

## Determination of carbon dioxide emissions from fuel use in wheat, sugar beet, and potato production in Türkiye and future projection estimates

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**Abstract:** Due to the negative effects of natural disasters caused by climate change, the agricultural sector, ecosystems, and the economy are under serious threat. In this study, carbon dioxide emissions from fuel use in wheat, sugar beet, and potato production between 2015 and 2024 (10 years) were determined in Türkiye, and projections for 2025-2034 were examined. In calculating fuel-based CO<sub>2</sub> emissions for wheat, sugar beet, and potato production, the total CO<sub>2</sub> emissions from fuel and oil sources described in the Intergovernmental Panel on Climate Change were considered. The Chain Index method was used in programming the projection coefficients. For this effect, percentages of value increase and decrease over the years were calculated, and the average projection coefficients for these percentages were determined. The range of variations was found for total carbon dioxide emissions as a maximum of 1263.32 ktCO<sub>2</sub>, and a minimum of 1064.49 ktCO<sub>2</sub> in wheat production, a maximum of 134.35 ktCO<sub>2</sub>, and a minimum of 101.29 ktCO<sub>2</sub> in sugar beet production, and a maximum of 26.48 ktCO<sub>2</sub>, and a minimum of 18.39 ktCO<sub>2</sub> in potato production. It is predicted that TCOE in wheat, sugar beet, and potato production will increase in Türkiye during 2025-2034. Accordingly, 13.31% increase in TCOE is predicted for wheat production, 13.31% in sugar beet production, and 13.39% in potato production. In this context, efforts can be made to raise awareness about environmental protection and sustainable agricultural methods and to encourage their widespread adoption by farmers. Environmentally friendly alternative production techniques should be planned for soil cultivation systems, planting, fertilization, maintenance, irrigation, pesticide application, harvesting, and post-harvest processing in Türkiye, and farmers should be trained in these techniques.

**Keywords:** Agricultural machinery, agricultural emission, climate change, projection estimate, tractor,

### Türkiye'nin Buğday, Şeker Pancarı ve Patates Üretiminde Yakıt Kullanımından Kaynaklanan Karbondioksit Emisyonlarının Belirlenmesi ve Gelecek Tahminleri

**Öz:** İklim değişikliğinin neden olduğu doğal afetlerin olumsuz etkileri nedeniyle tarım sektörü, ekosistem ve ekonomi ciddi tehdit altındadır. Bu çalışmada, Türkiye'de 2015 ile 2024 yılları arasında (10 yıl) buğday, şeker pancarı ve patates üretiminde yakıt kullanımından kaynaklanan karbondioksit emisyonları belirlenmiş ve 2025-2034 yılları için tahminler incelenmiştir. Buğday, şeker pancarı ve patates üretimine ait yakıt kaynaklı CO<sub>2</sub> emisyonlarının hesaplanmasında, Hükümetlerarası İklim Değişikliği Paneli'nde açıklanan yakıt ve petrol kaynaklarından kaynaklanan toplam CO<sub>2</sub> emisyonları dikkate alınmıştır. Projeksiyon katsayılarının programlanmasında Zincirleme Endeks yöntemi kullanılmıştır. Bu etki için, yıllara göre değer artış ve azalış yüzdeleri hesaplanmış ve bu yüzdelerle ait ortalama projeksiyon katsayıları belirlenmiştir. Toplam karbondioksit emisyonları için değişim aralığı buğday üretiminde maksimum 1263.32 ktCO<sub>2</sub>, minimum 1064.49 ktCO<sub>2</sub>, şeker pancarı üretiminde maksimum 134.35 ktCO<sub>2</sub>, minimum 101.29 ktCO<sub>2</sub> ve patates üretiminde maksimum 26.48 ktCO<sub>2</sub>, minimum 18.39 ktCO<sub>2</sub> olarak bulunmuştur. Bu bağlamda, çevre koruma ve sürdürülebilir tarım yöntemleri konusunda farkındalığın artırılması ve bunların çiftçiler tarafından yaygın olarak benimsenmesini teşvik etmek için çaba gösterilebilir. Bu amaca yönelik olarak, Türkiye'de toprak işleme sistemleri, ekim, gübreleme, bakım, sulama, pestisit uygulaması, hasat ve hasat sonrası işleme için çevre dostu alternatif üretim teknikleri planlanmalı ve çiftçilerin bu teknikler konusunda eğitilmesi sağlanmalıdır.

