation, which sets short-, medium-, and long-term strategic objectives and contributes to the legislation to be drafted on climate in line with the country’s 2053 net zero emission and green development strategies. Transposition and implementation of EU Directives on climate change are critical for Turkey to implement its road map for 2053. Turkey has sought to become a full member of the EU since 1987 by aligning its legal framework with the EU standards. As part of the harmonization process, Turkey is harmonising its regulatory framework in the environmental sector, which includes the harmonisation of renewable energy systems. As a result, the EU has various effects on Turkey's renewable energy strategy, including biomass-based energy production and utilization.

To achieve successful harmonization with the EU Climate and Environment Acquis, Turkey should increase biofuel blending, integrate electric cars, and utilise low-carbon fuels.

1.2. Goal and Objective

The main objective of this study is to examine the Life Cycle Assessment of GHG emissions from biofuel production in Turkey (Biodiesel and Bioethanol) by analysing the biofuel production by selected feedstocks. These feedstocks are determined taking into account the Turkish agricultural system: rapeseed to produce biodiesel, waste oil to produce biodiesel, sugar beet to produce bioethanol, and corn to produce bioethanol. Secondly, this study aims to forecast the GHG emission saving potential from the Turkish transportation sector by substituting petroleum transport fuels with produced biofuels by considering different biofuel blending rates.

A comparison analysis was conducted between the life cycle of biodiesel and bioethanol GHG emissions to their fossil fuel alternatives to calculate the emission reduction potential of biofuels. Besides, a comparison analysis was conducted for calculated life cycle GHG emissions of biofuels with EU RED default values. Based on the life cycle GHG emissions of the biofuel production pathways, a policy analysis was conducted to understand the GHG contribution of the different stages: cultivation, biorefinery and transport in the system boundary of each pathway.

In addition, GHG emission reduction potentials of different blending ratios of the produced biodiesel and bioethanol are estimated until 2030. Finally, crop demand analysis for biofuel production was conducted according to various blending ratios until 2030.

1.3. Scope of the Study

This study provides baseline information on the life cycle GHG emissions of biodiesel and bioethanol production based on the most common feedstocks used for biofuel generation in Turkey, mainly rapeseed, waste oil, sugar beet, and corn. The analyses included the cradle-to-gate concept and used BioGrace GHG Calculation Tool [7], recognized as a voluntary scheme by the European Commission. The baseline information includes comparison analyses to provide policy advice, namely, a comparison of the lifecycle of biodiesel and bioethanol GHG emissions to their fossil fuel alternatives to show the emission reduction potentials of biofuels in Turkey. In addition, a comparison analysis of lifecycle GHG emissions of biofuels with EU context, which is given as EU RED default values, is included to show the differences between the EU and Turkish context.

In the study, a forecasting scenario of GHG emission saving potential from the Turkish transportation sector by substituting petroleum transport fuels with produced biofuels is given. Different biofuel blending rates were considered, and the projections were made until 2030. The base year was selected as 2020, and relevant data was taken from TURKSTAT. Due to data availability for the base year, only passenger cars were used to develop blending scenarios for all vehicle types. The study considered five types of blending rates for biodiesel (B0.5, B2, B5, B20, B100) and six types of blending rates for bioethanol (E3, E5, E10, E20, E85, E100). Crop demand analyses for rapeseed, sugar beet and corn were conducted to provide baseline information for biofuel production in Turkey by considering different blending ratios until 2030.

1.4. Structure of the Study

There are seven chapters in this study. In the first chapter, preliminary information about the study, problem definition, goal and objective, and scope of the study are presented. In Chapter 2, background information on biofuels is given. This includes Turkey's biofuel situation, historical development, legal situation, a review of EU biofuel directives, and biofuel- food production dilemma. Studies on these subjects are included in Chapter 3. In Chapter 4, information on BioGrace Calculation Tool is presented. The methodology and data sources of the study are given in Chapter 5. In Chapter 6, the results of the study are presented, and discussions are made on these results. In the last chapter, Chapter 7, the conclusions of the study are presented.

2. BACKGROUND INFORMATION

This section provides detailed information on the definition and categorization of biofuels and Turkey’s biofuel situation, including historical development and legal status, policies, strategies, and targets.

2.1. What is Biofuel?

Biomass can be described as all biologically produced carbon-based materials on Earth, which is considered a significant renewable energy source. Biomass has a strategic role among renewable energy sources, as it is environmentally friendly and suitable for producing liquid, solid, and gaseous fuels. Also, biomass is considered the only naturally carbon-rich material source on Earth besides fossil fuels among all the other renewable energy sources [6].

Biomass is used widely as an energy source in today's world to improve energy supply security, reduce the dependence on imported fossil fuels, decrease GHG emissions, and thus, mitigate climate change and enhance local development. There are a lot of different feedstocks to produce biomass energy. Agriculture, forests, wastes and residues provide most of the world's usable biomass [7]. Algae culture is another area to produce biofuel; however, it is still developing.

Bioheat and biopower can be produced using several types of biomass sources. The origin and content of biomass can be characterized based on their organic matter elemental composition, calorific value, physical qualities, mineral matter and moisture content, biochemical composition, and so on. [7]. Table 1 shows the broad categories of biomass sources and their content and origin.

Table 1. Biomass categories, contents, and origins [7]

	Biomass Sources	
Category	**Woody**	**Non-woody**
Content	• Lignocellulose	• Lignocellulose • Sugar • Starch • Oil
Origin	• Forest • Agriculture • Wastes/Residues	• Agriculture • Wastes/Residues

Biomass is a broad term that encompasses all biologically produced matters, including growing plants and animal manure, such as oilseed plants (soybean, rapeseed, sunflower, etc.), wood (energy forests and woody leftovers), carbon hydrate plants (corn, wheat, potato, beet, etc.), fibre plants (sorghum, hemp plant, linseed, etc.), vegetal wastes (straw, stalk, branch, root, husk, etc.), animal wastes, industrial and municipal wastes; and algae [6].

Producing energy from biomass is a versatile system, and diverse biomass sources can be transformed using various conversation technologies. While some renewable energy sources produce heat and electricity, such as solar, wind, hydro, etc., biomass is considered the only alternative source to fossil sources to produce fuels, chemicals, and other carbon-based materials.

Based on the choice of feedstock, production process, and development stage, biofuels are typically divided into first-, second-, third-, and fourth-generation. However, the same biofuel may be classified differently depending on technology maturity, physical state, and other variables.

First-generation biofuels are currently used and produced in large amounts on commercial scales. Bioethanol from sugar and starch-based feedstocks, biodiesel from oil crop-based feedstock and biogas from anaerobic digestion are the most common. Although second-generation biofuels have been produced, their widespread use has been limited by technological difficulties and expensive costs. Bioethanol, biodiesel, biohydrogen and synthetic biofuels are some examples of second-generation biofuels. These fuels are produced from non-food crops that do not compete directly with food crops (lignocellulosic biomass such as agricultural and forestry residues/wastes, non-edible vegetable oils, used cooking oils, and animal fats). Third-generation biofuels will be applicable as of 2030 and are produced from algae or genetically modified feedstocks that contain less lignin and more cellulose, which will not compete with food crops. Similarly, fourth-generation biofuels will be applicable as of 2030 and are referred to as carbon-negative biofuels. They are produced from feedstocks with consummated genetics. Advanced technologies like sequestration and carbon storage will lower the expected CO_2 emissions [6].

Based on technology maturity, there are two types of biofuel technologies classification: “conventional” and “advanced”.

While conventional biofuel technologies cover first-generation biofuels, advanced biofuel technologies cover second-, third- and fourth-generation biofuels, which are still in research and development.

Biofuels can also be classified based on their physical forms;

- as solid (biochar, biopellet, woodchip, biobriquette, etc.),
- as liquid (bioethanol, biodiesel, biomethanol, etc.),
- and as gas (biogas, biohydrogen, biosynthesis gas, etc.) [8].

The development of biorefineries is currently being driven by the liquid biofuel industry (mostly biodiesel and bioethanol plants).

2.1.1. Biorefinery Technology

The biorefinery idea has emerged for the conversion of biomass into energy carriers (biofuels, bioheat, biopower, biocold) and a variety of valuable products (biomaterials, biochemicals) such as food and feed [8].

Biorefinery technology can produce a flexible product mixture and energy carriers through different biomass conversation technologies such as biochemical, physicochemical, thermochemical, and physical/mechanical, depending mainly on features of the biomass feedstock and the desired intermediate and final products . Figure 2 presents the schematic biorefinery technology.

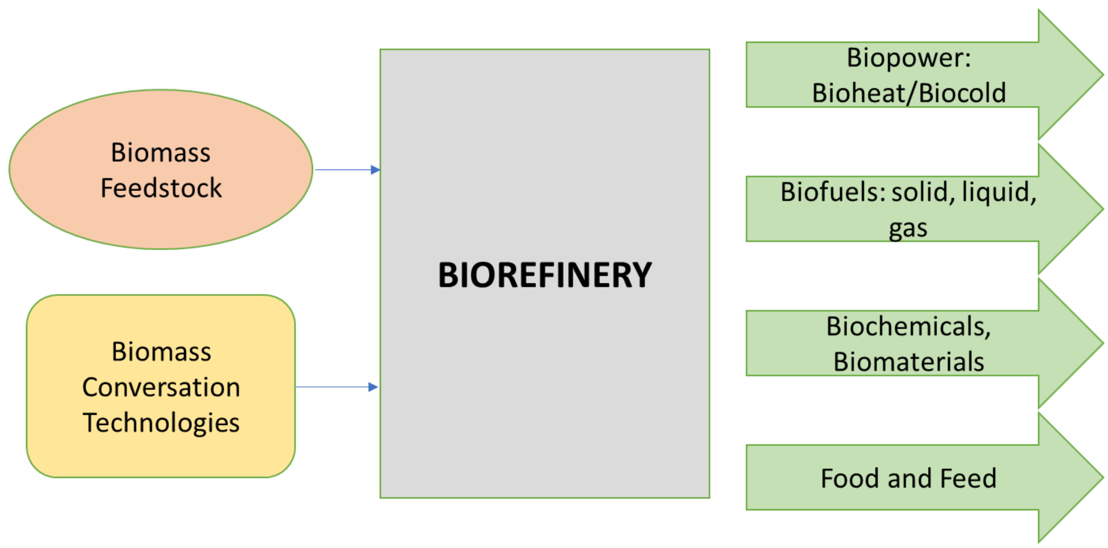


Figure 2. Schematic Biorefinery Technology [9]

Biorefineries function similarly to petrochemical (oil) refineries. Unlike fossil-based refineries, which create a range of energy carriers and products from fossil sources like crude oil, biorefineries utilise biomass as a feedstock and create safe and environmentally friendly products like food and feed. Furthermore, a biorefinery designed for energy generation must not compete with food production; therefore, food and feed sources cannot be used ethically as raw materials for a biorefinery. Biorefineries offer considerable economic and environmental benefits comparing fossil-based refineries and other biomass utilization concepts. Traditional and modern biomass use for energy production is the primary category. Conventional biomass utilization worldwide includes direct combustion to heat and cook, widely used in rural regions. Modern biomass utilization in the world includes biomass energy systems to transform biomass into useful forms of energy.

2.1.2. Liquid Biofuels

Biodiesel and bioethanol are the most important and the first liquid biofuels that come to mind worldwide. They are the most important commercially available industrial liquid biofuels, with a market share growing by the day.

In 2020, bioethanol and biodiesel supplied about 3.5% of the energy used in transportation. After dropping in 2020 due to a decrease in transportation demand caused by the COVID-19 epidemic, biofuel production levels returned to 2019 levels in 2021. However, high feedstock production costs limited biofuel production in 2021. Production of bioethanol increased by 26% between 2011 and 2021. In addition, between 2011 and 2021, the world's biodiesel production doubled [10].

Biofuels are now seen as key players in circular and creative economies. They have a unique role in bio trade, which entails collecting, producing, transforming, and commercialising natural biodiversity goods and services according to environmental, economic, and social sustainability criteria [11].

Bioethanol and biodiesel play a significant role in the transportation sector to support countries' strategies towards sustainability, low carbon economy, and climate change mitigation. Biofuels are important in fighting climate change as they are considered carbon-neutral. Biofuels do not contribute to an increase in the carbon dioxide (CO_2) concentration because the amount of CO_2 emitted during combustion is balanced by the CO_2 absorbed from the atmosphere by photosynthesis when biomass feedstock is grown. Even if biofuels are essential in fighting climate change, their effects on biodiversity, water resources, soils, and agricultural land-use change are crucial.

2.1.2.1. Biodiesel

Biodiesel is mainly made from vegetable oils, but it can also be made from animal fat or cooking oil. Based on the composition of the feedstock, various conversation technologies can be used to produce biodiesel. The most common process is transesterifying vegetable oils with methanol to make fatty acid methyl esters; FAME. Low concentrations of water and free fatty acids in vegetable oil can provide high conversation efficiencies. Therefore, in the case of animal fats and used cooking oils, free fatty acids should be esterified or separated to increase efficiency. Only two manufacturing facilities often carry out integrated biodiesel plants with oil mills and transesterification. Oilseeds are used as feedstock in integrated plants, and the oil is produced directly in the biodiesel plant. Oils are obtained from external oil mills by plants focusing on pure transesterification. In both types, the oils or fats are transesterified, and the biodiesel and the resulting by-product, glycerol (mostly), are refined. Figure 3 shows the schematic biodiesel production in integrated biodiesel plants and pure transesterification plants.

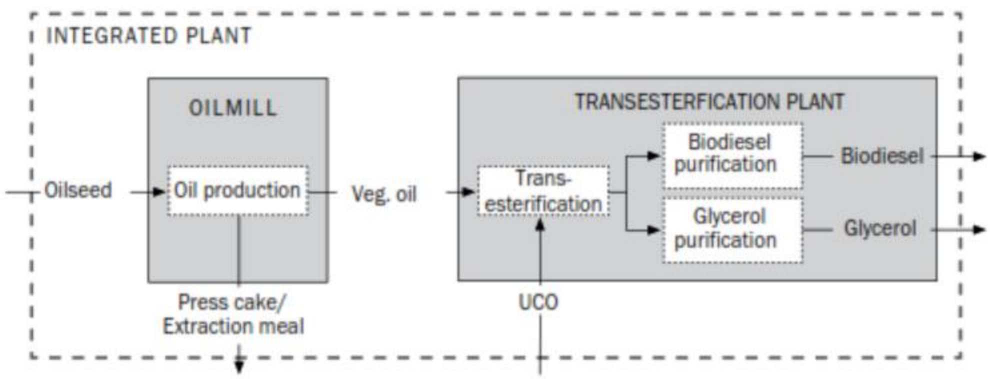


Figure 3. Biodiesel production in integrated biodiesel plants and pure transesterification plants [12]

The production and use of biodiesel started in the 1890s with the invention of the first diesel engine by Rudolf Diesel. At the Paris Exposition in 1900, Rudolf Diesel displayed his diesel engine running on peanut oil. In the next 20-30 years, many countries started using vegetable oils as fuels in internal combustion engines. In 1937, G. Chavanne was granted a patent for the use of ethyl esters of palm oil as diesel fuel, which is most likely the first mention of what is now known as biodiesel. The subject did not receive widespread attention until high petroleum prices in the 1970s prompted substantial study into alternate fuels. The Scientist E. Parente invented the first industrial-scale biodiesel synthesis technology using ethanol transesterification in 1977. The world's first industrial-scale biodiesel facility began operations in 1989 in Austria, using rapeseed as a biomass feedstock. Biodiesel has been commercially produced worldwide since the early 1990s, and applicable ASTM and EN standards were developed in 2001 and 2002, respectively. Today, biodiesel has many forms in the market: as a blend component, as an additive, and as a pure-neat fuel (B100) [6], [13].

Biodiesel production in the world reached 45 billion litres in 2021. With an 18% production rate (more than 8 billion litres in 2021), Indonesia is now the world’s leading biodiesel producer. Indonesia increased its biodiesel blending target from 20% to 30% in 2020 and set a 40% target for 2021 to lessen its reliance on imported oil. However, this target was postponed to 2020 due to high feedstock costs. By producing and using biodiesel as an alternative fuel, Indonesia was able to decrease its import oil cost by 4 billion USD in 2021. Brazil raised its biodiesel production to 6.5 billion litres in 2021 and placed itself as the world’s second-largest biodiesel producer. Brazil also put biodiesel blending targets as 13% for 2021 and 15% for 2022. However, the blending rate in 2021 was reduced to 10% due to high soya oil prices, raising biodiesel's cost and declining demand. The USA increased its biodiesel production level to 70% between 2011 and 2021. However, biodiesel production partially decreased in 2021 because of the high soya oil cost, making manufacturing financially unattractive [10].

In 2020, the EU biodiesel production declined by 2% compared to 2019 because of lower domestic consumption and lower demand from the world market. Germany, with a 4.1 million litre production, was the most prominent European producer in 2021, followed by France, with a 2.1 million litre production [14].

2.1.2.2. Bioethanol

Bioethanol is primarily produced from feedstocks that contain sugar, such as sugar beet, molasses, sugar cane, sweet sorghum or starch, such as wheat, maize, triticale, and rye, as well as materials derived from lignocellulose such as forest and agricultural residues. Bioethanol production involves a series of different process phases. Firstly, a fermentable sugar solution is produced as part of the feedstock processing. The methods used include mechanical, thermal, chemical, and biochemical processes. In fermentation, yeasts are utilized to transform the sugar solution into alcohol (ethanol) and CO_2, which can then be processed to produce a co-product. The distillation and rectification processes remove water and residues from the feedstock from the ethanol. Before marketing, the ethanol is dehydrated to a concentration of 99.9 wt.%. If the feedstock is sugar, the main co-product is vinasse. If the feedstock is starch, the main co-product is stillage. These co-products can be processed and utilized as fertilizer, animal feed, or to produce biogas. Different co-products, such as bran, gluten, and germ oil, can be produced from starch and sugar feedstocks. Also, carbonatation lime and beet pulp can be produced as co-products. The below figure shows an overview of the bioethanol production process.

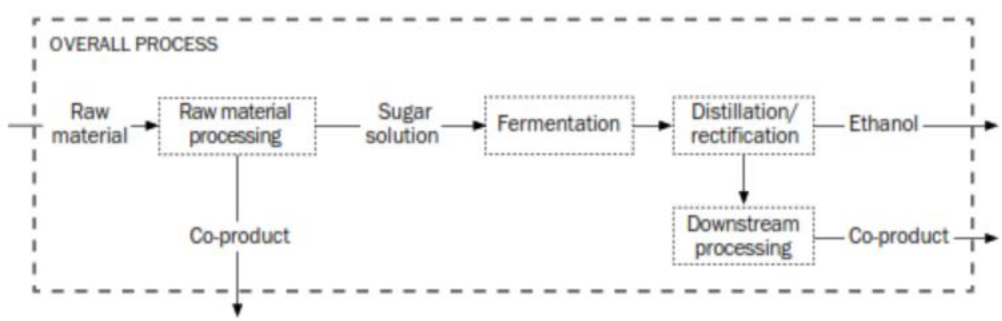


Figure 4. Overview of the bioethanol production process [15]

Bioethanol has a long history as an engine fuel, dating back to the invention of internal combustion engines. Nikolaus August Otto, the inventor of the modern four-cycle internal combustion engine, used alcohol as fuel in his engine studies. The combustion of alcohol was taken into account by Henry Ford in his design studies, and the first automobile powered by ethanol (the Ford Motor T) was manufactured in the United States in 1908. Bioethanol was first used in Brazil in 1931, with 5% blending to gasoline. US army built the first industrial-scale fuel ethanol plant in the 1940s. In the 1970s, the oil crisis increased interest in ethanol as a fuel. The 1980s and 1990s were important periods for bioethanol production as there were solid steps in designing and engineering studies. Bioethanol is now the world's leading engine biofuel. Bioethanol can be used in blends or its pure form. Bioethanol can be blended with any proportion of gasoline or diesel fuel. However, the most popular blending ratios are gasoline + 5% alcohol at maximum (e-gasoline); gasoline + 10% alcohol (gasohol); gasoline + 20%, + 25%, +85% (E20, E25, E85 respectively), diesel fuel + 15% alcohol at maximum (e-diesel or diesohol, or oxydiesel) [6],[13].

Bioethanol remained the leading source of transport biofuels in the world in 2021, with a production amount of 150 billion litres. However, production slightly declined in 2020 due to the pandemic. The USA and Brazil stayed the world's leading producers, accounting for 83% of the global output in 2021. The USA produced 54% of the worldwide supply, mainly from corn, while Brazil produced 29% primarily from sugar cane but growing levels from corn. China became the third largest bioethanol producer in 2021, with a production amount of 3.3 billion litres, where it was responsible for 3% of the global supply, followed by India, with a production amount of 3.2 billion litres [10].

In 2020, the EU bioethanol production was 4.7 billion litres, with a cut of around 10% due to the COVID-19 crisis. Bioethanol production fell mainly in France and Belgium in 2020; however, the production suffered from the reduced demand in the domestic and export markets. The bioethanol production in 2021 was nearly 8 billion litres. There were some limits on the production of first-generation bioethanol, and the expansion of cellulosic bioethanol production remained limited due to high costs and a lack of certainty in the EU policy-making process [14].

2.2. Biofuel Sector in Turkey

At the National Agriculture Conference, liquid biofuels and the need to use locally produced engine fuels were first considered in Turkey in 1931 to reduce the country's dependency on imported petroleum. In 1936, the second five-year industrialization plan created under the leadership of Mustafa Kemal Atatürk, the founder of the Turkish Republic, included a section on the necessity to produce non-petroleum-based engine fuels using domestic resources. The idea, however, could not be implemented due to the start of World War II. Liquid biofuels became important in Turkey in the 1970s due to oil shortages and price changes, as in many other countries. With the increased importance in the market, legal regulations on liquid biofuels were also developed [16].