**Anahtar kelimeler:** Tarım makinaları, tarımsal emisyon, iklim değişikliği, tahmin projeksiyonu, traktör.

## 1. Introduction

Agricultural production and food security face numerous challenges in many countries due to the adverse effects of climate change and the unequal distribution of land and water resources. Overcoming these challenges requires implementing resource-efficient practices, reducing input costs (e.g., water, chemical fertilizers, and fossil fuels), and limiting environmental costs (Liu et al., 2016; Jamali et al., 2021). The combustion of fossil fuels is a major contributor to the increase in CO<sub>2</sub> and overall greenhouse gas emissions. Therefore, analyzing and forecasting CO<sub>2</sub> emissions are vital to a clean energy economy (Pao et al., 2012).

The agriculture sector, ecosystem, and economy are under significant threat due to changes in rainfall patterns, increases in temperature, drought, desertification, and the negative effects of natural disasters caused by climate change (Hayaloğlu, 2018). Climate change, urbanization, and excessive use of pesticides and chemical fertilizers are damaging agricultural lands. A decrease of 2.4 million hectares in total agricultural land was observed between 2001 and 2015 (Ağaçayak and Öztürk, 2017).

By 2022, global agri-food systems emissions were 16.2 billion tonnes of carbon dioxide equivalent (GtCO<sub>2</sub>eq) (Anonymous, 2024a). In the first quarter of 2023, greenhouse gas emissions in the European Union economy totaled 821 million tons of CO<sub>2</sub> equivalent, with the manufacturing industry ranking first at 23.5% of emissions, while agriculture ranked fourth at 14.3% (Lee et al., 2023). For example, Poland's greenhouse gas (GHG) emissions for 2022 were estimated at 315.5 million tonnes. This means that they were 33.2% lower than the emissions in 1988 and 4.8% lower than those in 2021. CO<sub>2</sub> emissions accounted for 82.9% of the total greenhouse gas emissions in Poland in 2022 (Sokal and Kachel, 2025). It is estimated that the food system alone accounts for approximately 21-37% of annual emissions globally (Lynch et al., 2021). As global, the emission intensity of agri-food systems was 2.6 kg CO<sub>2</sub>eq per international dollar (I\$), with values above the world average in Africa (6.0 kg CO<sub>2</sub>eq/I\$), the Americas and Oceania (3.4 kg CO<sub>2</sub>eq/I\$), and lower in Asia and Europe (1.8-2.0 kg CO<sub>2</sub>eq/I\$) in 2022.

According to TUIK data for 2023, Türkiye's total greenhouse gas emissions are equivalent to 552.2 MtCO<sub>2</sub>, with the largest share (71.6%, followed by

agriculture at 13.0%. Energy sector emissions were calculated at 395.4 MtCO<sub>2</sub> equivalent, and agriculture sector emissions at 71.8 MtCO<sub>2</sub> equivalent (Anonymous, 2025c). In the agricultural sector, technological developments in soil cultivation, planting, irrigation, spraying, harvesting, and post-harvesting processes are based on both profitability and productivity. In line with this objective, the increased use of more powerful tractors and agricultural machinery of various sizes has led to a significant increase in exhaust emissions due to fuel and motor oil consumption, thereby contributing to climate change through agricultural production.

The IPCC prepares its reports every 5-7 years, with the first report published in 1990, followed by reports in 1995, 2001, 2007, and 2013-2014 (Anonymous, 2025a). Gołasa et al. (2021) have explained the necessity of conducting country-based, regional, and small-scale provincial emission studies aimed at reducing emissions, and of continuing these studies at an increasing rate. In Türkiye, greenhouse gas emissions from the agricultural sector have increased significantly since 2010, while agricultural land has declined in recent years. Since global warming and climate change are the most important issues worldwide and in Türkiye, investment plans to reduce carbon dioxide emissions must be made (Aydın, 2023). Aydın and Aktuz (2023) emphasized the need for serious action given the significant impact of climate change on Türkiye's agricultural ecosystem. More efficient use of energy for sustainable agriculture, reduced fuel consumption, and reduced CO<sub>2</sub> emissions is possible (Öztürk, 2017). It is also necessary to reduce the fuel and oil consumed by tractors and agricultural machinery, as well as the use of chemical pesticides and fertilizers in production (Gözübüyük et al., 2012). Öztürk and Vulkan (2017) emphasize that establishing a power balance between tractors and agricultural machinery and preventing engine overloading could help reduce carbon dioxide emissions.

Wheat is a strategic product, the raw material for bread, the most-consumed food item in Türkiye. Due to the continuous increase in input prices in wheat production, the very low level of input support, the failure of product prices to rise to the desired level, and the lack of support purchases by the Grain Board, there has been a significant decrease in wheat production areas (Anonymous, 2022). According to TUIK data, the total wheat production area in Türkiye in 2024 will be

7,023,808 ha with a production of 20,800,000 tons, while wheat yield in 2024 will be 2.96 tons ha<sup>-1</sup>, which is below the world average yield (3.47 tons ha<sup>-1</sup>). In the 2023/24 production season, approximately 80% of global wheat production is accounted for by China, the EU, India, Northwest Asia, Russia, and the US. In 2021, Türkiye accounted for approximately 2.2% of global wheat production and 3.1% of global wheat cultivation area (Anonymous, 2024b; Anonymous, 2025d).

Sugar beet is an important strategic industrial crop that makes significant contributions to Turkish agriculture and economy. According to FAO data for 2021, sugar beet production is carried out at 4.6 million hectares in 52 countries worldwide. Russia has the largest sugar beet cultivation area, accounting for 21.5% of the global total, while Türkiye ranks fifth with 6.2%. According to FAO data for 2021, France ranks first with 85.5 tons per hectare, while Türkiye ranks fourth with 63.2 tons per hectare. The global average sugar beet yield is 60.1 tons per hectare (Anonymous, 2025d). According to 2024 data, Türkiye has 324,665 ha of cultivated land, 23,000,000 tons of production and yield potential of 70.92 tons per hectare of sugar beet (Anonymous, 2025d).

Potatoes are a crop that can be grown in different climatic conditions around the world and have a variety of uses. Potatoes are an important industrial crop, ranking fourth in global production after wheat, corn, and rice. According to 2024 TUIK data, potatoes are grown on 195,767 ha of land in Türkiye, with a production of 6,900,000 tons and a yield potential of 35.25 tons ha<sup>-1</sup> (Anonymous, 2025d).

Although studies have been conducted at the provincial, regional, and national levels in Türkiye to estimate carbon dioxide emissions from fuel sources for various crop production systems, these studies remain limited. Sugar beet in Kırklareli (Baran and Gokdogan, 2016), wheat and corn across Türkiye (Öztürk and Vulkan, 2017), cotton across Türkiye (Öztürk et al., 2017), lentils in the Southeastern Anatolia Region (Küsek, 2018), olives in the Eastern Mediterranean Region (Bilgili et al., 2018), barley, chickpeas, corn, cotton, lentils, bitter beans, rice, sugar beets, sunflowers, figs, and wheat throughout Türkiye (Eren et al., 2019). In the Eastern Mediterranean Region, carbon dioxide emissions from fuel in wheat and corn production (Kuzu et al., 2024) were examined. In the TR83 Region, rice (Altuntaş, 2024a), in the TR71 Region, potatoes (Altuntaş, 2024b), wheat and corn in the TR62 Region

(Altuntaş, 2024c), and wheat in the Central Anatolia Region-Sivas Province (Altuntaş and Özgöz, 2024) have been determined, and projections for future years have been made.