2.2.1. Biodiesel in Turkey

The first biodiesel-related study in Turkey was conducted in 1934 at the Atatürk Forest Farm under Atatürk's directions, titled "use of vegetable oils for agricultural tractors". Following the oil crisis of the 1970s, research into the use of vegetable oils as a fuel alternative increased, especially in the 1980s. Industrial biodiesel production has been popular in Turkey since the early 2000s. Regulations for the biodiesel industry started in 2003 and have continued until now. After petrol and diesel, biodiesel is now Turkey's third engine fuel in the liquid fuel market. As a liquid fuel, biodiesel is subject to all legal definitions, regulations, and inspections. Biodiesel producers must get a processing license from the Energy Market Regulatory Authority (EMRA) to produce biodiesel under license and following the Turkish Standards Institute's (TSE) standards. Biodiesel producers should submit a report annually to EMRA on the production amount they can present to the market for the upcoming year and three months' production amounts within the year. EMRA is also responsible for all quality controls, including controlling blending rates [6]. Table 2 shows the biodiesel delivery amount in Turkey in 2020.

Table 2. Amount of biodiesel delivered in Turkey in 2020 [17]

Company Name	City	Feedstock	Delivery to Distributor	Total
DB Tarımsal Enerji Sanayi ve Ticaret A.Ş	İzmir	Vegetable Oil, Waste Oil	58,678,421	58,678,421
Aves Enerji Yağ ve Gıda Sanayi A.Ş.	Mersin	Vegetable Oil	14,805,316	14,805,316
Ömer Bucak İnşaat Taahhüt Sanayi ve Ticaret Limited Şirketi	Şanlıurfa	N/A	650,000	650,000
Maysa Yağ Sanayi A.Ş	İstanbul	N/A	442,015	442,015
			Total:	74,575,752

Sunflower and cottonseed are Turkey's most important oilseed crops, accounting for over 90% of the total production of 3,131,193 tons. Groundnut, soybean, rapeseed, and safflower are other important oilseed crops. Rapeseed and safflower production, which are not used primarily for food in the country, has seen significant growth in the recent decade. In Turkey, biodiesel producers have chosen rapeseed and safflower crops as their raw materials, particularly as they have been doing contractual farming across the country. Safflower is particularly popular in low-yielding, low-rainfall farmlands, providing a solid, satisfying income for the farmer thanks to government subsidies. Camelina has become popular for biodiesel producers as it offers farmers a good and reliable alternative crop [18].

On the other hand, even though Turkey possesses arable land for oilseed crop development, the area assigned to oilseed cultivation in the country is less than 5%. Unfortunately, oilseed production in Turkey does not cover the country's consumption rate, and thousands of tons of oilseeds and vegetable oils (even for food) are imported annually. Imports provide 75% of the raw material requirements for the vegetable oil sector. As a result, increasing the production of oilseeds is critical for Turkey's long-term development goals [19] [20].

Table 3. Turkey's oilseed production in 2020 [19]

	Sunflower	Rapeseed	Cotton seed	Soybean
Production (Tons)	2,067,004	121,542	106,4189	155225
Area Sown (Hectare)	728,854	34,989	359,220	35,135

In addition to oilseed crops, waste vegetable oils are the other significant raw material potential for biodiesel manufacturing in Turkey. Turkey has the capacity to collect more than 150,000 tons of waste vegetable oil every year. Only 38,000 tons of waste vegetable oil were collected and used to produce biodiesel in 2017 [21]. The legal framework for collecting used cooking oil is under development. The Ministry of Environment, Urbanization, and Climate Change implements an online system for registering and processing used cooking oils from the source to its conversion to biodiesel. The system aims to collect and process used cooking oils with complete monitoring, ensuring they do not re-enter the food chain. The biodiesel industry provides a large quantity of labour and management capacity to collect and process more used cooking oils for biodiesel production. The expectation is that the volumes will gradually increase to their maximum capacity.

2.2.2. Bioethanol in Turkey

Bioethanol was first discussed in Turkey in 1931 during a National Agriculture Conference to minimize dependence on imported petroleum. Mustafa Kemal Ataturk's Second Five-Year Development Plan emphasized the need to create non-petroleum-based engine fuels using domestic sources. In 1942, 20 % bioethanol was blended with gasoline and used in the army. In 1974, after the oil crisis worldwide, Turkish Sugar Factories started exploring bioethanol production to use it as fuel.

Tarkim Bitki Koruma San ve Tic A.Ş, Turkey's first and leading bioethanol producer, has a capacity of 40 million litres per year and is the first E2 (2% ethanol and 98% petroleum) supplier in the liquid fuel sector. Çumra Sugar Integrated Plant (Konya Şeker) is one of the biggest bioethanol producers in Turkey, with a capacity of 84 million litres per year. In addition, Tezkim Tarımsal Kimya A.Ş. produces 100,000 litres of bioethanol daily using corn as raw material and has a capacity of 26 million litres per year. Eskisehir Sugar Plant, which has a capacity of 20 million litres per year, is one of the bioethanol plants established in Turkey. According to official data from the Tobacco and Alcohol Market Regulatory Authority (TAMRA) [6]. Turkey's overall bioethanol production capacity is approximately 162 million litres annually; 46.9% of this amount is used as fuel. A share of 8% of bioethanol is exported, and 92% is blended with gasoline to meet the country's fuel needs [22].

The bioethanol plants in Turkey use sugar- or starch-based feedstocks, known as first-generation bioethanol production. These feedstocks are produced from energy crops and can also be consumed as food.

In 2019, there were 13 companies registered as producers of ethyl alcohol in Turkey, with a total capacity of 237,811,000 litres per year [23]. Table 4 shows the bioethanol delivery amount in Turkey in 2020.

Table 4. Bioethanol delivery amount in Turkey in 2020 [17]

Company Name	Blended Products	City	Feedstock	Delivery to Refinery (tons)	Delivery to Distributor (tons)	Total (tons)
Tarkim Tarımsal Kimya A.Ş.	**Bioethanol**	Bursa	Maize	-	20,094,630	20,094,630
Konya Şeker A.Ş.	**Bioethanol**	Konya	Sugar beet, molasses	5,542,750	10,655,76	16,198,486
Tezkim Tarımsal Kimya A.Ş.	**Bioethanol**	Adana	Maize, wheat	-	15,974,916	15,974,916
			Total:	5,542,750	121,301,034	126,843,784

Sugar beet, molasses, wheat, and maize (corn) are Turkey's most common feedstocks for bioethanol production.

2.3. Energy Crops Used for Biofuel Production or Food

Currently, there is an ongoing debate on using energy crops for fuel production or food production all over the World. Energy crops are valuable, and producing biofuel from those materials may put the food supply at risk due to the increased use of food crops and lead to food insecurity. Currently, food insecurity is one of the most significant problems in the world, with roughly 842 million people worldwide estimated to be suffering from a lack of regular access to sufficient and nutritious food. The rapid development of the global biofuel industry is anticipated to exacerbate this problem. As a result of the growing use of food crops, increased biofuel production may affect food availability. Figure 5 presents the impacts of biofuels on food security.

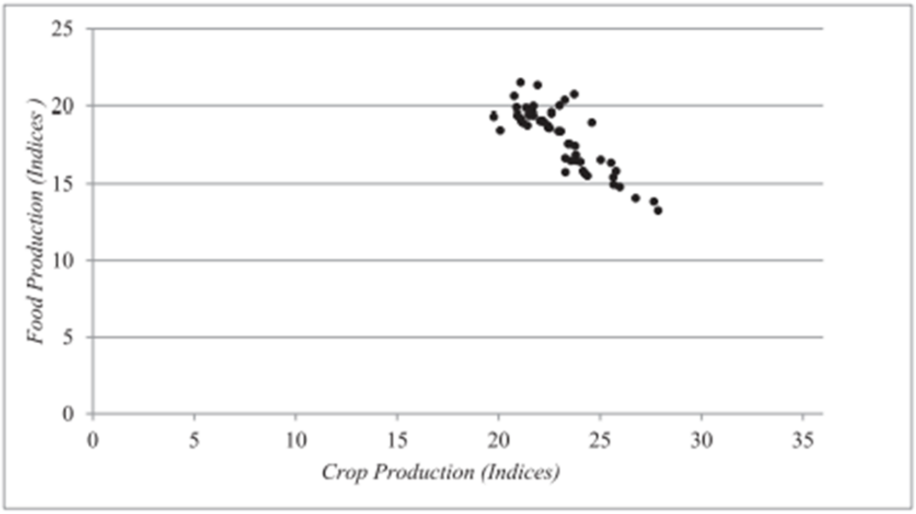


Figure 5. Total crop and food production indices of 51[1] developing countries between 2011 and 2016 [24]

In Figure 5, the historical relationship between crop production and food production is presented. It demonstrates that while total crop production in 51 developing countries increases, the total food production tends to decrease, which is against the expectation that it should also increase. This could be linked to the rapidly growing biofuel sector in the same period, as shown in Figure 6.

[1] Angola, Belarus Argentina, Bulgaria, Bolivia, Brazil, China, Colombia, Costa Rica, Ecuador, Egypt, El Salvador, Ethiopia, Guatemala, Honduras, India, Indonesia, Kazakhstan, Kenya, Malawi, Mexico, Mozambique, Nicaragua, Pakistan, Panama, Paraguay, Peru, Philippines, Romania, Russian Federation, Rwanda, Serbia, Sudan, South Africa, Thailand, Turkey, Ukraine, United Republic of Tanzania, Uruguay, Viet Nam, Barbados, Croatia, Cuba, Fiji, Iran, Mauritius, Jamaica, Swaziland, The former Yugoslav Republic of Macedonia, Trinidad and Tobago and Zimbabwe

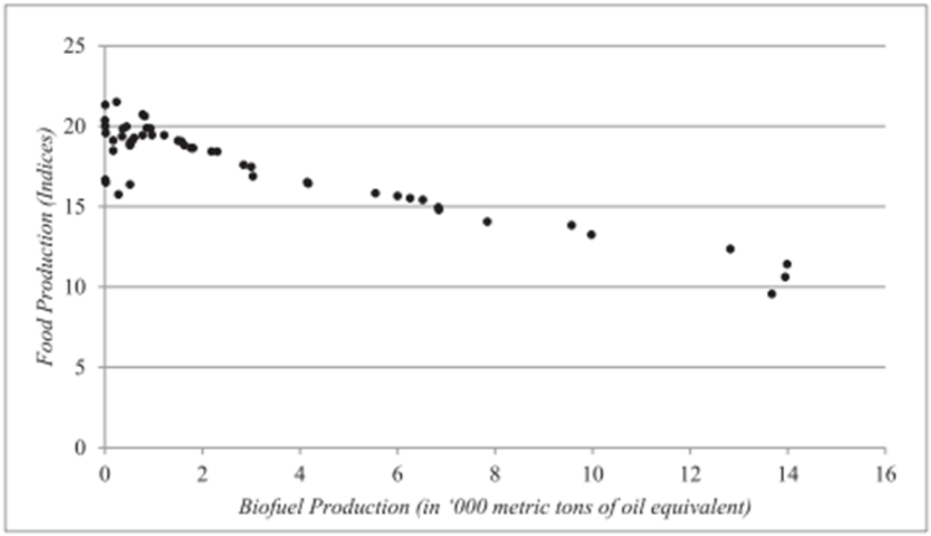


Figure 6. Total Biofuel and food production of 51 developing countries [24]

The primary source of this debate assumes that the competition between biofuel production and food production drives up food prices and price volatility, which ultimately causes food insecurity. Increased use of basic agricultural commodities for biofuel production inevitably leads to crop shortages and higher food commodity prices [25].

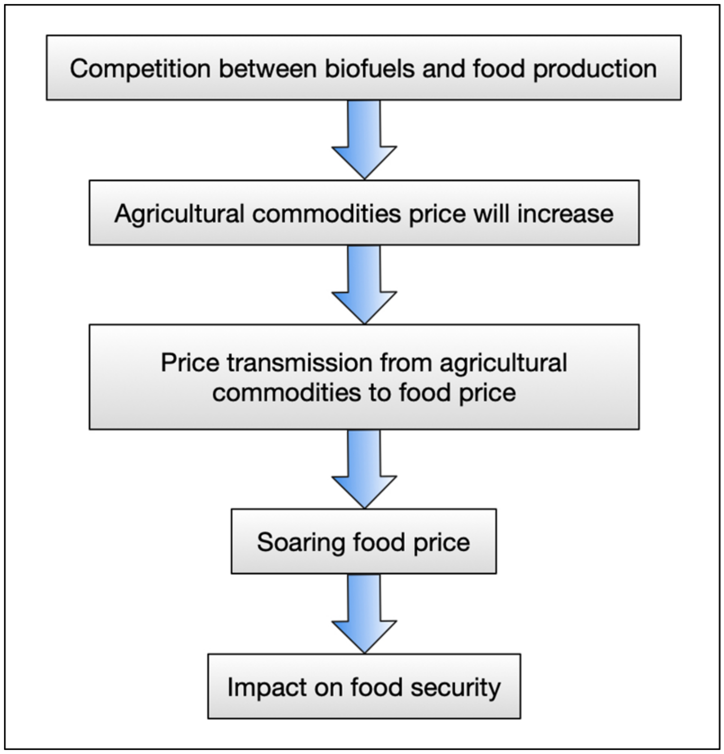


Figure 7. The relationship between biofuels and food security [25]

In this regard, second-generation biofuel production has gained importance around the world. Second-generation biofuel production uses lignocellulosic feedstocks, the most studied since they do not compete with food production. As a significant cereal producer, Turkey has enormous potential for growing energy crops, plant leftovers and other cellulosic biomaterials suitable for producing second-generation bioethanol [26]. However, there is currently no industrial production of second-generation bioethanol in Turkey.

2.4. Legal Situation of The Biofuel Sector in Turkey

On December 4, 2003, the term "biodiesel" was included among the blended products for the first time in the "petroleum market law no. 5015". Biodiesel production has increased quickly since the law exempted it from the special consumption tax. On September 10, 2004, biodiesel was accepted as fuel oil, and on June 17, 2005, the imports, distribution, transportation, and end-user sales were included in the petroleum market license. Turkish Standards Institution (TSE) published the first Turkish biodiesel standards (TS EN 14214 for auto biodiesel and TS EN 14213 for fuel oil biodiesel) in 2005, the same as the EU standards. Energy Market Regulatory Authority (EMRA), in 2006, with its technical regulation communiqué on the production of diesel oil types, their supply from domestic and international sources, and delivery to the market, enabled a blending ratio of up to 5% in the transportation sector. Again, in 2006, in response to claims of unfair competition in the petroleum market, a special consumption tax was applied to auto biodiesel within the framework of "income tax law no: 5479". In addition, due to the high special consumption tax, the biodiesel sector was exempted from the special consumption tax in 2006 if the blending ratio for auto biodiesel produced from domestic agricultural products was at least 2%. As a result, an optional biodiesel contribution of 2% to diesel fuel has started. On September 27, 2011, the Turkish official gazette published the amendment to the communiqué on technical requirements for diesel types numbered 28067. With this, blending biodiesel from local agricultural feedstocks to the diesel types supplied as fuel oil to the market became mandatory to apply a minimum of 1% in 2014, 2% in 2015, and 3% in 2016. This communiqué was later cancelled. The technical regulatory communiqué on the production of fuel biodiesel and its delivery from domestic and international sources (Turkish official gazette of February 4, 2015, numbered 29257) was also lifted from enforcement.

Based on the communiqué, numbered 30098, on blending biodiesel to diesel fuel issued in the Turkish official gazette on June 6, 2017, biodiesel produced from local agricultural feedstocks and/or waste vegetable oils must now be blended with the diesel fuel provided by refineries at a minimum of 0.5 % (v/v). In addition, the Turkish biodiesel standard, TS EN 14214:2012+A1:2014 (liquid petroleum products - Fatty acid methyl esters (FAME) for use in diesel engines and heating applications - Requirements and test methods), has been cancelled by TSE. However, the Ministry maintained it as a mandatory practice for the indication of blending ratio [27].

On April 19, 2005, the regulation for producing biodiesel from waste vegetable oils as an alternate source of raw material for biodiesel production was issued for the first time (Turkish official gazette numbered 25791). It was afterwards lifted from enforcement. Currently, the regulation on waste vegetable oil control numbered 29378, published in the Turkish official gazette on June 6, 2015, is applicable. The Ministry of Environment, Urbanization and Climate Change is in charge of waste vegetable oil collection and transportation, as well as recycling process licenses and control procedures.

In addition, Turkey has sought to become a full member of the EU since 1987 by aligning its legal framework with the EU standards. As part of the harmonization process, Turkey is harmonizing its regulatory framework in the environmental sector, including developing renewable energy. Therefore, the EU has a variety of effects on Turkey's policy towards renewable energy, including biomass-based energy production and utilization.

2.5. Scope of EU Biofuels Directives

To enhance energy supply security by reducing the reliance on imported fossil fuels, decreasing GHG emissions, and thus, mitigating climate change, the EU defined sustainable criteria for the whole bioenergy sector. This is accomplished under the Renewable Energy Directive 2009/28/EC (EU RED) and Renewable Energy Directive 2018/2001 (EU RED II), which is a recast of Directive 2009/28/EC and adapted in 2018 as part of “Clean energy for all Europeans Package” [28].

The EU RED established a common framework for promoting energy from renewable sources in the EU. This directive established a binding target for renewable energy to be met by 2020 with a contribution of 20% to the total final energy supply in the EU and at least 10% to the transport sector in each Member State. EU RED II covers the period between 2021 and 2030 and sets a new binding renewable energy target for 2030: at least 32% of the gross final energy consumption and at least 14% of renewable energy supply in the transportation sector.[29]. In terms of binding sustainability criteria and bioenergy verification requirements, RED I specified at least 35% and 60% savings for waste/residues and biofuels produced in installations starting on or after January 1, 2017, respectively. RED II specified at least 65% for biofuels, biogas used in transportation, and bioliquids produced in operation from January 1, 2021 [28].

Due to the substantial uncertainty about the environmental performance of bioenergy chains, many countries have required some minimum requirements for biofuel production to be eligible for public incentives [30].

Fulfilling the specific criteria is significant to reach the above targets of EU RED to receive financial support. Energy production from biofuel is playing a key role in fulfilling these targets [31].

EU RED II also requires a 6.8% increase in the share of other "low-emission fuels" in transportation, such as renewable electricity and advanced biofuels. Moreover, the Commission states that advanced biofuels produce at least 70% less GHG emissions than fossil fuels (compared to savings of 60% in 2018 for new production plants by RED). This seems to indicate a trend in which the EC will continue to assist the development of advanced alternative fuels for transportation by enforcing a blending mandate on fuel suppliers while progressively phasing out the contribution of food-based biofuels. The negative public view partly drives the trend that biofuels compete directly with food. As Marie Donelly, Former Director for Renewables, Research, and Energy Efficiency in the Commission's Energy directorate, puts it, "we have to be very sensitive to the reality of citizens' concerns, sometimes even if these concerns are emotive rather than factual based or scientific [32]".

2.6. Closing Remarks

Biomass is considered one of the most important renewable energy sources and the only alternative source to fossil sources to produce fuels, chemicals and other carbon-based materials. Biofuels are usually categorised into 1st, 2nd, 3rd, and 4th

generation biofuels based on feedstock choice, production process and development stage. 1st generation biofuels are currently used and produced in large amounts on commercial scales. Bioethanol, biodiesel and biogas are the most common ones. The most critical and first liquid biofuels are biodiesel and bioethanol. They are commercially available, and their market share is steadily increasing. In 2020, bioethanol and biodiesel provided about 3.5% of transportation energy. Biofuel production levels returned to 2019 levels in 2021 after falling in 2020 due to reduced transportation demand caused by the COVID-19 pandemic. Biofuels are essential in combating climate change because they are carbon-neutral. Thus, bioethanol and biodiesel play a vital role in the transportation sector to support countries' sustainability and low-carbon development strategies.

To improve energy supply security by reducing the dependence on imported fossil fuels, decreasing GHG emissions, and thus, mitigating climate change, the EU defined sustainable criteria for the whole bioenergy sector. This is accomplished through the EU RED and EU RED II directives. EU RED established a binding target for renewable energy to be met by 2020 with a contribution of 20% to the total final energy supply in the EU and at least 10% to the transport sector in each Member State. EU RED II covers the period between 2021 and 2030 and sets a new binding renewable energy target for 2030: at least 32% of the gross final energy consumption and at least 14% of renewable energy supply in the transportation sector. Regarding GHG saving thresholds for transportation biofuels, RED I specified at least 60% savings for biofuels produced in installations starting on January 1, 2017, and RED II set at least 65% for biofuels produced in operation from January 1, 2021. Turkey is aligning its regulatory framework in the environmental sector with the EU standards, including developing renewable and biomass-based energy production and utilization.

3. PREVIOUS STUDIES

The emissions from the whole life cycle of producing and delivering biofuels must be favourable to ensure they successfully reduce GHG emissions from the transport sector [33]. According to Matthew Aylott from UK's National Non-Food Crop Centre, measuring the life cycle GHG emissions of biofuels is a serious and complex issue. The emissions from a biofuel supply chain cannot be measured directly; instead, models or tools are required to calculate the effects of biofuel production [34]. The provision of biofuel involves the consumption of non-renewable sources during cultivation, harvesting, transport, and processing [34].