This study demonstrates that the limited provincial, regional, and national studies conducted across Türkiye, as mentioned above, are insufficient. To this end, we aim to generate projections using the new, updated TUIK data and the chain index method, and to determine carbon dioxide emissions as a basis for strategies to reduce fuel consumption and carbon dioxide emissions in the strategically important production of wheat, sugar beet, and potatoes nationwide. This aims to contribute to steps that can reduce global carbon dioxide emissions. In this context, awareness of environmental protection and sustainable agricultural methods can be raised, and their widespread adoption by farmers can be ensured.

## 2. Materials and Methods

According to 2025 data, Türkiye, with a total area of 769,630 km<sup>2</sup>, is expected to have a population density of 114 people per km<sup>2</sup> and a population of 87,985,426 (Anonymous, 2025b). According to Türkiye's 2024 data, the production areas for wheat, sugar beet, and potatoes are 7,023 ha, 324,665 ha, and 195,767 ha, totaling 7,544,240 ha. In terms of production volume, wheat, sugar beet, and potato production volumes are 20,800,000 tons, 23,000,000 tons, and 6,900,000 tons, respectively, totaling 50,700,000 tons. Türkiye's wheat, sugar beet, and potato yield values are 2.96 tons ha<sup>-1</sup>, 70.92 tons ha<sup>-1</sup>, and 35.25 tons ha<sup>-1</sup>, respectively (Anonymous, 2025d). The changes in wheat, sugar beet, and potato areas in Türkiye over the years are presented in Tables 1, 2, and 3.

According to Table 1, across Türkiye, between 2015 and 2024, there was a 10.72% decrease in wheat cultivation areas and a 7.96% decrease in production quantities, while there was a 3.06% increase in yield values (Table 1). Türkiye's sugar beet production, including production area, production volume, and yield, for the period 2015-2024, is presented in Table 2. According to Table 2, across Türkiye, sugar beet cultivation areas increased by 18.28%, production quantities by 43.55%, and yields by 21.27% between 2015 and 2024.

Table 3 shows the planting area, production volume, and yield values for potato production in Türkiye between 2015 and 2024. According to Table 3, across Türkiye, there was a 27.29% increase in potato planting

**Table 1.** Cultivated area, production, and yield of wheat in Türkiye (Anonymous, 2025d).

Years	Cultivated area (ha)	Crop production (ton)	Yield (ton ha <sup>-1</sup> )
2015	7,866,887	22,600,000	2.87
2016	7,671,945	20,600,000	2.69
2017	7,668,879	21,500,000	2.80
2018	7,299,270	20,000,000	2.74
2019	6,846,327	19,000,000	2.78
2020	6,922,236	20,500,000	2.96
2021	6,744,666	17,650,000	2.62
2022	6,628,739	19,750,000	2.98
2023	6,832,602	22,000,000	3.22
2024	7,023,808	20,800,000	2.96
<b>Mean</b>	<b>7,150,536</b>	<b>20,440,000</b>	<b>2.86</b>

**Table 2.** Cultivated area, production, and yield of sugar beet in Türkiye (Anonymous, 2025d).

Years	Cultivated area (ha)	Crop production (ton)	Yield (ton ha <sup>-1</sup> )
2015	7,866,887	22,600,000	2.87
2016	7,671,945	20,600,000	2.69
2017	7,668,879	21,500,000	2.80
2018	7,299,270	20,000,000	2.74
2019	6,846,327	19,000,000	2.78
2020	6,922,236	20,500,000	2.96
2021	6,744,666	17,650,000	2.62
2022	6,628,739	19,750,000	2.98
2023	6,832,602	22,000,000	3.22
2024	7,023,808	20,800,000	2.96
<b>Mean</b>	<b>7,150,536</b>	<b>20,440,000</b>	<b>2.86</b>