By identifying and quantifying energy and materials flows and waste and emissions emitted, the LCA approach is frequently used to assess the environmental impacts associated with a product, process, or activity. The method has been used as a standard to determine biofuels' life-cycle GHG emissions. The International Organization for Standardization (ISO) standards provide a general structure for conducting the assessment. Defining scope, system boundaries, functional units, and reference systems; determining mass and energy flows; addressing co-products; and attributing impacts to energy and material flows are all steps in the overall procedure [35].

New criteria for effective GHG reduction strategies are currently emerging in response to global climate change. As a result of the specialized evaluation demands for GHG emissions, interest in life cycle studies for energy applications has grown. Significant effort is being made, particularly in EU nations, to determine life cycle GHG emissions using LCA principles to achieve ecologically sustainable biofuel production.

3.1. Studies on Life Cycle GHG Emissions of Biofuel Generation

Acquaye et al. assessed the life cycle GHG emissions of biodiesel and bioethanol and compared them to fossil fuels to analyze the potential of biofuels contributing to the UK emission reduction targets and, thus, EU emission reduction targets [36]. The results of the study showed that the life cycle GHG emission of rapeseed-based biodiesel is found as 55.5 kg CO_2 eq/GJ, waste oil-based biodiesel is found as 10.6 kg CO_2 eq/GJ, sugar beet-based bioethanol is found 26.6 kg CO_2 eq/GJ, and corn-based bioethanol is found 70.3 kg CO_2 eq/GJ. Based on these results, waste oil-based biodiesel and sugar beet-based bioethanol offer the most significant potential for emission saving in the UK context.

Another study in the UK is conducted to compare the life cycle GHG emissions of large-scale and small-scale biodiesel production from rapeseed oil. According to Gupta et al., large-scale biodiesel production systems in the UK have an annual global warming potential of 2.63 tons CO_2eq/ton biodiesel [37]. Small-scale biodiesel production systems in the UK have an annual global warming potential of 2.88 ton CO_2eq/ton biodiesel, whereas the rapeseed agriculture stage caused more than 65% carbon emissions.

Fridrihsone et al. analyzed the global warming potential of the seasonal cultivation of rapeseed in Latvia [38]. Due to more agricultural inputs and a higher yield, winter rapeseed production has a lesser environmental impact than spring rapeseed agriculture. Seasonal variation of GWP for rapeseed-based biodiesel production was found as 1.27 and 1.06 ton CO_2eq/ton biodiesel for spring and winter, respectively.

Foteinis et al. examined the environmental sustainability of second-generation biodiesel, which is used as cooking oil on an industrial scale in Greece [39]. It is found that the life cycle GHG emission of used cooking oil-based biodiesel is 14 g CO_2eq/MJ. This is 40% lower than first-generation biodiesel, an order magnitude lower than third-generation biodiesel (microalgae) since it is not a fully-fledged technology yet. Given its overall low environmental footprint and commercial availability, second-generation biodiesel, which currently accounts for 15% of the biodiesel market in Greece, could serve as a stepping stone toward decarbonizing Europe's transportation sector and improving supply and energy security.

In Brazil, Pereira et al. [40] analyzed the main differences and similarities in the methodological structures, calculation procedures, and assumptions for the major commercial bioethanol by using three LCA calculation tools which are: BioGrace (EU), GHGenius (Canada), and GREET (U.S.). The calculated emissions across the models for corn-based bioethanol ranged from 43.4 g CO_2 eq/MJ (BioGrace), 61.9 g CO_2 eq/MJ (GHGenius), and 57.7 g CO_2 eq/MJ (GREET). The main differences, in this case, are due to how the coproducts were treated. The default method used by BioGrace (energy) resulted in a 50% partitioning of GHG emissions between ethanol and its coproducts. In contrast, the substitution methods used by GREET and GHGenius provide credits for non-energy products to ethanol of 12.8 and 16.7 g CO_2eq per MJ, respectively.

3.2. Studies Using the BioGrace Tool

Most of the studies conducted in the EU have employed the BioGrace tool for the calculation of life cycle GHG emissions of biofuels. For instance, a study used the BioGrace tool to calculate the life-cycle assessment of GHG emissions from sunflower cultivation for biodiesel production in Tuscany, Italy, using different case studies from five other farms. The study showed that different cultivation techniques (Table 5) have a different impact on the life cycle GHG emission of biodiesel.

Table 5. Sunflower cultivation energy inputs related to one ha for each farm in Tuscany, Italy [41]

Cultivation input[a]	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	BioGrace reference
Diesel[b]	6565	5740	6743	6311	5560	3437
N-fertiliser	3674	5585	4581	4948	5977	1911
P_2O_5-fertiliser	1401	762	274	1401	548	457
K_2O-feriliser	–	–	232	445	203	213
Pesticides	59	260	35	220	134	537
Seeds	47	47	47	47	47	47

a Fossil energy input coefficients (BioGrace Project, 2011): Diesel = 1.16 MJ MJ^{-1} ; N-fertiliser = 48.99 MJ kg^{-1} [N]; P_2O_5-fertiliser = 15.23 MJ kg^{-1} [P_2O_5]; K_2O-fertiliser = 9.68 MJ kg^{-1} [K_2O]; Pesticides = 268.40 MJ kg^{-1} [a. i.] Sunflower seeds = 7.87 MJ kg^{-1}.
b LHV = 43.1 MJ kg^{-1}.

The results of the study showed that the life cycle GHG emission of biodiesel from sunflower-*Farm 1* is 53.4 g CO_2-eq/MJ, *Farm 2*= 79.4 g CO_2-eq/MJ, *Farm 3*= 61.9 g CO_2-eq/MJ, Farm 4= 53.8 g CO_2-eq/MJ, Farm 5= 72.3 g CO_2-eq/MJ. The GHG emissions from sunflower farming in the five case studies are higher than the default value (18 g CO_2eq /MJ) indicated by the RED. The main reasons for this difference with the default value are; diesel consumption and extensive use of nitrogen fertilizer which cause higher GHG emissions than the default value. These findings suggest that without a considerable change in local farm practices, primarily oriented toward reducing the use of nitrogen fertilizers and diesel consumption. It will be difficult to comply with such requirements on GHG emissions for the sunflower biodiesel cultivation phase in Tuscany [41].

Another study conducted in Germany used BioGrace Tool to calculate GHG emissions of sugar beet cultivation in Germany by using data from farm surveys. However, in this study, the BioGrace tool was used for calculations concerning sugar beet cultivation only, as the tool allows for examining the production of the biofuel crops separately. The study considered emissions from producing and using fertilizers and pesticides, tillage, and field emissions. As a result, total GHG emissions of sugar beet cultivation in Germany between 2010 and 2012 were estimated as 2626 CO_2eq kg ha^{-1} $year^{-1}$ when applying mineral plus organic fertilizer and 1782 CO_2eq kg ha^{-1} $year^{-1}$ when only organic fertilizer was applied. CO_2eq emissions from N fertilization were 2.5 times higher than diesel and further production factors. The absence of emissions for producing organic fertilizers led to 12% less total CO_2eq emissions than mineral fertilisers. However, there were more emissions via diesel due to larger volumes transported by using organic fertilizer only [42].

3.3. Studies on GHG Emission Estimation of Turkish Crops

To the best of our knowledge, there is no scientific study conducted for the Life Cycle Assessment of GHG emissions from biofuel production in Turkey. In Turkey's context, BioGrace default values are used by some studies to calculate GHG emissions for the cultivation process of specific feedstocks. For example, in a study, GHG emissions of cotton cultivation in the Besiri region of Batman province in Turkey were determined using various default values such as chemicals, nitrogen, phosphorus, and potassium (NPK) fertilizers, and electricity data listed in the BioGrace Calculation tool. The necessary cultivation data is collected through face-to-face surveys with 64 selected farms in the 2018-2019 cultivation season. The total GHG emission of cotton cultivation was calculated as 3742.50 kg CO_2eq /ha [43]. Similarly, in another study conducted in Turkey to determine GHG in the production of different aromatic plants, various default values from the BioGrace Calculation tool, NPK fertilizers and pesticides are used. The results indicated that total GHG emissions for four different aromatic plant productions (guar, lavender, sesame, and tobacco) were computed as 1488.50 kgCO_2eq /ha, 494.81 kg CO_2eq /ha, 907.13 kg CO_2eq /ha, 6604.58 kg CO_2eq /ha respectively [44].

3.4. Closing Remarks

In this section, we analysed various studies to examine different practices to better understand *(i)* life cycle GHG emissions of biofuels, mainly of biodiesel production from rapeseed and waste oil, bioethanol production from sugar beet and corn, *(ii)* BioGrace use to analyse different feedstock's GHGs, *(iii)* Turkey context. The results of the studies analysed above are shown in the tables below.

As seen in Table 6, the life cycle GHG emission estimates of biodiesel production from rapeseed range from 27.5 g CO_2 eq/MJ to 74.6 g CO_2 eq/MJ. This difference could be due to the scale of the biodiesel production facility, the global warming potential of the seasonal cultivation of rapeseed, different cultivation methods such as using different amounts of fertilizers, and the energy intensity of the countries. The life cycle GHG emission estimates of biodiesel production from waste oil range from 14 g CO_2 eq/MJ (Greece) to 10.6 g CO_2 eq/MJ (UK), which is a smaller range than that of the rapeseed. In a study conducted in the UK, the life cycle GHG emission of sugar beet-based bioethanol is found to be 26.6 g CO_2 eq/MJ, which offers the most significant potential for emission savings in the UK context with waste oil-based biodiesel. Life cycle GHG emission of bioethanol from corn ranges from 43.4 g CO_2 eq/MJ to 70.3 g CO_2 eq/MJ. Based on these estimates, we can say that different calculation tools can give different results alongside different bioethanol production styles, different cultivation methods, and the energy intensity of the countries.

The studies estimating life cycle GHG emissions of biofuels using BioGrace are listed in Table 7. In a study in Italy, the life cycle GHG emission of bioethanol from sunflowers was examined by comparing different farming techniques, and emissions ranged from 53.4 g CO_2 eq/MJ to 79.4 g CO_2 eq/MJ. The other practices of using the BioGrace tool in the literature are for calculating GHG emissions of feedstock cultivation, such as sugar beet calculation in Germany, and cotton, guar, lavender, sesame and tobacco cultivation in Turkey. The studies conducted using BioGrace for the Turkish crops are listed in Table 8.

To the best of our knowledge, there is no scientific study conducted for the Life Cycle Assessment of GHG emissions from biofuel production in Turkey. This study aims to fill this gap in the Turkish context.

Table 6: Previous Studies on life cycle GHG emissions of biofuel generation

Country	**Feedstock**	**Emission (g CO_2 eq/MJ)**	**Remarks**	**Ref.**
UK	Rapeseed to Biodiesel	55.5 g CO_2 eq/MJ	NA	[36]
UK	Waste Oil to Biodiesel	10.6 g CO_2 eq/MJ	NA	[36]
UK	Sugar beet to Bioethanol	26.6 g CO_2 eq/MJ	NA	[36]
UK	Corn to Bioethanol	70.3 g CO_2 eq/MJ	NA	[36]
UK	Rapeseed to Biodiesel	68.2 g CO_2 eq/MJ	Large-scale biodiesel production from rapeseed	[37]
UK	Rapeseed to Biodiesel	74.6 g CO_2 eq/MJ	Small-scale biodiesel production from rapeseed	[37]
Latvia	Rapeseed to Biodiesel	27.5 g CO_2 eq/MJ	Winter season	[38]
Latvia	Rapeseed to Biodiesel	32.9 g CO_2 eq/MJ	Spring season	[38]
Greece	Waste oil to Biodiesel	14 g CO_2 eq/MJ	NA	[39]
Brazil	Corn to Bioethanol	43.4 g CO_2 eq/MJ	BioGrace Calculation Tool	[40]
Brazil	Corn to Bioethanol	61.9 g CO_2 eq/MJ	GHGenius Calculation Tool	[40]
Brazil	Corn to Bioethanol	57.7 g CO_2 eq/MJ	GREET Calculation Tool	[40]

Table 7: Previous studies using the BioGrace Tool

Country	**Feedstock**	**Emission (g CO_2 eq/MJ)**	**Remarks**	**Ref.**
Italy	Sunflower to Bioethanol	53.4 g CO_2 eq/MJ	Farm 1-LCA	[41]
Italy	Sunflower to Bioethanol	79.4 g CO_2 eq/MJ	Farm 2-LCA	[41]
Italy	Sunflower to Bioethanol	61.9 g CO_2 eq/MJ	Farm 3-LCA	[41]

Country	Feedstock	Emission (g CO_2 eq/MJ)	Remarks	Ref.
Italy	Sunflower to Bioethanol	53.8 g CO_2 eq/MJ	Farm 4-LCA	[41]
Brazil	Corn to Bioethanol	43.4 g CO_2 eq/MJ	BioGrace Calculation Tool	[40]
Germany	Sugar beet cultivation	2626 kg CO_2eq/ha	Sugar beet cultivation emission in Germany by applying mineral plus organic fertilizer	[42]
Germany	Sugar beet cultivation	1782 kg CO_2eq/ha	Sugar beet cultivation emission in Germany by applying organic fertilizer	[42]

Table 8: Previous studies using the BioGrace Tool on GHG emission estimation of Turkish crops

Feedstock	Emission (g CO_2 eq/MJ)	Remarks	Ref.
Cotton cultivation	3742.5 kg CO_2eq/ha	Cotton cultivation in Besiri Region	[43]
Guar cultivation	1488.5 kg CO_2eq /ha	Emission of production of different aromatic plants in Turkey	[44]
Lavender cultivation	494.81 kg CO_2eq /ha	Emission of production of different aromatic plants in Turkey	[44]
Sesame cultivation	907.13 kg CO_2eq /ha	Emission of production of different aromatic plants in Turkey	[44]
Tobacco cultivation	6604.58 kg CO_2eq /ha	Emission of production of different aromatic plants in Turkey	[44]

4. BIOGRACE-I GHG CALCULATION TOOL VERSION 4D FOR COMPLIANCE

The life cycle GHG emissions analyses of biofuel production and use were conducted using *"BioGrace-I GHG Calculation Tool Version 4d for Compliance".* BioGrace is a spreadsheet model for calculating biofuel GHG emissions that country model owners developed from Germany, the Netherlands, Spain, and the United Kingdom as part of a European cooperative harmonization effort to implement the EU Renewable Energy Directive (RED) and the EU Fuel Quality Directive (FQD). The calculation is based on a database that includes default values (EU averages) for 22 commercial feedstock/biofuels pathways developed by a collaborative group of experts, from the Joint European Commission (JEC), the Joint Research Center (JRC), the European Council for Automotive Research and Development (EUCAR), and the European Council for Clean Air and Water in Europe (CONCAWE) [45].
The BioGrace GHG calculation tool allows the reproduction of the Annex V default values of the Renewable Energy Directive (2009/28/EC) (EU RED) for biofuel production pathways and to perform individually adapted calculations.

4.1. Structure of the Estimation Tool

The GHG emission and the GHG savings along the entire biofuel production chain are added together to calculate the GHG emissions resulting from the production and use of biofuels. The System Boundary of the Life Cycle GHG Analysis was conducted for Biofuel production, and it was developed according to Point 6, article 2 of the Fuel Quality Directive (98/70/EC). "Life cycle greenhouse gas emissions" means all net emissions of CO_2, CH_4, and N_2O that can be assigned to the fuel (including any blended components) or energy supplied. This includes all relevant stages from extraction or cultivation, including land-use changes, transport, distribution, processing and combustion, irrespective of where those emissions occur" [46].

Table 9. Steps of the life cycle GHG analysis of biofuel production

Name of steps	Entire biofuel Production Chain
Biomass supply chain	• Cultivation of biomass energy crops and/or waste collection • Transport of energy crops and/or transport of wastes
Biorefinery	• Biofuel production processes applying biomass conversion technologies
Transport and distribution	• Transport of biofuel from production facility (biorefinery) to depot • Transport of biofuel from depot to filling station
Use	• Biofuel combustion in vehicles

Based on the steps of analysing GHG emissions from biofuel production, which are given in Table 9, the total emissions of biofuel production and use should be calculated following the methods defined in the EU RED. The regulations include concrete calculation formulas. A biofuel's GHG reduction potential is determined by the GHG emissions resulting from its production and use phases and on a comparison to a fossil fuel reference value.

Total emissions were calculated based on the following formula, which is generally binding formula as per EU FQD and based on GHG emissions and GHG emission savings. In the BioGrace tool, GHG emissions from the production and use of biofuels were calculated from *Equation 1* [46] :

$$E = e_{ec} + e_{l} + e_{p} + e_{td} + e_{u} - e_{sca} - e_{ccs} - e_{ccr} - e_{ee} \qquad (Eq.1)$$

where;

E = total emissions from the use of the fuel;

e_{ec} *= emissions from the extraction or cultivation of raw materials;*

e_{l} *= annualised emissions from carbon stock changes caused by land use change;*

e_{td} *= emissions from transport and distribution;*

e_{u} *= emissions from the fuel in use;*

e_{sca} *= emission savings from soil carbon accumulation via improved agricultural management;*

e_{ccs} *= emission savings from carbon capture and geological storage;*

e_{ccr} *= emission savings from carbon capture and replacement; and*

e_{ee} *= emission savings from excess electricity from cogeneration.*

The following Equation (Eq.2) is used in the calculation tool to calculate the GHG-saving potential of biofuels when compared to GHG emissions from fossil-based fuels [47].

$$SAVING = (E_F - E_B)/E_F \qquad (Eq.2)$$

where;

E_B = *total emissions from the biofuel; and*

E_F = *total emissions from the fossil fuel comparator.*

The selected feedstocks for producing biofuels in this study, which takes into account the Turkish agricultural system, are;

- Rapeseed to produce biodiesel
- Waste oil to produce biodiesel
- Sugar beet to produce bioethanol
- Corn to produce bioethanol

4.2. Closing Remarks

In this study, BioGrace- I GHG Calculation Tool Version 4d for Compliance was selected to provide baseline information on the life cycle GHG emission of biodiesel and bioethanol production based on the most common feedstocks used in Turkey. The BioGrace Calculation tool is recognized as a voluntary scheme by the EC and is in line with the sustainability criteria of EU RED.

5. METHODOLOGY AND DATA SOURCES

This chapter presents the methodologies of the life cycle GHG analysis for biofuels from the selected feedstocks and biofuel blending scenarios that are developed based on the results of life cycle GHG analysis of biofuel production and use.

The flow chart of the study's methodology is presented below:

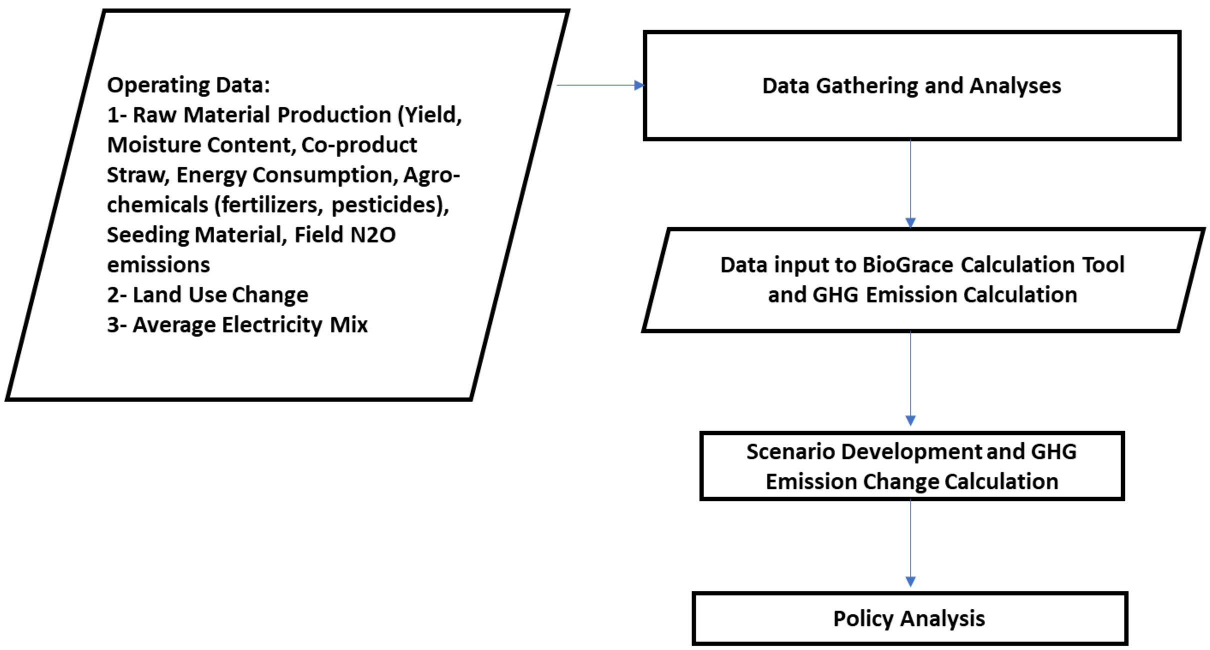


Figure 8. Methodology flow chart of the study

5.1. Data Gathering and Analyses

In this study, besides the standard values given in the BioGrace tool, various data types and parameters from different data sources are used in calculations. Some of the data used in calculations are presented in Table 10.