**Table 3.** Planting area, production, and yield of potato in Türkiye (Anonymous, 2025d).

Years	Cultivated area (ha)	Crop production (ton)	Yield (ton ha <sup>-1</sup> )
2015	153,802	4,760,000	30.95
2016	144,706	4,750,000	32.83
2017	142,851	4,800,000	33.60
2018	135,904	4,550,000	33.48
2019	140,766	4,979,824	35.38
2020	147,966	5,200,000	35.14
2021	138,513	5,100,000	36.82
2022	139,072	5,200,000	37.39
2023	150,905	5,700,000	37.77
2024	195,767	6,900,000	35.25
<b>Mean</b>	<b>153,802</b>	<b>4,760,000</b>	<b>30.95</b>

area, a 44.96% increase in production quantity, and a 13.98% increase in yield between 2015 and 2024.

For the total fuel consumption values used in the calculations of fuel-related CO<sub>2</sub> emissions in Türkiye's wheat, sugar beet, and potato production, the reference values reported by Altuntaş and Özgöz (2024), Baran and Gokdogan (2016), and Altuntaş (2024b) were considered. Accordingly, the fuel

consumption values per unit area for wheat, sugar beet, and potato production were 55.92 l ha<sup>-1</sup>, 128.50 l ha<sup>-1</sup>, and 47.11 l ha<sup>-1</sup>, respectively, in the calculations (Altuntaş and Özgöz, 2024; Baran and Gokdogan, 2016; Altuntaş, 2024b). The oil consumption values for wheat, sugar beet, and potato production in Türkiye were included in the calculations, based on 4.5% of the total fuel consumption for each

production (Özgöz et al., 2017). Accordingly, the total oil consumption for wheat, sugar beet, and potato production was determined to be 2.52 l ha<sup>-1</sup>, 5.78 l ha<sup>-1</sup>, and 2.12 l ha<sup>-1</sup>, respectively.

The thermal values and CO<sub>2</sub> emission factors for the fuels and oils used in wheat, sugar beet, and potato production in Türkiye were determined using the following equations. In calculating fuel-based CO<sub>2</sub> emissions for wheat, sugar beet, and potato production in Türkiye, the total CO<sub>2</sub> emissions from fuel and oil sources described in the Intergovernmental Panel on Climate Change were considered, and the following equations were used

$$TCOE = FCOE + OCOE \quad (1)$$

$$FCOE = T_{\text{diesel}} \times FLH \times FEF \quad (2)$$

$$OCOE = TCO \times OLH \times OEF \quad (3)$$

Where,

TCOE = Total CO<sub>2</sub> emissions

FCOE = Fuel-based CO<sub>2</sub> emissions (kgCO<sub>2</sub>)

OCOE = Oil-based CO<sub>2</sub> emissions (kgCO<sub>2</sub>)

TDiesel = Total diesel fuel consumption (l)

FLH = Fuel lower heating value (0.0371 GJ l<sup>-1</sup>)

FEF = Fuel emission factor (74.01 kgCO<sub>2</sub> GJ<sup>-1</sup>)

TCO = Total oil consumption (l)

OLH = Oil lower heating value (0.0382 GJ l<sup>-1</sup>)

OEF = Oil emission factor (73.28 kgCO<sub>2</sub> GJ<sup>-1</sup>) (Öztürk, 2017; Öztürk et al., 2017; Bilgili and Aybek, 2018; Küsek, 2018; Altuntaş, 2024a; Altuntaş, 2024b).

For the determination of product-based fuel consumption and product-based CO<sub>2</sub> emissions for wheat, sugar beet, and potato production across Türkiye, the following equations were used for specific fuel consumption (SpFC) and specific CO<sub>2</sub> emissions (SpCE) (Öztürk et al., 2017; Bilgili and Aybek, 2018; Küsek, 2018). When converting the total fuel consumption to grams, the density value of diesel fuel (0.84 g cm<sup>-3</sup>) was considered (Beşergil, 2014).

$$SpFC = \frac{CE}{PC} \quad (4)$$

$$SpCE = \frac{TCOE}{PC} \quad (5)$$

Where;

SpFC: Specific fuel consumption (gfuel kgproduct<sup>-1</sup>),

CF: Fuel consumption (gfuel),

PC: Product production (kgproduct),

SpCE: Specific CO<sub>2</sub> emissions (gCO<sub>2</sub> kgproduct<sup>-1</sup>),

TCOE: Total CO<sub>2</sub> emissions (gCO<sub>2</sub>).

For Türkiye, the calculated TCOE, SpFC, and SpCE change values for the period 2015-2024 were used to project total CO<sub>2</sub> emissions, specific fuel consumption, and specific CO<sub>2</sub> emissions for wheat, sugar beet, and potato production for the period 2025-2034. For the projection calculations, changes in total carbon dioxide emissions, specific fuel consumption, and specific carbon dioxide emissions over a 10-year period (2015-2024) were considered. Numerical increases and decreases in these values were calculated as percentage change rates, and projection coefficients were determined by averaging these percentages. Calculations for the change rate for two sample years can be formulated as follows:

$$C.R = \left[ \frac{(X2 - X1)}{X1} \right] * 100 \quad (6)$$

Where:

C.R: Change rate for two sample years (%)

X2 = Total carbon dioxide emission value for the current year

X1 = Total carbon dioxide emission value for the previous year.

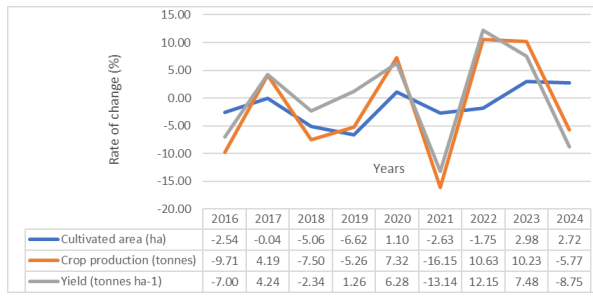
By multiplying the coefficient related to the total carbon dioxide emission value of the previous year with the total carbon dioxide emission value related to that total carbon dioxide emission, the next 10-year (2025-2034) projections of the total carbon dioxide emission values in wheat, sugar beet and potato production were estimated in line with the decrease and increase of the coefficients (Demir et al., 2013; Altuntaş, 2020).

### 3. Results and Discussion

#### 3.1. Carbon dioxide emission results and projection estimates based on fuel use for wheat production

In calculations related to carbon dioxide emissions from wheat production across Türkiye (total CO<sub>2</sub> emissions (TCOE), specific fuel consumption (SpFC), and specific CO<sub>2</sub> emissions (SpCE)), the wheat production area, production quantity, and yield values must be considered (Table 1). In this context, changes in Türkiye's wheat production area, production volume, and yield between 2015 and 2024, compared with previous years, are presented in Figure 1. TCOE, SpFC, and SpCE calculations for

wheat production in Türkiye for the years 2015-2024 are given in Table 4.



**Figure 1.** Changes in wheat production values over the years in Türkiye.

**Table 4.** Total CO<sub>2</sub> emissions, specific fuel consumption, and changes in specific CO<sub>2</sub> emissions in wheat production in Türkiye between 2015 and 2024.

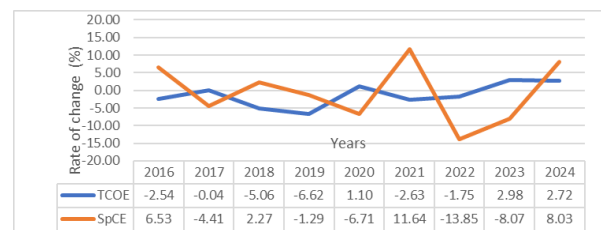
Years	TCOE (*)	SpFC	SpCE
2015	1263.32	16.35	55.90
2016	1232.02	17.49	59.81
2017	1231.53	16.75	57.28
2018	1172.17	17.14	58.61
2019	1099.44	16.93	57.87
2020	1111.63	15.86	54.23
2021	1083.11	17.95	61.37
2022	1064.49	15.77	53.90
2023	1097.23	14.59	49.87
2024	1127.94	15.86	54.23
<b>Mean</b>	<b>1148.29</b>	<b>16.47</b>	<b>56.31</b>

(\*): TCOE: Total carbon dioxide emissions (ktCO<sub>2</sub>), SpFC: Specific fuel consumption (g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>), SpCE: Specific carbon dioxide consumption (gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>).