Table 10. The data set used in calculations

Type of Data	Value	Unit	Data Source
The average carbon emissions from the fossil part of gasoline and diesel	83.8	CO_2eq/MJ	EU Fuel Quality Directive[48]
Diesel fuel - Lower Heating Value	36.0	MJ/ litre	[49]
Gasoline fuel - Lower Heating Value	32.0	MJ/litre	[49]
Biodiesel - Lower Heating Value	32.1	MJ/ litre	[50]

Bioethanol - Lower Heating Value	21.2	MJ/litre	[50]
Biodiesel density	832	kg/ m3	[51]
Bioethanol density	794	kg/ m3	[51]
CO_2 emissions from the Turkish electricity production mix	464	g CO_2 / kWh	[52]
Fuel consumption of diesel and gasoline passenger car	0.06	Litre/km	[48]
Global Warming Potential (GWP) of CO_2	1	g CO_2eq	[48]
Global Warming Potential (GWP) of CH_4	23	g CO_2eq	[48]
Global Warming Potential (GWP) of N_2O	296	g CO_2eq	[48]

- In the tool, in accordance with FQD, the functional unit was chosen as 1 MJ of fuel energy generated. Additionally, energy content was expressed in terms of the lower heating value (LHV) under dry conditions.
- Unlike BioGrace tool standard values, country-specific NPK fertiliser values based on the selected crop type are provided from the official source (these data are given in the following sections)
- Other required data related to crop and fuel production was given in the tables in the following sections.

Due to the lack of data, some required values for calculations are taken from the tool's database. Some of them are:

- Pesticide usage amounts for all crop cultivation, energy consumption and transportation data, the yield for waste oil
- In accordance with FQD, the tool also calculates GHG emissions from direct land use change during the cultivation of crops based on the required data for the country-specific. The default calculation method given in BioGrace is considered. The calculations made using the data from the guidelines on Commission Decision for the calculation of land use carbon stocks and GHG emission from the resulting land use change were found to be 0.11 ton CO_2 ha^{-1} $year^{-1}$. Table 11 shows the details of the data used in the calculation [36].

Table 11. The data used for the calculation of GHG emissions resulting from the land use change

	Actual Land Use	Reference Land Use
Climate region	Warm temperate, dry	Warm temperate, dry
Vegetation/crop (land use)	Cultivated/cropland	Cultivated/cropland
Soil type	High activity clay	High activity clay
Soil management	Full-tillage	Reduced-tillage
Soil organic carbon [ton C / ha]	38	38
Land use factor reflecting the difference in soil organic carbon associated with the type of land use compared to the standard organic carbon [-]	0.8	0.8
Management factor reflecting the difference in soil organic carbon associated with the principle management practice compared to the standard soil organic carbon [-]	1	1.02
Input factor reflecting the difference in soil organic carbon associated with different levels of carbon input to soil compared to the standard soil organic carbon [-]	1	1

5.2. Data Input to BioGrace Calculation Tool and GHG Emission Calculation

In the following sections, the data types are given based on the selected feedstock in biofuel production.

5.2.1. Data Used for Biodiesel Production from Rapeseed

Various data are needed to calculate the life cycle GHG emissions of biodiesel production and use from rapeseed. Figure 9 presents all production pathways defined in the BioGrace tool.

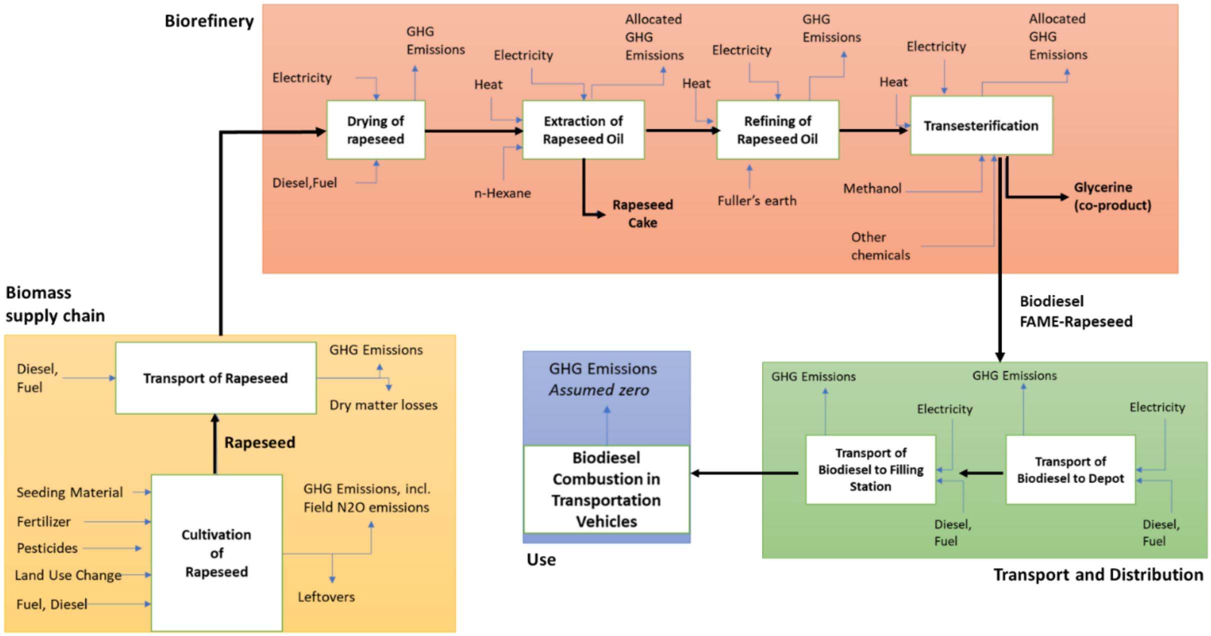


Figure 9. Production pathway of Biodiesel-Rapeseed in the BioGrace tool [53]

The production process is divided into four steps, as shown in Table 9. The first step is the biomass supply chain which covers the cultivation and transport of rapeseed. The required data for this step are given in the following table.

Table 12. The data used in the BioGrace tool in the step of the biomass supply chain of life cycle GHG emissions from biodiesel-rapeseed

Type of Data	Value	Unit	Source
Cultivation area	35,000	ha	[54]
Production	122,000	tons	
Yield	3485.7	kg ha^{-1} year^{-1}	
Moisture Content	10%		[55]
Energy Consumption, Diesel	2.87	MJ ha^{-1} year^{-1}	[56]
N fertiliser	122.5	kg N ha^{-1} year^{-1}	[57]
P fertiliser	50	kg P_2O_5 ha^{-1} year^{-1}	[57]
K fertiliser	50	kg K_2O ha^{-1} year^{-1}	[57]
Pesticides	1.2	kg ha^{-1} year^{-1}	[51]
Seeding material	10	kg ha^{-1} year^{-1}	[58]

Rapeseed is mostly grown in Turkey's Thrace region. The amount of fertilizer required for rapeseed growing varies depending on the agricultural region's soil and climate characteristics. The fertilizer requirement rates specific to the Thrace region for rapeseed were obtained and applied in the model using the fertilizer recommendation guideline [57] prepared by the Ministry of Agriculture and Forestry of Turkey.

The tool calculates direct and indirect N_2O emissions from managed soils during rapeseed cultivation based on the IPCC Tier 1 approach using the required data in the table above. According to the result, the overall (direct and indirect) N_2O emissions from rapeseed cultivation were found as *4.18 kg N_2O ha^{-1} $year^{-1}$*.
Biorefinery is the name given to the second step. This step was divided into six different processes in the tool.

1. Drying of rapeseed
2. Transport of rapeseed
3. Extraction of rapeseed oil
4. Transport of rapeseed oil
5. Refining of rapeseed oil
6. Transesterification

Table 13 gives the data used in this step to calculate GHG emissions in every process.

Table 13. The data used in the step of biorefinery of rapeseed [51]

DRYING OF RAPESEED		
Rapeseed	1000	$MJ_{rapeseed}/MJ_{rapeseed}$, BioGrace
Diesel	0.00018	$MJ/MJ_{rapeseed}$, BioGrace
Average Electricity Mix in Turkey	0.00308	$MJ/MJ_{rapeseed}$, BioGrace
TRANSPORT OF RAPESEED		
Rapeseed	0.990	$MJ_{rapeseed}/MJ_{rapeseed}$, BioGrace
Truck for dry product- Fuel type: Diesel	50	km, BioGrace
EXTRACTION OF RAPESEED OIL		
Yield:		
Crude vegetable oil	0.6125	$MJ_{oil}/MJ_{rapeseed}$, BioGrace
Co-product rapeseed cake	0.3875	$MJ_{rapeseedcake}/MJ_{rapeseed}$, BioGrace
Energy Consumption:		
Average Electricity Mix in Turkey	0.0118	MJ/MJ_{oil}, BioGrace
Steam (from NG boiler)	0.0557	MJ/MJ_{oil} (Heat), BioGrace
NG Boiler:		
Natural gas input/MJ steam	1.111	MJ/MJ_{steam} , BioGrace
Natural gas (4000 km, EU mix quality)	0.062	MJ/MJ_{oil}, BioGrace

Electricity input/MJ steam	0.020	MJ/MJ_{steam} , BioGrace
Average electricity mix in Turkey	0.001	MJ/MJ_{oil}, BioGrace
Chemicals:		
n-Hexane	0.0043	MJ/MJ_{oil}, BioGrace
TRANSPORT OF RAPESEED OIL		
Crude vegetable oil	1000	MJ_{oil}/MJ_{oil}, BioGrace
Truck for liquids- Fuel Type: Diesel	0	km, BioGrace
REFINING OF RAPESEED OIL		
Yield:		
Rapeseed oil	0.96	MJ_{oil}/MJ_{oil}, BioGrace
Energy Consumption:		
Average Electricity Mix in Turkey	0.0008	MJ/MJ_{oil}, BioGrace
Steam (from NG boiler)	0.0115	MJ/MJ_{oil}, BioGrace
NG Boiler:		
Natural gas input/MJ_{steam}	1.111	MJ/MJ_{steam} , BioGrace
Natural gas (4000 km, EU mix quality)	0.013	MJ/MJ_{oil}, BioGrace
Electricity input/MJ_{steam}	0.020	MJ/MJ_{steam} , BioGrace
Average electricity mix in Turkey	0.000	MJ/MJ_{oil}, BioGrace
Chemicals:		
Fuller's earth	0.0002	kg/MJ_{oil}, BioGrace
TRANSPORT OF REFINED RAPESEED OIL		
Refined vegetable oil	1000	MJ_{oil}/MJ_{oil}, BioGrace
Truck for liquids- Fuel Type: Diesel	0	km, BioGrace
ESTERIFICATION		
Yield:		
FAME	0.9936	MJ_{fame}/MJ_{oil}, BioGrace
Co-product refined glycerol	105.6	kg/$ton_{biodiesel}$, BioGrace
Energy Consumption:		
Average Electricity Mix in Turkey	0.0041	MJ/$MJ_{biodiesel,}$ BioGrace
Steam (from NG boiler)	0.1006	MJ/$MJ_{biodiesel}$, BioGrace
NG Boiler:		
Natural gas input/MJ_{steam}	1.111	MJ/MJ_{steam} , BioGrace
Natural gas (4000 km, EU mix quality)	0.112	MJ/$MJ_{biodiesel}$, BioGrace
Electricity input/MJ_{steam}	0.020	MJ/MJ_{steam}, BioGrace
Average electricity mix in Turkey	0.002	MJ/$MJ_{biodiesel}$, BioGrace
Chemicals:		
Phosphoric acid (H_3PO_4)	0.000061	kg/$MJ_{biodiesel}$, BioGrace
Hydrochloric acid (HCl)	0.000753	kg/$MJ_{biodiesel}$, BioGrace
Sodium carbonate (Na_2CO_3)	0.000094	kg/$MJ_{biodiesel}$, BioGrace
Sodium Hydroxide (NaOH)	0.000253	kg/$MJ_{biodiesel}$, BioGrace
Methanol	0.0818	kg/$MJ_{biodiesel}$, BioGrace

The third step is the transport and distribution of biodiesel which includes GHG emission calculation from the processes of transport of biodiesel to a depot and then to a filling station. Table 14 depicts the data used in this step.

Table 14. The data used in the step of transport and distribution [51]

TRANSPORT OF BIODIESEL TO DEPOT		
Biodiesel	1000	$MJ_{biodiesel}/MJ_{biodiesel}$, BioGrace
Truck for liquids- Fuel Type: Diesel	150	km, BioGrace
Energy Consumption depot, Average electricity mix in Turkey	0.00084	$MJ/MJ_{biodiesel}$, BioGrace
TRANSPORT OF BIODIESEL TO FILLING STATION		
Biodiesel	1000	$MJ_{biodiesel}/MJ_{biodiesel}$, BioGrace
Truck for liquids- Fuel Type: Diesel	150	km, BioGrace
Energy Consumption filling station, Average electricity mix in Turkey	0.0034	$MJ/MJ_{biodiesel}$, BioGrace

The fourth step is the use of biodiesel, which does not cause GHG emissions. Explanation of the data:

- The leftovers, such as straw, tops, leaves, etc., were not included in the life cycle. Those could be used as animal feed or organic fertiliser.
- It is assumed that the soil pH is not lower than 6.5, meaning calcium fertilizer is not needed.
- For the "Biorefinery" and Transport & Distribution" stages, FQD default values have been used - FQD default values are accessible in BioGrace software.
- The average electricity mix in Turkey is used as input, as processes are considered to be occurring in Turkey.
- There is no available Turkey-specific information on heat & steam requirements. Therefore, a natural gas boiler based on BioGrace standard values was used in the analysis.
- Under the FQD, direct land use change during rapeseed cultivation has been considered in the analysis. Default calculation is used. Reference land use is taken as "reduced tillage", and actual land use is taken as "full tillage," as described above.
- Under the FQD, indirect land use is considered taken as zero.
- N_2O field emissions were calculated under IPCC, Tier 1, as described above in detail.

5.2.2. Data Used for Biodiesel Production from Waste Oil

Unlike rapeseed, known as the first-generation feedstock, waste oil is considered second-generation. In the tool, the collection of vegetable or animal waste oils is considered in biofuel production. The below figure shows all the steps of biodiesel production from waste oil based on country-specific data, mainly found in literature and the tool's database.

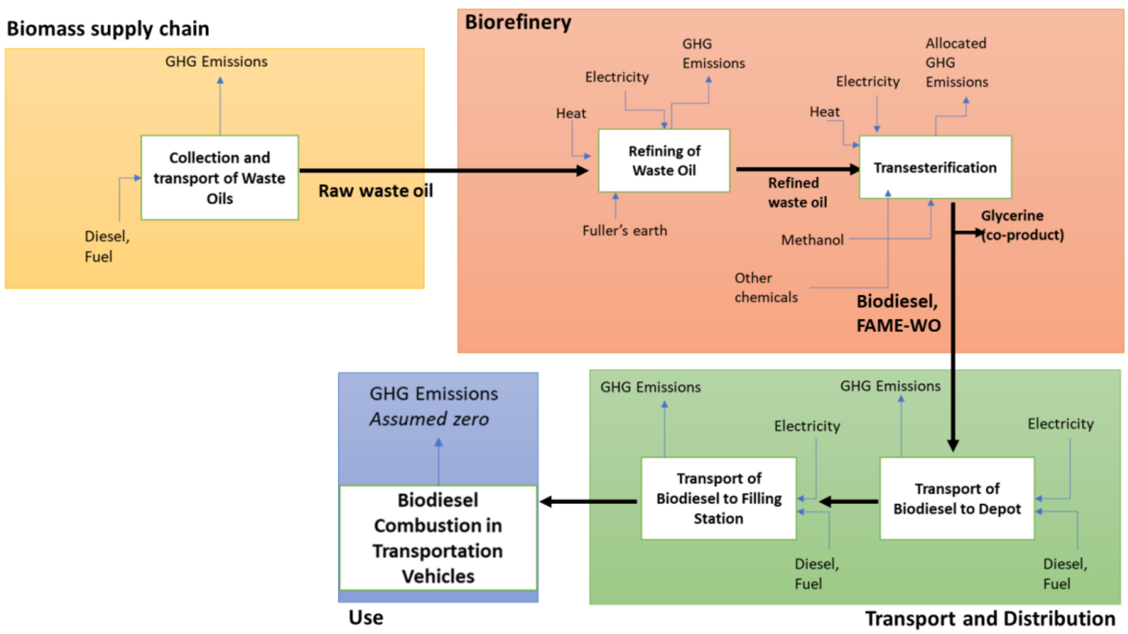


Figure 10. Production pathway of Biodiesel-Waste oil in the BioGrace tool [53]

As mentioned above, for biodiesel production from waste oil, there are four production steps defined in the tool (see Figure 10). The data required for the first step are given in Table 15.

Table 15. The data used in the BioGrace tool in the step of the biomass supply chain of life cycle GHG emissions from biodiesel-waste oil [51]

COLLECTION OF WASTE OIL		
Yield	0.9782	MJ/MJ $_{\text{refined waste oil}}$, BioGrace
Moisture Content	0.25 %	[21]

The second step is biorefinery which includes GHG emission calculation from the transport, refining, and transesterification of waste oil. The below table depicts the data used in this step.

Table 16. The data used in the step of biorefinery of waste oil [51]

TRANSPORT OF WASTEOIL		
Waste vegetable/animal oil	1000	MJ_{oil}/MJ_{oil}, BioGrace
Transport per Truck for liquids (Diesel)	100	km, BioGrace
REFINING OF WASTEOIL		
Yield:		
Waste vegetable/animal oil	0.96	MJ_{oil}/MJ_{oil}, BioGrace
Energy Consumption:		
Average Electricity Mix in Turkey	0.0008	MJ/MJ_{oil}, BioGrace
Steam (from NG boiler)	0.0115	MJ/MJ_{oil}, BioGrace
NG Boiler:		
Natural gas input/MJ_{steam}	1.111	MJ/MJ_{steam}, BioGrace
Natural gas (4000 km, EU mix quality)	0.013	MJ/MJ_{oil}, BioGrace
Electricity input/MJ_{steam}	0.020	MJ/MJ_{steam}, BioGrace
Average electricity mix in Turkey	0.000	MJ/MJ_{oil}, BioGrace
Chemicals:		
Fuller's earth	0.0002	kg/MJ_{oil}, BioGrace
TRANSPORT OF REFINED OIL		
Refined vegetable oil	1000	MJ_{oil}/MJ_{oil}, BioGrace
Truck for liquids- Fuel Type: Diesel	0	km, BioGrace
ESTERIFICATION		
Yield:		
Biodiesel	0.9782	$MJ_{biodiesel}/MJ_{oil}$, BioGrace
Co-product refined glycerol	0.0432	$MJ/MJ_{biodiesel}$, BioGrace
Co-product bio-oil	0	$MJ/MJ_{biodiesel}$, BioGrace
Energy Consumption:		
Average Electricity Mix in Turkey	0.0057	$MJ/MJ_{biodiesel}$, BioGrace
Natural gas (4000 km, EU Mix quality)	0.1374	$MJ/MJ_{biodiesel}$, BioGrace
Chemicals:		
Phosphoric acid (H_3PO_4)	0.000548	$kg/MJ_{biodiesel}$, BioGrace
Potassium hydroxide (KOH)	0.000510	$kg/MJ_{biodiesel}$, BioGrace
Potassium sulphate (K_2SO_4)	-0.001004	$kg/MJ_{biodiesel}$, BioGrace
Methanol	0.08471	$kg/MJ_{biodiesel}$, BioGrace

The third step is the transport and distribution of biodiesel which includes GHG emission calculation from the processes of transport of biodiesel to a depot and then to a filling station (Table 17).

Table 17. The data used in the transportation and distribution step [51]

TRANSPORT OF Biodiesel TO DEPOT		
Biodiesel	1000	$MJ_{biodiesel}/MJ_{biodiesel}$, BioGrace
Truck for liquids- Fuel Type: Diesel	150	km, BioGrace
Energy Consumption depot, Average electricity mix in Turkey	0.00084	$MJ/MJ_{biodiesel}$, BioGrace
TRANSPORT TO THE FILLING STATION		
Biodiesel	1000	$MJ_{biodiesel}/MJ_{biodiesel}$, BioGrace
Truck for liquids- Fuel Type: Diesel	150	km, BioGrace
Energy Consumption filling station, Average electricity mix in Turkey	0.0034	$MJ/MJ_{biodiesel}$, BioGrace

The fourth step is the use of biodiesel, which does not cause GHG emissions.

Explanation of the data:

- The average distance chosen between the cultivation area and the biorefinery is 100 km, as the collection activities of waste oils need to be included.
- It was assumed that waste oils have a moisture content of 0.25% and are transported at this moisture content.
- It was assumed that the refining of waste oils follows the same procedure as provided in the Biodiesel-Rapeseed pathway.
- Waste oil methyl esters, such as biodiesel (Biodiesel-Waste oil) and glycerine co-products, are produced as a result of the transesterification reaction of the refined waste oil with methanol.
- It was assumed that the methanol used in the production was recovered in the biorefinery.

5.2.3. Data Used for Bioethanol Production from Sugar Beet

Sugar beet is one of the most preferred crops in ethanol production due to its high yield preference. For each tonne of sugar beet, approximately 0.108 m^3 of bioethanol can be produced [59]. The required data to calculate GHG emissions from sugar beet are obtained from various sources. The below figure presents the production pathway of ethanol from sugar beet.

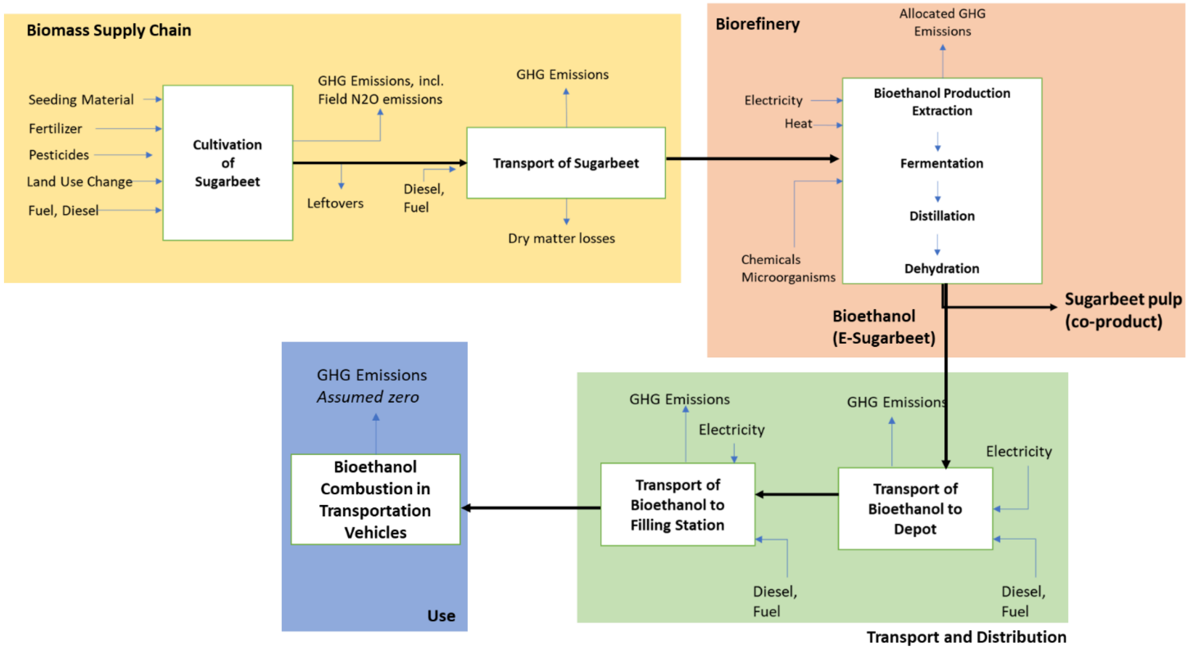


Figure 11. Production pathway of Bioethanol-Sugar beet in the BioGrace tool [53]

Like biodiesel, the production process can be divided into four steps. However, especially the processes during biorefinery will differ from biodiesel production.

The first step is again the biomass supply chain which covers the cultivation and transport of sugar beet. The required data for this step are given in the following table.

Table 18. The data used in the BioGrace tool in the step of the biomass supply chain of life cycle GHG emissions from ethanol-sugar beet

Type of Data	Value	Unit	Source
Cultivation area	338,000	ha	[54]
Production	21,000,000	tons	
Yield	62,130	kg ha^{-1} $year^{-1}$	
Moisture Content	75%		[60]
Energy Consumption, Diesel	6684.2	MJ ha^{-1} $year^{-1}$	BioGrace Standard Values [51]
Nitrogenous fertiliser	142.22	kg N ha^{-1} $year^{-1}$	[57]
Potassium fertiliser	100.83	kg K_2O ha^{-1} $year^{-1}$	
Phosphorus fertiliser	68.44	kg P_2O_5 ha^{-1} $year^{-1}$	
Pesticides	1.3	kg ha^{-1} $year^{-1}$	BioGrace Standard Values [51]
Seeding material	3.25	kg ha^{-1} $year^{-1}$	[61]
Transport of Sugar beet	0.990	MJ sugar beet/MJ sugar beet	BioGrace Standard Values [51]
Transport per Truck for dry product (Diesel)	50	km	BioGrace Standard Values [51]

Sugar beet is grown in various regions of Turkey, and fertilizer requirements vary according to the agricultural region's soil and climate characteristics. The average fertiliser requirements were determined using the fertilizer recommendation guideline considering the agricultural region's soil and climate characteristics.

The tool calculates direct and indirect N_2O emissions from managed soils during the cultivation of sugar beet based on the IPCC Tier 1 approach by using the data given above. The result shows that the overall (direct and indirect) N_2O emissions from sugar beet cultivation are *5.04 kg N_2O ha^{-1} $year^{-1}$*.

The second step is biorefinery which includes GHG emission calculation from the processes of the ethanol plant. Table 19 gives the data used in this step.

Table 19. The data used in the step of biorefinery of sugar beet [51]

ETHANOL PLANT		
Yield:		
Ethanol	0.544	$MJ_{ethanol}/MJ_{sugar\ beet}$, BioGrace
Co-product Sugar beet pulp	0.219	$MJ_{sugar\ beet\ pulp}$ / $MJ_{sugar\ beet}$, BioGrace
Energy Consumption:		
Average Electricity Mix in Turkey	0.048	$MJ/MJ_{ethanol}$, BioGrace
Steam (from NG boiler)	0.393	$MJ/MJ_{ethanol}$, BioGrace
NG Boiler- CH_4 and N_2O emissions from the NG boiler		
Natural gas input/MJ steam	1.111	MJ/MJ_{steam}, BioGrace
Natural gas (4000 km, EU mix quality)	0.436	$MJ/MJ_{ethanol}$, BioGrace
Electricity input/MJ steam	0.020	MJ/MJ_{steam}, BioGrace
Average electricity mix in Turkey	0.008	$MJ/MJ_{ethanol}$, BioGrace

The third step is the transportation and distribution of bioethanol which includes GHG emission calculation from the processes of transport of bioethanol to a depot and then to a filling station. Table 20 gives the data used in this step.

Table 20. The data used in the step of transport and distribution [51]

TRANSPORT OF ETHANOL TO DEPOT		
Ethanol	1000	$MJ_{ethanol}/MJ_{ethanol}$, BioGrace
Truck for liquids- Fuel Type: Diesel	150	km, BioGrace
Energy Consumption depot, Average electricity mix in Turkey	0.00084	$MJ/MJ_{ethanol}$, BioGrace

TRANSPORT OF ETHANOL TO FILLING STATION		
Ethanol	1000	$MJ_{ethanol}/MJ_{ethanol}$, BioGrace
Truck for liquids- Fuel Type: Diesel	150	km, BioGrace
Energy Consumption filling station, Average electricity mix in Turkey	0.0034	$MJ/MJ_{ethanol}$, BioGrace

5.2.4. Data Used for Bioethanol Production from Corn

Various data are needed to calculate life cycle GHG emissions from corn to produce bioethanol. The below figure presents the production pathway of bioethanol from corn.

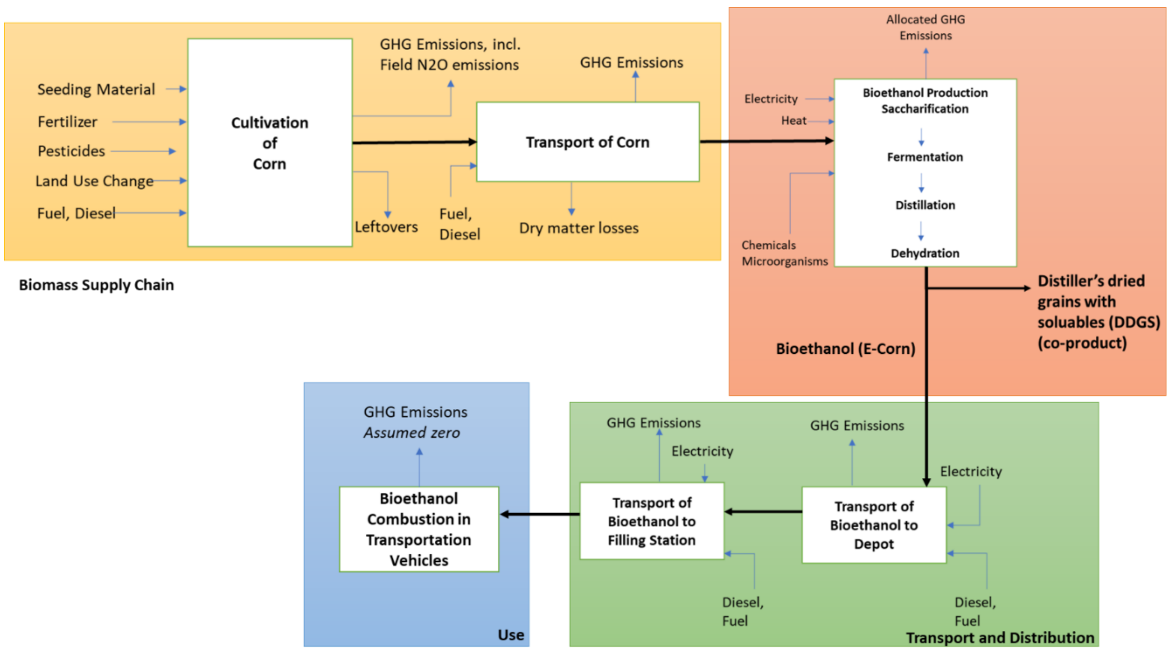


Figure 12. Production pathway of Bioethanol-Corn in the BioGrace tool [53]

The production process is divided into four steps, as presented in Table 9. The first step is the biomass supply chain which covers the cultivation and transport of corn. The required data for this step is given in the following table.

Table 21. The data used in the BioGrace tool in the step of the biomass supply chain of life cycle GHG emissions from ethanol-corn

Type of Data	Value	Unit	Source
Cultivation area	692,000	ha	[54]
Production	6,500,000	tons	
Yield	9,393	kg ha^{-1} $year^{-1}$	
Moisture Content	20%		[62]
Energy Consumption, Diesel	1586.5	MJ ha^{-1} $year^{-1}$	[63]
Nitrogenous (N) fertiliser	160.83	kg N ha^{-1} $year^{-1}$	[57]
Potassium (K) fertiliser	97.22	kg K_2O ha^{-1} $year^{-1}$	
Phosphorus (P) fertiliser	66.56	kg P_2O_5 ha^{-1} $year^{-1}$	
Pesticides	2.5	kg ha^{-1} $year^{-1}$	BioGrace Standard Values [51]
Seeding material	3	kg ha^{-1} $year^{-1}$	[62]
Transport of Corn	0.990	MJ_{corn}/MJ_{corn}	BioGrace Standard Values [51]
Transport per Truck for dry product (Diesel)	50	km	BioGrace Standard Values [51]

Corn is grown in various regions of Turkey, and fertilizer requirements vary according to agricultural areas' climatic and geographic characteristics. The average NPK fertiliser requirements were determined using the fertilizer recommendation guideline prepared by the Ministry of Agriculture and Forestry.

The tool calculates direct and indirect N_2O emissions from managed soils during the cultivation of corn based on the IPCC Tier 1 approach by using the required data given in the above table. According to the result, the overall (direct and indirect) N_2O emissions from corn cultivation were found as *4.92 kg N_2O ha^{-1} $year^{-1}$*.

The second step is biorefinery which includes GHG emission calculation from the processes of the ethanol plant. The below table depicts the data used in this step.

Table 22. The data used in the step of biorefinery of corn [51]

ETHANOL PLANT		
Yield:		
Ethanol	0.516	$MJ_{ethanol}/MJ_{corn}$, BioGrace
Co-product - Dried Distillers Grains (DDGS)	1.392	$ton_{DDGS}/ton_{Ethanol}$, BioGrace
Energy Consumption:		
Electricity (NG CCGT)	0.075	$MJ/MJ_{ethanol}$, BioGrace
Steam (from NG CHP)	0.682	$MJ/MJ_{ethanol}$, BioGrace
Natural Gas CHP:		
Size of CHP Steam prod. considered	0.682	$MJ/MJ_{ethanol}$, BioGrace
Input to CHP:		

NG input per MJ steam	1.866	MJ/MJ_{steam}, BioGrace
NG input per MJ ethanol	1.273	$MJ/MJ_{ethanol}$, BioGrace
Electricity Generation in CHP Plant:		
CHP net output / MJ steam	0.662	MJ/MJ_{steam}, BioGrace
CHP net output / MJ Ethanol	0.451	$MJ/MJ_{ethanol}$, BioGrace
Net production or consumption in ethanol plant	-0.376	$MJ/MJ_{ethanol}$, BioGrace
Electricity credit (NG CCGT)	0.376	$MJ/MJ_{ethanol}$, BioGrace

The third step is the transportation and distribution of bioethanol which includes GHG emission calculation from the processes of transport of bioethanol to a depot and then to a filling station. The table depicts the data used in this step.

Table 23. The data used in the step of transport and distribution [51]

TRANSPORT OF ETHANOL TO DEPOT		
Ethanol	1000	$MJ_{ethanol}/MJ_{ethanol}$, BioGrace
Truck for liquids- Fuel Type: Diesel	150	km, BioGrace
Energy Consumption depot, Average electricity mix in Turkey	0.00084	$MJ/MJ_{ethanol}$, BioGrace
TRANSPORT OF ETHANOL TO FILLING STATION		
Ethanol	1000	$MJ_{ethanol}/MJ_{ethanol}$, BioGrace
Truck for liquids- Fuel Type: Diesel	150	km, BioGrace
Energy Consumption filling station, Average electricity mix in Turkey	0.0034	$MJ/MJ_{bioethanol}$, BioGrace

5.3. Developing Biofuel Blending Scenarios

The second part of the study includes forecasting the GHG emission saving potential from the Turkish transportation sector by substituting petroleum transport fuels with produced biofuels. Different biofuel blending rates were taken into account for this analysis. The projections were made until 2030, and the base year was selected as 2020. Due to data availability for the base year, only passenger cars were used to develop blending scenarios for all vehicle types. The study considered five types of blending rates for biodiesel and six types of blending rates for bioethanol. The below table presents the applied biofuel blend rates.

Table 24. Commonly used biofuel blend rates for vehicles

Biodiesel		**Bioethanol**	
Scenario Name	**Blending ratios, %**	**Scenario Name**	**Blending ratios, %**
B0.5	0.5	E3	3
B2	2	E5	5
B5	5	E10	10

B20	20	E20	20
B100	100	E85	85
		E100	100

5.3.1. Biodiesel Blending

B100 is the name given to pure, unblended biodiesel. B20 is the most popular biodiesel mix, which contains 6% to 20% biodiesel blended with petroleum diesel. However, B5 (a biodiesel blend of 5% biodiesel and 95% diesel) is commonly used in fleet vehicles. Many diesel vehicles can run on B20 and lower-level blends without any engine modifications. B2 (a biodiesel blend of 2% biodiesel and 98% diesel) is one of the most common blends associated with biodiesel. It is used in fleets, tractor-trailers, off-road heavy equipment, and on-road light-duty fleets. In Turkey, the government imposed a 0.5% biodiesel blend in early 2018 via a communiqué issued 30098 on blending biodiesel to diesel types [64].

5.3.2. Bioethanol Blending

E100 is the name given to unblended bioethanol. Even if we provided different blend ratios for bioethanol in the study, such as E3, E5, E10, and E20, the most common blend in the world is E10 (10% ethanol and 90% gasoline). Vehicle engines require no modifications to run on E10, and vehicle warranties are unaffected. Only flexible fuel vehicles can run on up to 85% ethanol and 15% petrol blends (E85). In Turkey, the government imposed a 3% bioethanol blend as of early 2014 via a communique issued 31876 on the blending of bioethanol to gasoline types [65].

5.3.3. Passenger Car Stock, Fuel Type and Milage

Some critical data are required to develop blending scenarios. These data are the total vehicle number stock and total mileage by vehicle fuel type for the base year.
According to the official data taken from TURKSTAT, these data are only available for passenger cars for the base year of the projection study. Table 25 and Table 26 give passenger car numbers and the total mileage of these cars by fuel type, respectively.

Table 25. The number of passenger cars based on fuel type in 2020 for Turkey [66]

Fuel type	Number	Share
Gasoline	3,201,894	24.4%
Diesel	5,014,356	38.3%
LPG	4,810,018	36.7%
Electric	36,487	0.3%
Others	36,286	0.3%
TOTAL	13,099,041	

Table 26. 2020 Passenger Cars' total mileage by fuel type [67]

Fuel type	Mileage, billion km	Share
Gasoline	29.41	18%
Diesel	80.56	49%
LPG	53.11	33%
TOTAL	163.40	

The other required data for calculations is the average fuel consumption for gasoline and diesel-fuelled passenger cars. Therefore, according to the international energy agency's tracking report for fuel consumption of cars and vans in 2020, the average fuel consumption for diesel and gasoline cars was applied as 0.06 litres per km [68]. Based on this, diesel fuel consumption in 2020 is calculated as 4,833,431,160 litres, and gasoline fuel consumption in 2020 is calculated as 1,764,741,600 litres.

While developing blending scenarios, passenger car stock projections should be made based on various parameters such as GDP growth, population, the historical growth rate for vehicle numbers, etc. In this study, the projections of passenger cars from the study of "*Long-term characterization of the vehicle stock in Turkey* [69] " was considered. The base year in this study was 2018, and the projections were conducted until 2030. Thus, the actual passenger car stock for 2019 and 2020 was taken from [66], and projections between 2021 and 2030 were conducted using the estimated annual growth rate from the mentioned study.

5.4. Closing Remarks

All life cycle steps from crop production to biofuel use were considered. Four biofuel production pathways were considered in the Turkish context: biodiesel production from rapeseed and waste oil and bioethanol production from sugar beet and corn. The analysis follows the methodology in the EU directives and applies the principles of Life Cycle Assessment. Life cycle GHG emissions were expressed in g CO_2eq/MJ.

6. RESULTS AND DISCUSSIONS

As stated in Chapter 5, this study consists of four stages: estimation of the life cycle GHG emissions of biodiesel and bioethanol production, creation of scenarios, crop demand and policy analysis. This section presents the results for each phase of the study. The base year in the study was taken as 2020. All forecasts and calculations cover the years 2020-2030. In the first part, the life cycle GHG emissions of biodiesel from rapeseed and waste oil, bioethanol from sugar beet and corn were estimated. In the second part, blending scenarios were created. In the following sections, crop demand and policy analyses were conducted based on scenarios.

6.1. Life Cycle GHG Emission Estimation for Biofuel Production

In this section, an estimation of life cycle GHG emissions of biofuel production, particularly rapeseed-based and waste oil-based biodiesel production and sugar beet-based and corn-based bioethanol production, is presented.

6.1.1. Biodiesel Production

The GHG emissions due to biodiesel production from rapeseed and waste oil and use were estimated using the BioGrace tool and presented in this section.

6.1.1.1. Rapeseed

Table 27 shows the calculation results of life cycle GHG emissions of biodiesel production and use from rapeseed for Turkey and its comparison with EU default values based on EU RED. According to the results, biodiesel production and use from rapeseed in Turkey emit 53.2 $g\ CO_2eq\ /\ MJ_{biodiesel}$ emissions, while the EU RED default value is 52.06 $g\ CO_2eq\ /\ MJ_{biodiesel}$. The difference between the two values is minimal. If land-use change emissions are excluded, life cycle emissions in Turkey will be lower than the EU RED default levels. Furthermore, it can be seen from the results the primary source of emissions of rapeseed-based biodiesel production is the cultivation of rapeseed step, which is 28.7 g CO_2eq/MJ. Reduction of nitrogen fertilizer use in rapeseed cultivation could significantly impact reducing the emissions in this step. In addition, based on the results presented in Chapter 3 and listed in Table 6, biodiesel production from rapeseed in Turkey has a similar emission amount to the UK [36]. The biofuel production in Latvia [38] results in less emission than in Turkey, considering both winter and spring cultivation seasons.

Table 27. Life cycle GHG emissions of biodiesel production from rapeseed

All results	Turkey	Default values RED Annex V.D
	g $CO_2eq/MJ_{Biodiesel}$	*g $CO_2eq/MJ_{Biodiesel}$*
Step-1: Biomass Supply Chain		
Land use change	1.36	-
Cultivation of rapeseed	28.24	28.51
Rapeseed drying	0.44	0.42
Step-2: Biorefinery		
Extraction of oil	3.88	3.82
Refining of vegetable oil and esterification	17.82	17.88
Step-3: Transport and distribution		
Transport of rapeseed	0.17	0.17
Transport of rapeseed oil	0.00	0.00
Transport of refined vegetable oil	0.00	0.00
Transport of Biodiesel to the depot	0.47	0.82
Transport to the filling station	0.82	0.44
TOTAL	**53.20**	**52.06**

Furthermore, the potential life cycle GHG emission reductions (%) of various rapeseed-based biodiesel blending ratios were estimated. According to the calculations, replacing the base year total diesel consumption of the passenger cars (as given in section 5.3.3) with rapeseed-based biodiesel would result in a 36.51% reduction in emissions (B100), as shown in Table 28. In these calculations, the average reference value of the life cycle GHG emission of fossil fuel counterpart was taken as 83.8 g CO_2eq /MJ (see Table 10). In addition, the emission reduction potentials (emission savings) of different blending scenarios (B20, B5, B2, B0.5) were also calculated and expressed as percentages in Table 28. As seen here, as the blending ratio of biodiesel decreases, the GHG emission reduction decreases.

Table 28. GHG emission reduction potentials of various blending ratios of biodiesel in comparison to base-year diesel consumption

Scenario Name	Blending Ratios, %	GHG Reduction Potential
B100	100	36.51%
B20	20	7.30%
B5	5	1.83%
B2	2	0.73%
B0.5	0.5	0.18%

6.1.1.2. Waste Oil

Table 29 shows the calculation results of life cycle GHG emissions of biodiesel production and use from waste oil for Turkey and its comparison with EU default values based on EU-RED. According to the results, biodiesel production and use from waste oil in Turkey emits 21.89 $g\ CO_2eq/MJ_{biodiesel}$ emissions, while the EU RED default value is 14.07 $g\ CO_2eq\ /\ MJ_{biodiesel}$. As seen here, 93% of the emissions result in refining vegetable oil and the esterification step. It can also be seen that the EU default value in refining vegetable oil and the esterification stage is much lower than Turkey's results. The reason for this difference is Turkey's average electricity mix is higher than the EU's, according to the BioGrace standard values. In addition, based on the results presented in Chapter 3 and listed in Table 6, biodiesel production from waste oil, both UK [36] and Greece [39] have less emission than Turkey.