Table 4 shows that the average TCOE for wheat production in Türkiye between 2015 and 2024 is 1148.29 ktCO<sub>2</sub>, the average SpFC is 16.47 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>, and the average SpCE is 56.31 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>. The lowest values for TCOE, SpFC, and SpCE between 2015 and 2024 were calculated as 1064.49 ktCO<sub>2</sub> in 2022, 14.59 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup> in 2023, and 49.87 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup> in 2023, respectively. The highest TCOE, SpFC, and SpCE values for wheat production between 2015 and 2024 were calculated as 1263.32 ktCO<sub>2</sub> in 2015, 17.95 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup> in 2021, and 61.37 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup> in 2021, respectively. Figure 2 shows the change in total CO<sub>2</sub> emissions and specific CO<sub>2</sub> emissions from wheat production in Türkiye between 2015 and 2024 compared to the previous year.

Öztürk and Vulkan (2017) reported that the TCOE value from fossil fuels in wheat production across Türkiye between 2010 and 2015 was 1.4 MtCO<sub>2</sub> year

1. Kuzu et al. (2024) reported that the highest and lowest TCOE values for wheat production in the Eastern Mediterranean Region were 50.64 ktCO<sub>2</sub> in Adana province and 15.07 ktCO<sub>2</sub> in Osmaniye province, respectively. Altuntaş and Özgöz (2024) reported that the TCOE value in the Central Anatolia-Sivas region was 42.12 ktCO<sub>2</sub>. Öztürk and Vulkan (2017) reported that the SpFC value in Türkiye between 2010 and 2015 was 20.7 g<sub>diesel</sub> kg<sub>wheat</sub><sup>-1</sup>, while Kuzu et al. (2024) reported that within the Eastern Mediterranean Region, SpFC values were highest in Hatay Province at 154.27 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup> and lowest in Adana at 107.81 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>. Khoshroo (2014) reported that SpFC values in Iran between 2008 and 2010 ranged from 69.12 to 83.17 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>, while Altuntaş and Özgöz (2024) reported that SpFC values were calculated as 21.88 g<sub>fuel</sub> kg<sub>unit</sub> in the Sivas example in the Central Anatolia Region. Öztürk and Vulkan (2017) found that the SpCE value for wheat production in Türkiye between 2010 and 2015 was 67.7 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>; Kuzu et al. (2024) found that the SpCE values for wheat production in the Eastern Mediterranean Region provinces ranged from 327.49 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup> to 228.87 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup> for Adana; Altuntaş and Özgöz (2024) report that these values were calculated as 74.81 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup> for the Central Anatolia Region example of Sivas. Projections for 2025-2033 were calculated using TCOE, SpFC, and SpCE values for wheat production in Türkiye for 2015-2024, and these are presented in Table 5.



**Figure 2.** Changes in total CO<sub>2</sub> emissions and specific CO<sub>2</sub> emissions from wheat production over time in Türkiye

The projection coefficients found in the projection calculations for TCOE, SpFC, and SpCE values in wheat production in Türkiye were -1.205 for TCOE and -0.024 for SpFC and SpCE. In the projections for 2025-2034, TCOE values are expected to increase by 13.31%, from 1143.71 to 1295.96, an increase of 13.31%, SpFC values are projected to increase by 0.189% to between 15.86 and 15.89, and SpCE values

are projected to increase by 0.129% to between 54.24 and 54.31. It is projected that in 2034, the TCOE, SpFC, and SpCE values for wheat production in Türkiye will be 1,295.96 ktCO<sub>2</sub>, 15.89 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>, and 54.31 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>, respectively (Table 5).

**Table 5.** Projected estimates of TCOE, SpFC ve SpC values for wheat production of Türkiye for the years 2025-2034 based on the years 2015-2024.