Table 29. Life cycle GHG emissions of biodiesel production from waste oil

All results	Turkey	Default values RED Annex V.D
	$g\ CO_2eq/MJ_{biodiesel}$	$g\ CO_2eq/MJ_{biodiesel}$
Step-1: Biomass Supply Chain		
Collection of waste vegetable or animal oil	0.00	0.00
Step-2: Biorefinery		
Refining of vegetable oil and esterification	20.35	12.80
Step-3: Transport and distribution		
Transport of waste vegetable or animal oil	0.24	0.00
Transport of refined oil	0.00	0.00
Transport of Biodiesel to a depot	0.47	0.83
Transport to the filling station	0.82	0.44
TOTAL	**21.89**	**14.07**

Furthermore, the potential life cycle GHG emission reductions (%) of various waste oil-based biodiesel blending ratios were estimated. According to the calculations, replacing the base year total diesel consumption of the passenger cars (as given in section 5.3.3) with waste oil-based biodiesel would result in a 73.88% reduction in emissions (B100), as shown in Table 30. In addition, the emission reduction potentials (emission savings) of different blending scenarios (B20, B5, B2, B0.5) were also calculated and expressed as percentages in Table 30.

Table 30. GHG emission reduction potentials of various blending ratios of biodiesel in comparison to base-year diesel consumption

Scenario Name	Blending Ratios, %	GHG Reduction Potential
B100	100	73.88%
B20	20	14.78%
B5	5	3.69%
B2	2	1.48%
B0.5	0.5	0.37%

6.1.2. Bioethanol Production

The GHG emissions due to bioethanol production from sugar beet and corn and their use were estimated using the BioGrace tool and presented in this section.

6.1.2.1. Sugar Beet

Table 31 shows the calculation results of life cycle GHG emissions of bioethanol production and use from sugar beet for Turkey and its comparison with EU default values based on EU-RED. This table shows that bioethanol production from sugar beet in Turkey emits 46.13 g $CO_2eq/MJ_{bioethanol}$ emissions while the EU RED default value is 40.34 g $CO_2eq/MJ_{bioethanol}$. As can be seen, there is a significant variation between the two values. The use of nitrogen fertilizer during sugar beet cultivation is the main reason for this difference. As seen here, 58% of the emissions result from the ethanol plant. In addition, based on the results presented in Chapter 3 and listed in Table 6 regarding bioethanol production from sugar beet, the UK [36] has lower emissions than Turkey.

Table 31. Life cycle GHG emissions of ethanol production from sugar beet

All results	Turkey	Default values RED Annex V.D
	g CO_2eq/$MJ_{bioethanol}$	*g CO_2eq/$MJ_{bioethanol}$*
Step-1: Biomass Supply Chain		
Land use change	0.58	
Cultivation of sugar beet	16.05	11.54
Step-2: Biorefinery		
Ethanol plant	26.61	26.418
Step-3: Transport and distribution		
Transport of sugar beet	1.32	0.84
Transport of ethanol to a depot	0.61	1.1
Transport to the filling station	0.96	0.44
TOTAL	**46.13**	**40.34**

Furthermore, the potential life cycle GHG emission reductions (%) of various sugar beet-based bioethanol blending ratios were estimated. According to the calculations, replacing the base year total gasoline consumption of the passenger cars (as given in section 5.3.3) with sugar beet-based bioethanol would result in a 44.95% reduction in emissions (E100), as shown in Table 32. In addition, the emission reduction potentials (emission savings) of different blending scenarios (E85, E20, E10, E5, E3) were also calculated and expressed as percentages in Table 32.

Table 32. GHG emission reduction potentials of various blending ratios of bioethanol in comparison to base-year gasoline consumption

Scenario Name	Blending Ratios, %	GHG Reduction Potential
E100	100	44.95%
E85	85	38.21%
E20	20	8.99%
E10	10	4.49%
E5	5	2.25%
E3	3	1.35%

6.1.2.2. Corn

Table 33 shows the calculation results of life cycle GHG emissions of bioethanol production and use from corn for Turkey and its comparison with EU default values based on EU-RED. This table shows that bioethanol production from corn in Turkey generates 44.03 g CO_2eq/$MJ_{bioethanol}$ emissions. The GHG emission presented in EU RED was 42.96 g CO_2eq/$MJ_{bioethanol}$. It can be seen from the results the primary sources of emissions of corn-based bioethanol production are from the cultivation of corn step, which is 20.7 g CO_2eq/MJ, and from the conventional natural gas ethanol plant, which is 21.5 g CO_2eq/MJ. Reduction of nitrogen fertilizer in the cultivation stage and integration of combined heat and power (CHP) systems into corn bioethanol production could help to reduce emissions. In addition, based on the results presented in Chapter 3 and listed in Table 6 for bioethanol production from corn, the UK [36] has more emissions than Turkey, and Brazil [40] has a similar emission amount to Turkey.

Table 33. Life cycle GHG emissions of bioethanol production from corn

All results	**Turkey**	**Default values RED Annex V.D**
	g CO_2eq/$MJ_{biothanol}$	*g CO_2eq/$MJ_{bioethanol}$*
Step-1: Biomass Supply Chain		
Land use change	0.86	
Cultivation of corn	20.71	20.18
Step-2: Biorefinery		
Ethanol plant	21.45	20.958
Step-3: Transport and distribution		
Transport of corn	0.29	0.28
Transport of ethanol to a depot	0.61	1.1
Transport to the filling station	0.96	0.44
TOTAL	**44.03**	**42.96**

Furthermore, the potential life cycle GHG emission reductions (%) of various corn-based bioethanol blending ratios were estimated. According to the calculations, replacing corn-based bioethanol with its fossil fuel counterpart, gasoline, would result in a 46.44% reduction in emissions. The emission reduction potentials (emission savings) of different blending scenarios (E85, E20, E10, E5, E3) were also calculated and expressed as percentages in Table 34.

Table 34. GHG emission reduction potentials of various blending ratios of bioethanol in comparison to base-year gasoline consumption

Scenario Name	Blending Ratios, %	GHG Reduction Potential
E100	100	46.44%
E85	85	39.47%
E20	20	9.29%
E10	10	4.64%
E5	5	2.32%
E3	3	1.39%

6.1.3. Comparison of Life Cycle GHG Emissions of Biofuel Production

In terms of life cycle GHG emissions, each biofuel production pathway was compared to the EU RED default values based on the BioGrace tool results, as presented in Figure 13.

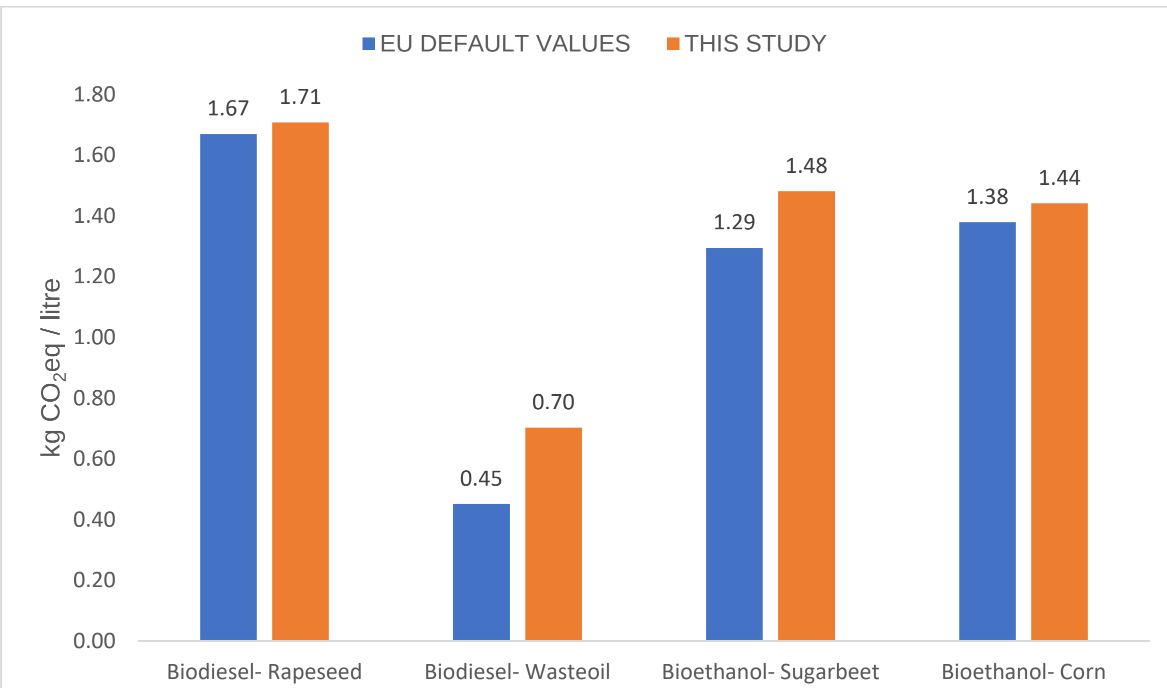


Figure 13. Comparison of Life Cycle GHG Emissions of Biofuel Production

The following results can be reached from the analysis results;

- Although the life cycle processes of rapeseed and corn are very similar in both Turkey and the EU, sugar beet and waste oil production cause much higher emissions in Turkey as Turkey's electricity mix GHG intensity is higher than the default values given in BioGrace Tool.

- Rapeseed biodiesel production has the highest life-cycle GHG emissions because of rapeseed cultivation emissions. In contrast, waste oil has the lowest as there is no impact on dedicated energy crop production.
- EU RED default values of GHG emissions are lower than Turkey's values at all processes.

6.2. Biofuel Consumption Blending Scenarios

The results of two different business-as-usual GHG emission potential scenarios, one for diesel passenger cars and one for gasoline passenger cars, with several blending scenarios for each selected biofuel source, were presented in this section.

6.2.1. Results of Biodiesel Blending Scenarios

This section presents passenger car stock and mileage data for 2020, the selected base year, with the estimated projections until 2030. The base year passenger car stock and total mileage by fuel type data are obtained from [TURKSTAT] as presented in Table 25 and Table 26, respectively. The annual passenger car increase rates determined in the study "*Long-term characterization of the vehicle stock Turkey*" were used to estimate the total and diesel passenger car stocks [69]. As mentioned, only passenger cars' stats for Turkey were considered due to the lack of data for other vehicle types.

Table 35 shows the total and diesel passenger car projections and the assumption of how many diesel cars will be blended with biodiesel through 2030. While developing the biofuel blending scenarios, it was assumed that by 2030, with a 5% annual rise, the proportion of biodiesel-blended diesel passenger cars will reach up to 50% of all diesel cars.

According to the results, the overall stock of passenger cars would increase by 65.3%, whereas diesel passenger cars would increase by only 20.8% by 2030. This slower diesel car stock growth rate can be attributed to the recent increase in electric car demand.

Table 35. Total, diesel-fueled, and biodiesel blended passenger car stock estimates

Year	Total Number of Passenger Cars	Number of Diesel Passenger Cars	Predicted Unblended Passenger Cars	Predicted Blended Passenger Cars	Share of Predicted Blended Passenger Cars
2020	13,099,041	5,014,356	5,014,356	-	0%
2021	13,765,909	5,150,945	4,893,397	257,547	5%
2022	14,448,934	5,180,175	4,662,158	518,018	10%
2023	15,115,594	5,339,735	4,538,775	800,960	15%
2024	15,834,059	5,427,694	4,342,155	1,085,539	20%
2025	16,669,810	5,539,553	4,154,665	1,384,888	25%
2026	17,604,739	5,665,801	3,966,061	1,699,740	30%
2027	18,571,525	5,782,305	3,758,498	2,023,807	35%
2028	19,541,962	5,879,557	3,527,734	2,351,823	40%
2029	20,552,398	5,968,030	3,282,417	2,685,614	45%
2030	21,646,762	6,058,806	3,029,403	3,029,403	50%

A scenario based on the current situation was developed and named the business-as-usual (BAU) scenario. The BAU scenario was developed based on the assumption that the biodiesel blend will not be applied during the projection period. In addition, five biofuel blending scenarios were also developed based on different biodiesel blending rates, as explained in Section 5.3 and Table 24.

The total number and mileage of diesel passenger cars in 2020 were 5,014,350 and 80,557,186,000 km, as presented in Table 25 and Table 26, respectively. Thus, the average mileage of a diesel car was estimated as 16,065 km per year. As given in Table 10, the average fuel consumption of a diesel car was taken as 0.06 litres per kilometre. The average emission factor from the fossil part of petrol and diesel was taken as 83.8 g CO_2eq/MJ, which equals 3.017 kg CO_2/litre diesel when the low heating value of diesel is taken as 36 MJ/litre. The total diesel passenger car mileages between 2021 and 2030 are calculated by multiplying the estimated diesel passenger car numbers given in Table 36 with the average diesel passenger car mileage and were assumed to remain the same during the projection period.

As a result, Table 36 presents the expected GHG emission based on the BAU scenario. According to the scenario results, GHG emissions from diesel passenger cars will grow by around 20.8% in 10 years due to increased passenger car numbers. According to the BAU scenario, emissions from diesel passenger cars were estimated to reach 17.6 million tons of CO_2 in 2030.

Table 36. GHG emissions estimates based on the BAU scenario (Diesel)

Year	**Total Diesel Passenger Car Mileage Million km**	**Total Diesel Fuel Consumption Million litres**	**GHG Emissions From Diesel Passenger Cars Million-ton CO_2eq**
2020	80,557	4,833	14.58
2021	82,752	4,965	14.98
2022	83,221	4,993	15.06
2023	85,785	5,147	15.53
2024	87,198	5,232	15.78
2025	88,995	5,340	16.11
2026	91,023	5,461	16.48
2027	92,895	5,574	16.81
2028	94,457	5,667	17.10
2029	95,878	5,753	17.35
2030	97,337	5,840	17.62

6.2.1.1. Biodiesel Blending Scenarios from Rapeseed

In this section, associated GHG emissions reduction potentials are estimated, assuming that the total diesel consumption would be replaced with a 5% annual rise (50% in 2030) with different blending ratios of rapeseed-based biodiesel (100%, 20%, 5%, 2%, 0.5%).

Table 37 and Figure 14 show the reductions in GHG emissions resulting from applying biodiesel produced by utilizing rapeseed oil to diesel cars at various rates. As a result, the blend ratio of 100% will have the most significant potential for a decrease. According to the results, a decrease of roughly 18.26% will be achieved in 2030 if the B100 blend is applied to the selected cars.

Table 37. GHG emission reduction potentials of all rapeseed-based biodiesel blending scenarios until 2030

Year	B100 Scenario % Reduction	B20 Scenario % Reduction	B5 Scenario % Reduction	B2 Scenario % Reduction	B0.5 Scenario % Reduction
2020	0.00	0.00	0.00	0.00	0.00
2021	1.83	0.37	0.09	0.04	0.01
2022	3.65	0.73	0.18	0.07	0.02
2023	5.48	1.10	0.27	0.11	0.03
2024	7.30	1.46	0.37	0.15	0.04
2025	9.13	1.83	0.46	0.18	0.05
2026	10.95	2.19	0.55	0.22	0.05
2027	12.78	2.56	0.64	0.26	0.06
2028	14.61	2.92	0.73	0.29	0.07
2029	16.43	3.29	0.82	0.33	0.08
2030	18.26	3.65	0.91	0.37	0.09

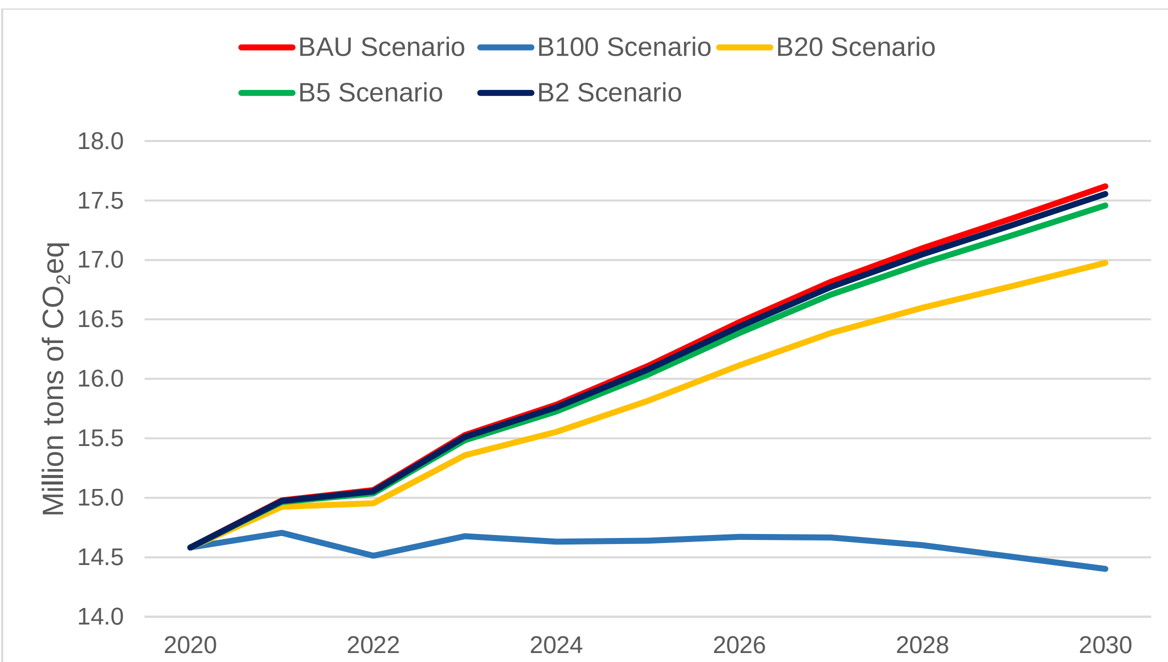


Figure 14. Comparison of GHG emission reduction potentials of all rapeseed-based biodiesel blending scenarios *(The B0.5 scenario was omitted from the figure because the difference with BAU is insignificant.)*

6.2.1.2. Biodiesel Blending Scenarios from Waste Oil

In this section, associated GHG emissions reduction potentials are estimated, assuming that the total diesel consumption would be replaced with a 5% annual rise (50% in 2030) with different blending ratios of waste oil-based biodiesel (100%, 20%, 5%, 2%, 0.5%).

Table 38 and Figure 15 show the reduction in GHGs resulting from applying biodiesel produced by using waste oil to diesel cars at various rates. As a result, the blend ratio of 100% will have the most significant potential for a decrease. According to the results, a decrease of roughly 37% will be achieved in 2030 if the B100 blend is applied to the selected cars.

Waste oil-based biodiesel offers a substantially better GHG reduction potential than rapeseed oil. This condition is explained by the fact that there is no waste generation step and that the only emissions come from the waste oil processing stage. As a result, we can clearly state that using waste oil in biofuel production rather than any crop-based oil has significant environmental benefits.

Table 38. GHG emission reduction potentials of all waste oil-based biodiesel blending scenarios until 2030

Year	B100 Scenario % Reduction	B20 Scenario % Reduction	B5 Scenario % Reduction	B2 Scenario % Reduction	B0.5 Scenario % Reduction
2020	0.00	0.00	0.00	0.00	0.00
2021	3.69	0.74	0.18	0.07	0.02
2022	7.39	1.48	0.37	0.15	0.04
2023	11.08	2.22	0.55	0.22	0.06
2024	14.78	2.96	0.74	0.30	0.07
2025	18.47	3.69	0.92	0.37	0.09
2026	22.16	4.43	1.11	0.44	0.11
2027	25.86	5.17	1.29	0.52	0.13
2028	29.55	5.91	1.48	0.59	0.15
2029	33.25	6.65	1.66	0.66	0.17
2030	36.94	7.39	1.85	0.74	0.18

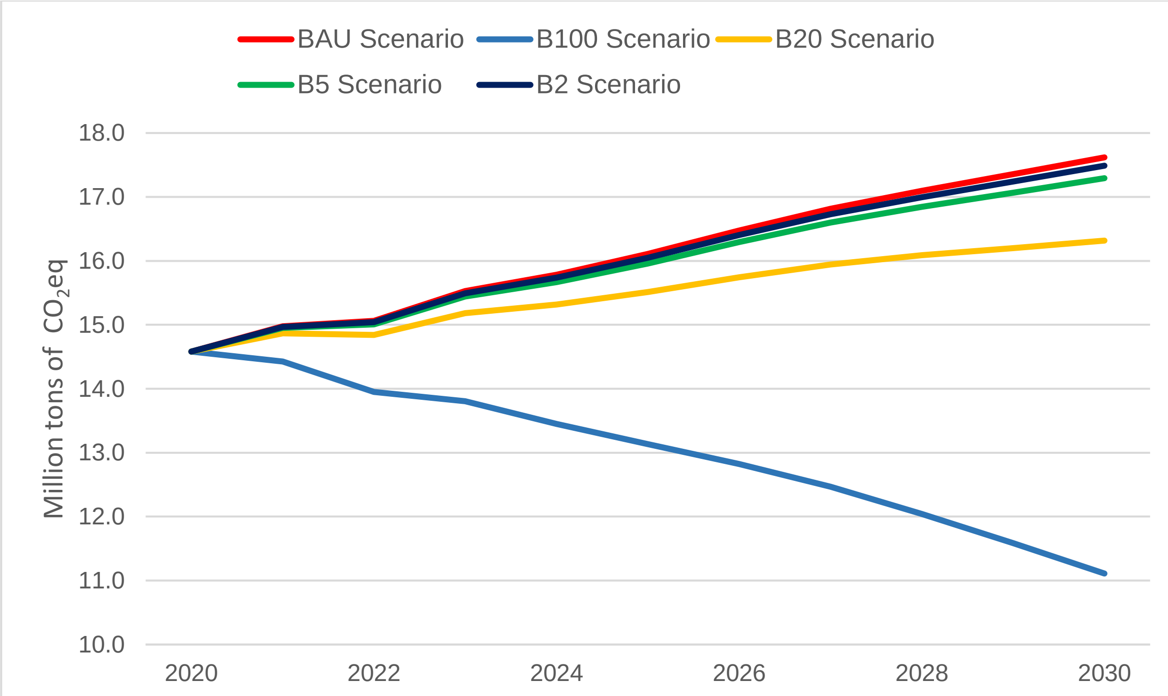


Figure 15. Comparison of GHG emission reduction potential of all waste oil-based biodiesel blending scenarios *(The B0.5 blend scenario was omitted from the figure because the difference with BAU is insignificant.)*

6.2.2. Results of Bioethanol Blending Scenarios

The forecast for gasoline passenger cars was developed using the same methodology as diesel (please see Section 6.2 for the applied methodology). Table 39 presents the projections of total, gasoline-fueled, and bioethanol-blended gasoline passenger car stock assumptions until 2030.

According to the results, the total stock of passenger cars will increase by 65.3%, while the number of gasoline passenger cars is estimated to increase by 78.1% by 2030. In contrast to the diesel car stock projection rate, the demand for gasoline cars will be higher than the total demand rate.

Table 39. Total, gasoline-fueled, and bioethanol blended passenger car stock estimates

Year	Total Number of Passenger Cars	Number of Gasoline Passenger Cars	Predicted Unblended Passenger Cars	Predicted Blended Passenger Cars	Share of Predicted Blended Passenger Cars
2020	13,099,041	3,201,894	3,201,894	0	0%
2021	13,765,909	3,238,832	3,076,890	161,942	5%
2022	14,448,934	3,444,813	3,100,331	344,481	10%
2023	15,115,594	3,651,122	3,103,454	547,668	15%
2024	15,834,059	3,874,285	3,099,428	774,857	20%
2025	16,669,810	4,131,017	3,098,262	1,032,754	25%
2026	17,604,739	4,417,874	3,092,512	1,325,362	30%
2027	18,571,525	4,718,686	3,067,146	1,651,540	35%
2028	19,541,962	5,026,497	3,015,898	2,010,599	40%
2029	20,552,398	5,350,803	2,942,942	2,407,861	45%
2030	21,646,762	5,703,557	2,851,778	2,851,778	50%

A BAU scenario was developed, assuming the bioethanol blend will not be applied during the projection period. In addition, five biofuel blending scenarios were developed based on different bioethanol blending rates, as explained in Section 5.3 and Table 24.

The total number and mileage of gasoline passenger cars in 2020 were 3,201,894 and 29,739,164,000 km, as presented in Table 25 and Table 26, respectively. Thus, the average mileage of a gasoline car was estimated as 9186 km per year. As given in Table 10, the average fuel consumption of a gasoline car was taken at 0.06 litres per kilometre. The average emission factor from the fossil part of petrol and diesel was taken as 83.8 g CO_2eq/MJ, which equals 2.7 kg CO_2/litre gasoline when the low heating value of gasoline is taken as 32 MJ/litre. The total gasoline passenger car mileages between 2021 and 2030 are calculated by multiplying the estimated gasoline passenger car numbers given in Table 40 with the average gasoline passenger car mileage and were assumed to remain the same during the projection period.

As a result, Table 40 presents the expected GHG emission based on the BAU scenario. According to the scenario results, GHG emissions from gasoline passenger cars will grow by around 78.1% in 10 years due to increased passenger car numbers. According to the BAU scenario, emissions from gasoline passenger cars were estimated to reach 8.43 million tons of CO_2 in 2030.

Table 40. GHG emissions results of BAU scenario (Gasoline)

Year	Total Gasoline Passenger Car Mileage Million Km	Total Gasoline Fuel Consumption Million-Litre	GHG Emission From Gasoline Passenger Cars Million-Ton CO_2eq
2020	29,412	1,765	4.73
2021	29,752	1,785	4.79
2022	31,644	1,899	5.09
2023	33,539	2,012	5.40
2024	35,589	2,135	5.73
2025	37,947	2,277	6.11
2026	40,582	2,435	6.53
2027	43,346	2,601	6.97
2028	46,173	2,770	7.43
2029	49,152	2,949	7.91
2030	52,392	3,144	8.43

6.2.2.1. Bioethanol Blending Scenarios from Sugar Beet

In this section, associated GHG emissions reduction potentials are estimated, assuming that the total gasoline consumption would be replaced with a 5% annual rise (50% in 2030) with different blending ratios of sugar beet-based bioethanol (100%, 85%, 20%, 10%, 5%, 3%).

According to the BAU scenario, emissions from passenger cars were estimated to reach 8.4 million tons of CO_2 in 2030. Table 41 shows the reduction in GHGs from applying bioethanol produced by utilizing sugar beet to gasoline cars at various rates. As a result, the blend ratio of 100% will have the most significant potential for a decrease. According to the results, a reduction of roughly 22.47% will be achieved in 2030 if the E100 blend is applied to the selected cars.

Table 41. GHG emission reduction potentials of all sugar beet-based bioethanol blending scenarios until 2030

Year	E100 Scenario % Reduction	E85 Scenario % Reduction	E20 Scenario % Reduction	E10 Scenario % Reduction	E5 Scenario % Reduction	E3 Scenario % Reduction
2020	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2021	2.25%	1.91%	0.45%	0.22%	0.11%	0.07%
2022	4.49%	3.82%	0.90%	0.45%	0.22%	0.13%
2023	6.74%	5.73%	1.35%	0.67%	0.34%	0.20%
2024	8.99%	7.64%	1.80%	0.90%	0.45%	0.27%
2025	11.24%	9.55%	2.25%	1.12%	0.56%	0.34%
2026	13.48%	11.46%	2.70%	1.35%	0.67%	0.40%
2027	15.73%	13.37%	3.15%	1.57%	0.79%	0.47%
2028	17.98%	15.28%	3.60%	1.80%	0.90%	0.54%
2029	20.23%	17.19%	4.05%	2.02%	1.01%	0.61%
2030	22.47%	19.10%	4.49%	2.25%	1.12%	0.67%

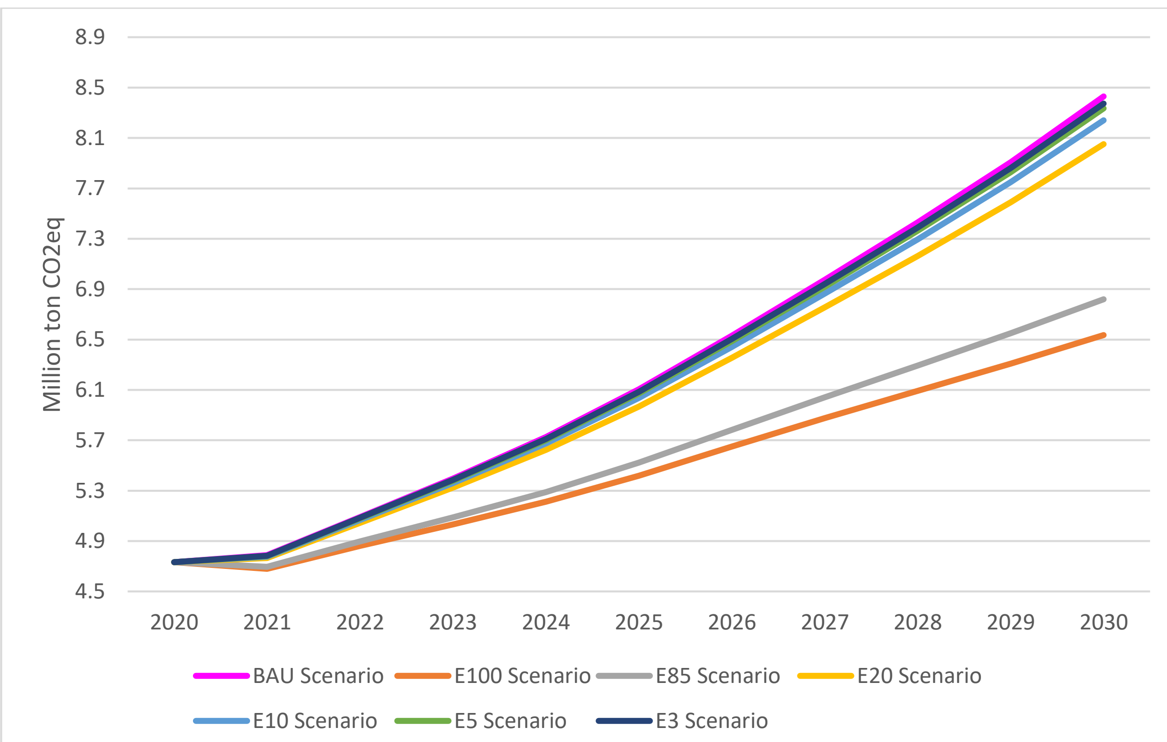


Figure 16. Comparison of GHG emission reduction potential of all sugar beet-based bioethanol blending scenarios

6.2.2.2. Bioethanol Blending Scenarios from Corn

In this section, associated GHG emissions reduction potentials are estimated, assuming that the total gasoline consumption would be replaced with a 5% annual rise (50% in 2030) with different blending ratios of corn-based bioethanol (100%, 85%, 20%, 10%, 5%, 3%).

Table 42 shows the reduction in GHGs resulting from applying bioethanol produced by utilizing corn to gasoline cars at various rates. According to the results, a decrease of roughly 23.22% will be achieved in 2030 if the E100 blend is applied to the selected cars.

Table 42. GHG emission reduction potentials of all corn-based bioethanol blending scenarios until 2030

Year	E100 Scenario % Reduction	E85 Scenario % Reduction	E20 Scenario % Reduction	E10 Scenario % Reduction	E5 Scenario % Reduction	E3 Scenario % Reduction
2020	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2021	2.32%	1.97%	0.46%	0.23%	0.12%	0.07%
2022	4.64%	3.95%	0.93%	0.46%	0.23%	0.14%
2023	6.97%	5.92%	1.39%	0.70%	0.35%	0.21%
2024	9.29%	7.89%	1.86%	0.93%	0.46%	0.28%
2025	11.61%	9.87%	2.32%	1.16%	0.58%	0.35%
2026	13.93%	11.84%	2.79%	1.39%	0.70%	0.42%
2027	16.25%	13.82%	3.25%	1.63%	0.81%	0.49%
2028	18.58%	15.79%	3.72%	1.86%	0.93%	0.56%
2029	20.90%	17.76%	4.18%	2.09%	1.04%	0.63%
2030	23.22%	19.74%	4.64%	2.32%	1.16%	0.70%

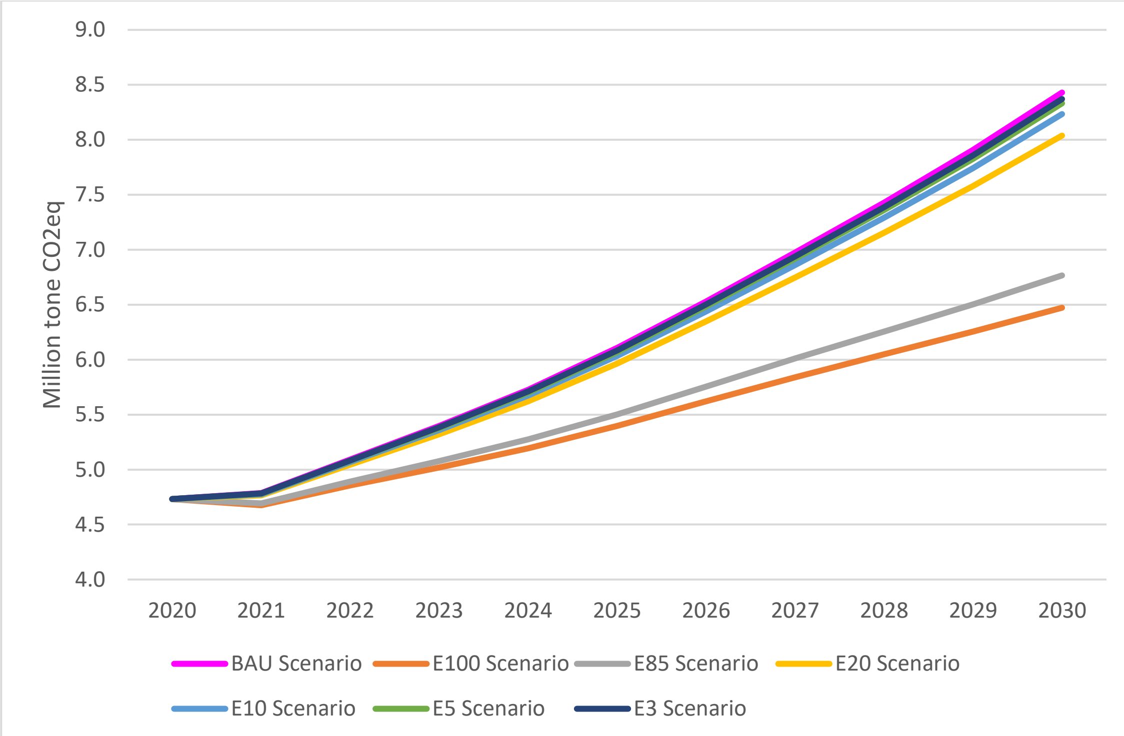


Figure 17. Comparison of GHG emission reduction potential of all corn-based bioethanol blending scenarios

6.3. Crop Demand Analysis for Biofuel Production (Turkey's context)

In this study, the production potentials of three crops (rapeseed for biodiesel production, sugar beet and corn for bioethanol production) were analyzed for biofuel production as a vehicle fuel. Using these crops in biofuel production can decrease GHG emissions compared to fossil fuel counterparts based on the different blending scenario's results, as stated before. However, using these crops in food production is a big dilemma regarding meeting the food demand. Moreover, in terms of production potential, cropland areas should also be considered to meet this demand. The demand analysis results were given crop by crop in the following.

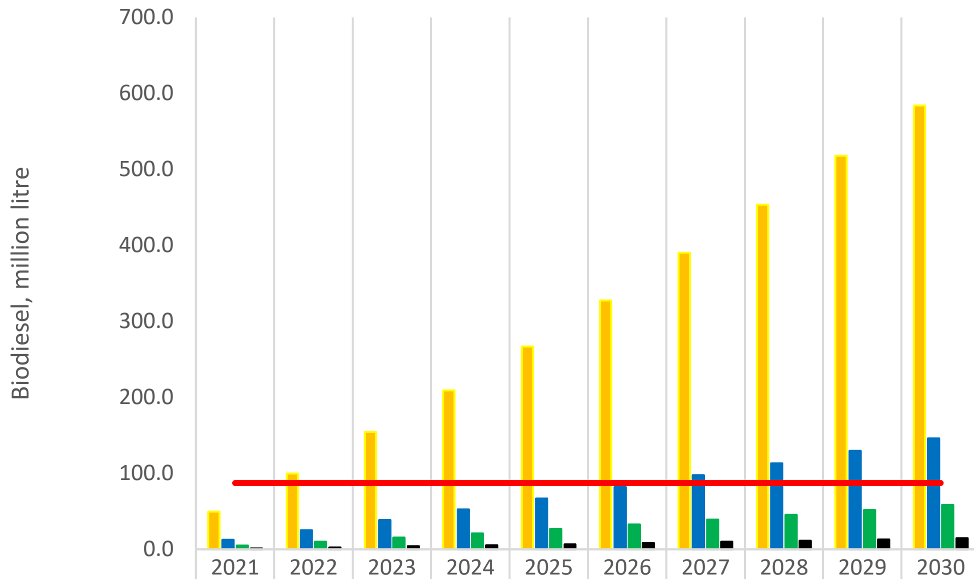
6.3.1. Rapeseed Demand Analysis for Biodiesel Production

In 2020, Turkey's rapeseed cultivated area was 35,000 hectares [54]. Based on the BioGrace tool calculation approach, 1 hectare of rapeseed cultivation area potentially yields 2491 litres of biodiesel. Thus, the base year biodiesel production potential from rapeseed was found to be 87.2 million litres, and it was assumed that this potential would stay constant over the projection period. Table 43 and Figure 18 demonstrate the estimated biofuel demand for various biofuel blending rates until 2030 and the required cultivation area for rapeseed.

The red values in the table represent cropland area equal to or less than the current cultivation area for biofuel production (35,000 ha for rapeseed in 2020), indicating which biofuel blending model can meet demand without expanding the cultivation area over the projection period.

Table 43. Projection of rapeseed cultivation area to meet biodiesel demand based on various biofuel blending rates (reference year is 2020 with 35,000 ha)

	B20		**B5**		**B2**		**B0.5**	
Year	**Biofuel Demand Mil. L**	**Area Demand (ha)**	**Biofuel Demand Mil. L**	**Area Demand (ha)**	**Biofuel Demand Mil. L**	**Area Demand (ha)**	**Biofuel Demand Mil. L**	**Area Demand (ha)**
2021	49.65	19,931	12.41	4.983	4.97	1.993	1.24	498
2022	99.87	40.088	24.97	10.022	9.99	4.009	2.50	1.002
2023	154.41	61.984	38.60	15.496	15.44	6.198	3.86	1.550
2024	209.27	84.007	52.32	21.002	20.93	8.401	5.23	2.100
2025	266.98	107.173	66.75	26.793	26.70	10.717	6.67	2.679
2026	327.68	131.538	81.92	32.885	32.77	13.154	8.19	3.288
2027	390.16	156.617	97.54	39.154	39.02	15.662	9.75	3.915
2028	453.39	182.001	113.35	45.500	45.34	18.200	11.33	4.550
2029	517.74	207.832	129.44	51.958	51.77	20.783	12.94	5.196
2030	584.02	234.437	146.00	58.609	58.40	23.444	14.60	5.861



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
20% Blend	49.7	99.9	154.4	209.3	267.0	327.7	390.2	453.4	517.7	584.0
5% Blend	12.4	25.0	38.6	52.3	66.7	81.9	97.5	113.3	129.4	146.0
2% Blend	5.0	10.0	15.4	20.9	26.7	32.8	39.0	45.3	51.8	58.4
0.5% Blend	1.2	2.5	3.9	5.2	6.7	8.2	9.8	11.3	12.9	14.6
Potential	87.2	87.2	87.2	87.2	87.2	87.2	87.2	87.2	87.2	87.2

Figure 18. Required biodiesel production amount from rapeseed by different blending scenarios and the base year (2020) production potential

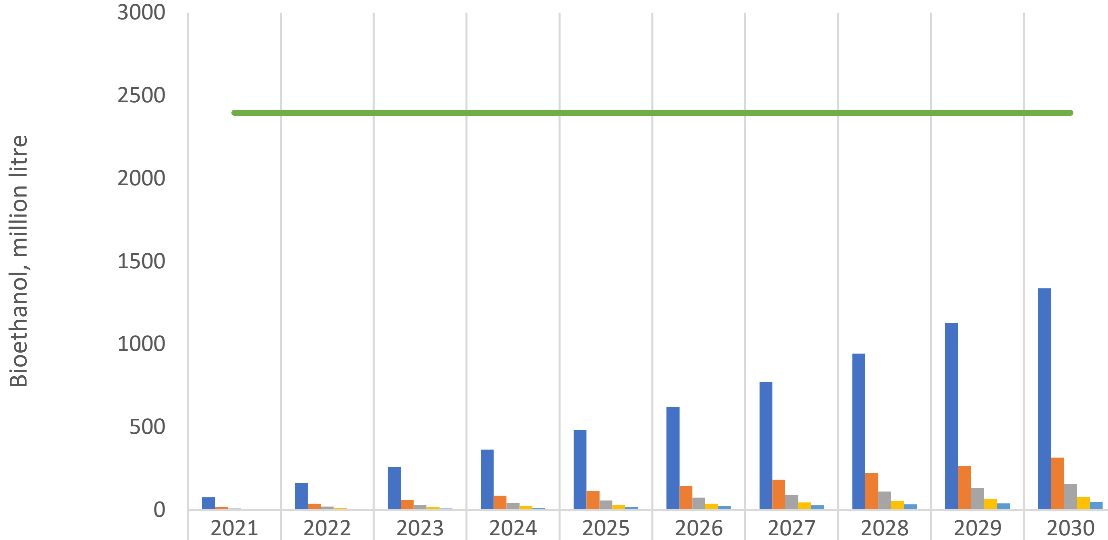
The extrapolation from the results is that B0.5 and B2 blending rates can easily meet the demand for biofuel production without expanding the cultivation rates until 2030. B5 blending rate can meet the demand until 2026. However, rapeseed cultivation for B20 blending rate could not meet the demand until the end of the projection period with the current production potential. In addition, crop demand for food production should also be considered. Thus, B0.5 is the ideal blending option for selected passenger cars in Turkey till 2030.

6.3.2. Sugar Beet Demand Analysis for Bioethanol Production

In 2020, Turkey's sugar beet cultivated area was 338,108 hectares [54]. Based on the BioGrace tool calculation approach, 1 hectare of sugar beet cultivation area potentially yield 7086 litres of bioethanol. Thus, the base year bioethanol production potential from sugar beet was found 2.39 billion litres and it was assumed that this potential will stay constant over the projection period. Table 44 and Figure 19 demostrate the estimated biofuel demand for various biofuel blending rates through 2030 and the required sugar beet cultivated area.

Table 44. Projection of sugar beet cultivation area to meet bioethanol demand according to various biofuel blending rates (reference year is 2020 with 338,108 ha)

	E85		E20		E10		E5		E3	
	Biofuel Demand Mil. L	**Area Demand (ha)**	**Biofuel Demand Mil. L**	**Area Demand (ha)**	**Biofuel Demand Mil. L**	**Area Demand (ha)**	**Biofuel Demand Mil. L**	**Area Demand (ha)**	**Biofuel Demand Mil. L**	**Area Demand (ha)**
2021	76	10,706	18	2,519	9	1,260	4	630	3	378
2022	161	22,774	38	5,359	19	2,679	9	1,340	6	804
2023	257	36,207	60	8,519	30	4,260	15	2,130	9	1,278
2024	363	51,227	85	12,053	43	6,027	21	3,013	13	1,808
2025	484	68,277	114	16,065	57	8,033	28	4,016	17	2,410
2026	621	87,622	146	20,617	73	10,309	37	5,154	22	3,093
2027	774	109,187	182	25,691	91	12,845	46	6,423	27	3,854
2028	942	132,925	222	31,276	111	15,638	55	7,819	33	4,691
2029	1,128	159,188	265	37,456	133	18,728	66	9,364	40	5,618
2030	1,336	188,537	314	44,362	157	22,181	79	11,090	47	6,654



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
85% Blend	76	161	257	363	484	621	774	942	1128	1336
20% Blend	18	38	60	85	114	146	182	222	265	314
10% Blend	9	19	30	43	57	73	91	111	133	157
5% Blend	4	9	15	21	28	37	46	55	66	79
3% Blend	3	6	9	13	17	22	27	33	40	47
Potential	2396	2396	2396	2396	2396	2396	2396	2396	2396	2396

Figure 19. Required bioethanol production amount from sugar beet by different blending scenarios and the base year (2020) production potential

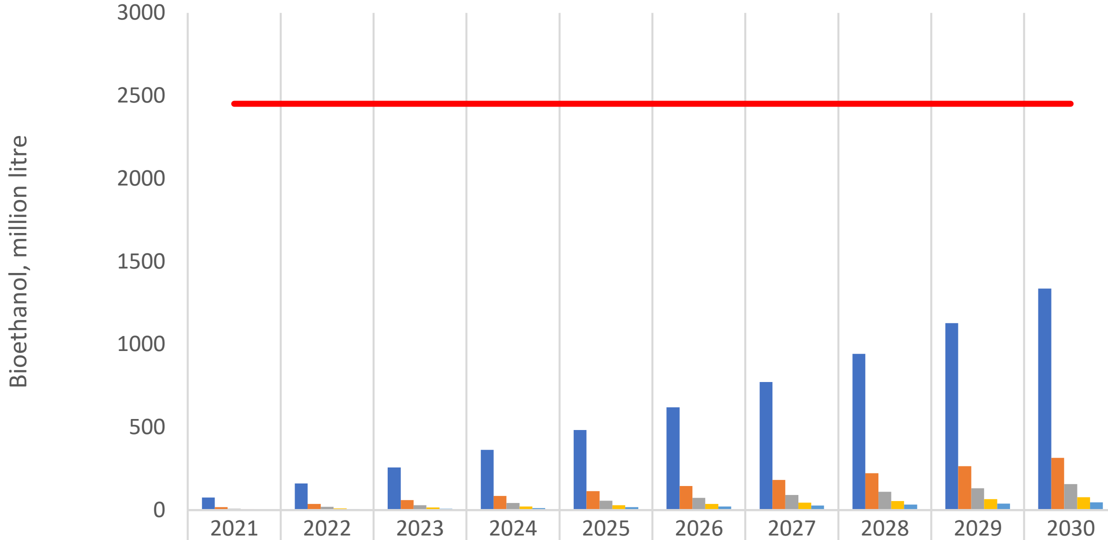
According to the calculation results, bioethanol production from sugar beet can be easily achieved with all blending rates by the end of 2030. However, crop production for food demand should also be considered. Thus, biofuel production does not compete with food production.

6.3.3. Corn Demand Analysis for Bioethanol Production

In 2020, Turkey's cultivated corn area was 691,632 hectares [54]. Based on the BioGrace tool calculation approach, 1 hectare of corn cultivation area could yield 3545 litres of bioethanol. Thus, the base year bioethanol production potential from corn was found to be 2.45 billion litres, and it was assumed that this potential would stay constant over the projection period. Even though corn is more efficient than sugar beet in bioethanol production (1 kilogram of corn yields 0.377 litres of ethanol), sugar beet has a production yield of roughly double that of corn. As a result, less cropland is required if sugar beet is used for bioethanol production. Table 45 and Figure 20 demonstrate the estimated biofuel demand for various biofuel blending rates through 2030 and the required corn cultivated area.

Table 45. Projection of corn cultivation area to meet bioethanol demand according to various biofuel blending rates (reference year is 2020 with 691,632 ha)

	E85	**E20**	**E10**	**E5**	**E3**	**E85**	**E20**	**E10**	**E5**	**E3**
	Biofuel Deman d Mil. L	**Area Demand (ha)**	**Biofuel Demand Mil. L**	**Area Demand (ha)**	**Biofuel Demand Mil. L**	**Biofuel Demand Mil. L**	**Area Demand (ha)**	**Biofuel Demand Mil. L**	**Area Demand (ha)**	**Biofuel Demand Mil. L**
2021	76	21,403	18	5,036	9	2,518	4	1,259	3	755
2022	161	45,528	38	10,712	19	5,356	9	2,678	6	1,607
2023	257	72,382	60	17,031	30	8,515	15	4,258	9	2,555
2024	363	102,408	85	24,096	43	12,048	21	6,024	13	3,614
2025	484	136,492	114	32,116	57	16,058	28	8,029	17	4,817
2026	621	175,164	146	41,215	73	20,608	37	10,304	22	6,182
2027	774	218,273	182	51,358	91	25,679	46	12,840	27	7,704
2028	942	265,727	222	62,524	111	31,262	55	15,631	33	9,379
2029	1,128	318,231	265	74,878	133	37,439	66	18,719	40	11,232
2030	1,336	376,901	314	88,682	157	44,341	79	22,171	47	13,302



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
85% Blend	76	161	257	363	484	621	774	942	1128	1336
20% Blend	18	38	60	85	114	146	182	222	265	314
10% Blend	9	19	30	43	57	73	91	111	133	157
5% Blend	4	9	15	21	28	37	46	55	66	79
3% Blend	3	6	9	13	17	22	27	33	40	47
Potential	2452	2452	2452	2452	2452	2452	2452	2452	2452	2452

Figure 20. Required bioethanol production amount from corn by different blending scenarios and the base year (2020) production potential

As with sugar beet, bioethanol production from corn can be easily achieved with all blending rates by the end of 2030. However, crop production for food demand should also be considered. Thus, biofuel production does not compete with food production.

6.4. Policy Analysis

Biofuel blending into diesel and gasoline is the most common way of reducing life cycle GHG emissions from fossil fuels in the transportation sector. The higher the biofuel ratio, the better the per cent decrease in fuel life cycle GHG emissions. The primary sources of GHG emissions from the lifecycle of biofuel are the cultivation of feedstock, biorefinery, transportation and distribution of products.

GHG emissions from biofuel combustion are assumed to be carbon-neutral since the CO_2 generated during biomass combustion is balanced by the CO_2 absorbed from the environment during photosynthesis when the biomass is grown.

The cultivation step results in the highest GHG emissions for all crops analysed in this study. Rapeseed, one of the crops studied, has the highest GHG emissions during the cultivation process, at 28.7 g CO_2eq/MJ. Reduced nitrogen fertilizer use in rapeseed production would be critical for reducing GHG emissions from the cultivation step. Sugar beet cultivation, on the other hand, emits the lowest GHG emissions,16 g CO_2eq/MJ, while corn cultivation emits 20.7 g CO_2eq/MJ.

For all the biofuel production pathways, transport activities have the least effect on the life cycle GHG emissions compared to cultivation and biorefinery stages. Among all production pathways, waste oil to biodiesel has the highest life cycle GHG emission savings (74%). As a result, we can clearly state that using waste oil in biofuel production rather than any crop-based oil has significant environmental benefits. However, waste oil results from distributed sources like restaurants or households, and high transportation costs could cause a low collection rate. The door-to-door collection is considered one of the most expensive collection methods. Increasing collection points can help mass transportation costs resulting from door-to-door collection and increase people's interest. Local governments should increase the number of collection points and raise citizens' awareness of the importance of delivering waste oils. This can be achieved by conducting awareness-raising campaigns to promote high delivery rates, as increased waste oil collection rates greatly reduce negative environmental impacts.

6.5. Closing Remarks

In this section, the life cycle GHG emission reduction potentials of biodiesel from rapeseed and waste oil and bioethanol from sugar beet and corn were calculated. Then, GHG emission reduction potentials of different blending ratios of biodiesel and bioethanol are estimated until 2030. Finally, crop demand and policy analysis for biofuel production in Turkey was conducted.

According to the results of each biofuel production pathway's life cycle GHG emissions, biodiesel production from waste oil has the lowest life cycle GHG emission, 21.9 g CO_2eq/MJ. This shows that there is no impact on dedicated energy crop production. Bioethanol production from corn (44.9 g CO_2eq/MJ) and sugar beet (46.1 g CO_2eq/MJ) follows biodiesel from waste oil. Biodiesel from rapeseed has the highest life cycle GHG emission, which is 53.2 g CO_2eq/MJ.

The selected pathways' life cycle GHG emissions in the EU are all lower than ones for the Turkish context, with 52 g CO_2eq/MJ for rapeseed, 14 g CO_2eq/MJ for waste oil, 40 g CO_2eq/MJ for sugar beet, and 43 g CO_2eq/MJ for corn. According to the BioGrace standard values, the main reason for these differences is that Turkey's average GHG intensity of the electricity mix is higher than that of the EU.

Cultivation (except for waste oil) and biorefinery steps contribute the highest GHG emissions among all biofuel production steps. However, transportation activities have the least impact on GHG emissions over the life cycle. This is because GHG emissions from biofuel combustion are assumed to be carbon-neutral. Thus, the CO_2 produced during biomass combustion is balanced by the CO_2 absorbed from the environment during photosynthesis when the biomass is grown.

Reducing nitrogen fertilizer use in crop cultivation, especially rapeseed cultivation, could significantly decrease GHG emissions in the cultivation step. Besides, using waste oil to produce biodiesel can reduce the negative impacts of the cultivation step. However, to reduce life cycle GHG emissions resulting from waste oil transportation, mainly from door-to-door collection, the number of collection points should be increased, and local governments should raise citizens’ awareness of the importance of the delivery of waste oils.

In the study's next step, various biodiesel and bioethanol blending scenarios were implemented to estimate the GHG emissions of biofuel-blended passenger cars. This is accomplished by assuming a 5% annual rise in the proportion of biofuel-blended passenger cars will reach up to 50% of all non-blended passenger cars in 2030, starting from 2020, which is selected as the base year. The following table summarizes the GHG emission reduction potentials of all biofuel pathways in 2030 based on scenario results.

Table 46. GHG emission reduction potentials of all biofuel pathways in 2030 based on biofuel blend rates

Biodiesel Blend Ratio	**Rapeseed**	**Waste oil**	**Bioethanol Blend Ratio**	**Sugar beet**	**Corn**
B100	18.26%	36.94%	E100	22.47%	23.22%
B20	3.65%	7.39%	E85	19.10%	19.74%
B5	0.91%	1.85%	E20	4.49%	4.64%
B2	0.37%	0.74%	E10	2.25%	2.32%
B0.5	0.09%	0.18%	E5	1.12%	1.16%
			E3	0.65%	0.7%

Projection studies were conducted for rapeseed, sugar beet, and corn cultivation area to see Turkey’s capacity to meet biodiesel and bioethanol demands in 2030 according to various biofuel blending rates. According to projection results, B0.5 and B2 blending rates can easily meet the demand for biodiesel production from rapeseed without expanding the cultivation rates. Regarding bioethanol production from sugar beet and corn can be easily achieved with all blending rates by the end of 2030. However, sugar beet and corn production for food demand should also be considered since biofuel production should not compete with food production.

7. CONCLUSION

This study aims to provide information on biofuel utilization in the road transportation sector and its effect on reducing life cycle GHG emissions from fossil fuels. In the study, life cycle GHG emissions of biofuels for selected biodiesel and bioethanol pathways in Turkey are analysed by following the methodology given in the relevant EU Directives: EU FQD and EU RED.

Biomass is considered one of the most important renewable energy sources and the only alternative source to fossil sources to produce fuels, chemicals and other carbon-based materials. Biofuels are usually categorised into 1st, 2nd, 3rd, and 4th generation biofuels based on feedstock choice, production process and development stage. 1st generation biofuels are currently used and produced in large amounts on commercial scales. Bioethanol, biodiesel and biogas are the most common ones. The most important and first liquid biofuels are biodiesel and bioethanol. They are commercially available, and their market share is steadily increasing. In 2020, bioethanol and biodiesel provided about 3.5% of transportation energy. Biofuel production levels returned to 2019 levels in 2021 after falling in 2020 due to reduced transportation demand caused by the COVID-19 pandemic. Biofuels are essential in combating climate change because they are carbon-neutral. Thus, bioethanol and biodiesel play a vital role in the transportation sector to support countries' sustainability and low-carbon development strategies.

To improve energy supply security by reducing the dependence on imported fossil fuels, decreasing GHG emissions, and thus, mitigating climate change, the EU defined sustainable criteria for the whole bioenergy sector. This is accomplished through the EU RED and EU RED II directives. EU RED established a binding target for renewable energy to be met by 2020 with a contribution of 20% to the total final energy supply in the EU and at least 10% to the transport sector in each Member State. EU RED II covers 2021-2030 and sets a new binding renewable energy target for 2030: at least 32% of the gross final energy consumption and 14% of the renewable energy supply in the transportation sector. Regarding GHG saving thresholds for transportation biofuels, RED I specified at least 60% savings for biofuels produced in installations starting on January 1, 2017, and RED II identified at least 65% for biofuels produced in operation from January 1, 2021. Turkey is aligning its regulatory framework in the environmental sector with the EU standards, including developing renewable and biomass-based energy production and utilization.

Various studies are analyzed to examine different practices to better understand *(i)* life cycle GHG emissions of biofuels, mainly of biodiesel production from rapeseed and waste oil, bioethanol production from sugar beet and corn, *(ii)* BioGrace use to analyse different feedstock's GHGs, *(iii)* Turkey context. The results of the studies analysed are shown in Table 6, Table 7 and Table 8. The life cycle GHG emission estimates of biodiesel production from rapeseed range from 27.5 g CO_2 eq/MJ to 74.6 g CO_2 eq/MJ. This difference could be due to the scale of the biodiesel production facility, the global warming potential of the seasonal cultivation of rapeseed, different cultivation methods such as using different amounts of fertilizers, and the energy intensity of the countries. The life cycle GHG emission estimates of biodiesel production from waste oil range from 14 g CO_2 eq/MJ (Greece) to 10.6 g CO_2 eq/MJ (UK), which is a smaller range than that of the rapeseed. As for the life cycle GHG emission of bioethanol from sugar beet, there is not much work. In a study conducted in the UK, the life cycle GHG emission of sugar beet-based bioethanol is 26.6 g CO_2 eq/MJ, which offers the most significant potential for emission savings in the UK context with waste oil-based biodiesel. Life cycle GHG emission of bioethanol from corn ranges from 43.4 g CO_2 eq/MJ to 70.3 g CO_2 eq/MJ. Based on the results, we can say that different calculation tools can give different results alongside different bioethanol production styles, different cultivation methods, and the energy intensity of the countries. The studies estimating life cycle GHG emissions of biofuels using BioGrace are listed in Table 7. In a study in Italy, the life cycle GHG emission of bioethanol from sunflowers was examined by comparing different farming techniques, and emissions ranged from 53.4 g CO_2 eq/MJ to 79.4 g CO_2 eq/MJ. The other practices of using the BioGrace tool in the literature are calculating GHG emissions of feedstock cultivation, such as sugar beet calculation in Germany, and cotton, guar, lavender, sesame and tobacco cultivation in Turkey. Further, biodiesel production from rapeseed in Turkey has a similar emission amount to the UK. The biofuel production in Latvia results in less emission than in Turkey, considering both winter and spring cultivation seasons.

Regarding biodiesel production from waste oil, both UK and Greece have lower emissions than Turkey. Regarding bioethanol production from sugar beet, the UK has lower emissions than Turkey. As for bioethanol production from corn, the UK has more emissions than Turkey, and Brazil has a similar emission amount to Turkey.

In this study, BioGrace- I GHG Calculation Tool Version 4d for Compliance was selected to provide baseline information on the life cycle GHG emission of biodiesel and bioethanol production based on the most common feedstocks used in Turkey. The BioGrace Calculation tool is recognized as a voluntary scheme by the EC and is in line with the sustainability criteria of EU RED.

All life cycle steps from crop production to biofuel use were considered. Four biofuel production pathways were considered in the Turkish context: biodiesel production from rapeseed and waste oil and bioethanol production from sugar beet and corn. The analysis followed the methodology in the EU directives and applied the principles of Life Cycle Assessment. Life cycle GHG emissions were expressed in g CO_2eq/MJ.

First, the life cycle GHG emission reduction potentials of biodiesel from rapeseed and waste oil and bioethanol from sugar beet and corn were calculated. Secondly, GHG emission reduction potentials of different blending ratios of the produced biodiesel and bioethanol are estimated until 2030. Finally, crop demand analyses for biofuel production were conducted according to various blending ratios until 2030.

As Turkish passenger car fuel standards (diesel and gasoline) are based on European standards, the base values for life cycle GHG emissions of diesel and gasoline are specified using EU FQD default values. These values are 83.8 g CO_2eq /MJ for both diesel and gasoline.

According to the results of each biofuel production pathway's life cycle GHG emissions, biodiesel production from waste oil has the least life cycle GHG emission, 21.9 g CO_2eq/MJ. This shows that there is no impact on dedicated energy crop production. Bioethanol production from corn (44.9 g CO_2eq/MJ) and sugar beet (46.1 g CO_2eq/MJ) follows biodiesel from waste oil. Biodiesel from rapeseed has the highest life cycle GHG emission, which is 53.2 g CO_2eq/MJ.

The selected pathways' life cycle GHG emissions in the EU are all lower than ones for the Turkish context, with 52 g CO_2eq/MJ for rapeseed, 14 g CO_2eq/MJ for waste oil, 40 g CO_2 eq/MJ for sugar beet, and 43 g CO_2eq/MJ for corn. According to the BioGrace standard values, the main reason for these differences is that Turkey's average GHG intensity of the electricity mix is higher than that of the EU.

Cultivation (except for waste oil) and biorefinery steps contribute the highest GHG emissions among all biofuel production steps. However, transportation activities have the least impact on GHG emissions over the life cycle. This is because GHG emissions from biofuel combustion are assumed to be carbon-neutral. Thus, the CO_2 produced during biomass combustion is balanced by the CO_2 absorbed from the environment during photosynthesis when the biomass is grown.

Reducing nitrogen fertilizer use in crop cultivation, especially rapeseed cultivation, could significantly decrease GHG emissions in the cultivation step. Besides, using waste oil to produce biodiesel can reduce the negative impacts of the cultivation step. However, to reduce life cycle GHG emissions resulting from waste oil transportation, mainly from door-to-door collection, the number of collection points should be increased, and local governments should raise citizens' awareness of the importance of the delivery of waste oils.

In the study's next step, various biodiesel and bioethanol blending scenarios were implemented to estimate the GHG emissions of biofuel-blended passenger cars. This is accomplished by assuming a 5% annual rise in the proportion of biofuel-blended passenger cars will reach up to 50% of all non-blended passenger cars in 2030, starting from 2020, which is selected as the base year. Table 46 summarizes the GHG emission reduction potentials of all biofuel pathways in 2030 based on scenario results.

Projection studies were conducted for rapeseed, sugar beet, and corn cultivation area to see Turkey's capacity to meet biodiesel and bioethanol demands in 2030 according to various biofuel blending rates. According to projection results, B0.5 and B2 blending rates can easily meet the demand for biodiesel production from rapeseed without expanding the cultivation rates. Bioethanol production from sugar beet and corn can be easily achieved with all blending rates by the end of 2030. However, sugar beet and corn production for food demand should also be considered since biofuel production should not compete with food production.

7.1. Future Studies

This study analysed the life cycle GHG emissions of biofuels for selected feedstock in Turkey. Selected feedstocks in the study are rapeseed, waste oil, sugar beet and corn. In future studies, life cycle GHG emissions of biofuels from different feedstocks from the Turkish agriculture system can be analysed, such as sunflower, cottonseed, safflower, camelina, soybean, wheat, and molasses.

In this study, country-level feedstock cultivation data was used. In future studies, based on feedstock potential, regional-level studies can be conducted to reach more concise results. In addition, other biomass sources to produce 2nd, 3^{rd,} and 4th generation biofuel can be analysed for the Turkish context.

In this study, BioGrace Calculation Tool was used to analyse the life cycle GHG emissions of biofuels. Different life cycle GHG emission tools can be used in future studies, and comparison studies can be conducted.

Due to data availability for the base year, only passenger cars were used to develop blending scenarios for all vehicle types. In future studies, different vehicle types can be included to develop different blending scenarios for using biofuel in the Turkish transportation sector.

In this study, the scenarios were developed until the year 2030. In future studies, scenarios can be conducted for a more extended period of time.

In this study, life cycle analysis was conducted only for GHG emissions. In the future studies, the life cycle can include other parameters to see more comprehensive results.

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