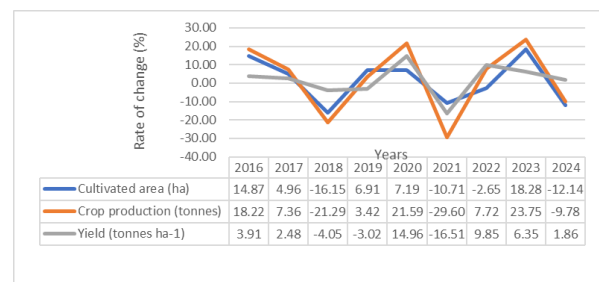
Years	TCOE (*)	SpFC	SpCE
2015	1263.32	16.35	55.90
2016	1232.02	17.49	59.81
2017	1231.53	16.75	57.28
2018	1172.17	17.14	58.61
2019	1099.44	16.93	57.87
2020	1111.63	15.86	54.23
2021	1083.11	17.95	61.37
2022	1064.49	15.77	53.90
2023	1097.23	14.59	49.87
2024	1127.94	15.86	54.23
<b>Projection coefficient</b>	<b>-1.21</b>	<b>-0.02</b>	<b>-0.02</b>
2025	1143.71	15.86	54.24
2026	1159.70	15.87	54.25
2027	1175.92	15.87	54.25
2028	1192.36	15.87	54.26
2029	1209.03	15.87	54.27
2030	1225.94	15.88	54.28
2031	1243.08	15.88	54.29
2032	1260.46	15.88	54.30
2033	1278.09	15.88	54.31
2034	1295.96	15.89	54.31

(\*): TCOE: Total carbon dioxide emissions (ktCO<sub>2</sub>), SpFC: Specific fuel consumption (g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>), SpCE: Specific carbon dioxide consumption (gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>).

### 3.2. Carbon dioxide emission results and projection estimates based on fuel use for sugar beet production

Changes in cultivated area, production volume, and yield values for 2015–2024, which were considered in calculations related to carbon dioxide emissions from sugar beet production across Türkiye, are shown in Figure 3. TCOE, SpFC, and SpCE calculations for sugar beet production in Türkiye for the years 2015-2024 are presented in Table 6. Table 6 shows the average TCOE for sugar beet production in Türkiye between 2015 and 2024 is determined to be 101.29 ktCO<sub>2</sub>, the average SpFC is 1.85 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>, and the average SpCE is 6.32 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>. The lowest values for TCOE, SpFC, and SpCE between 2015 and 2024 were calculated as

101.29 ktCO<sub>2</sub> in 2015, 1.52 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup> in 2024, and 5.21 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup> in 2024, respectively. In sugar beet production, the highest TCOE, SpFC, and SpCE values between 2015 and 2024 were calculated as 134.35 ktCO<sub>2</sub> in 2023, 1.88 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup> in 2019, and 6.41 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup> in 2019, respectively. The changes of the total CO<sub>2</sub> emissions and specific CO<sub>2</sub> emissions of sugar beet production over time in Türkiye in presented in Figure 4. Projections for 2025-2034 were calculated using TCOE, SpFC, and SpCE values for sugar beet production in Türkiye for 2015-2024, and these are presented in Table 7.



**Figure 3.** Changes in sugar beet production values over the years in Türkiye

**Table 6.** The changes of total CO<sub>2</sub> emissions, specific fuel consumption, and specific CO<sub>2</sub> emissions in sugar beet production of Türkiye between 2015 and 2024.

Years	TCOE (*)	SpFC	SpCE
2015	101.29	1.85	6.32
2016	118.99	1.78	6.07
2017	125.20	1.73	5.92
2018	107.79	1.81	6.18
2019	115.79	1.88	6.41
2020	124.77	1.59	5.42
2021	112.70	1.86	6.34
2022	109.79	1.67	5.70
2023	134.35	1.56	5.32
2024	119.81	1.52	5.21
<b>Mean</b>	<b>101.29</b>	<b>1.85</b>	<b>6.32</b>

(\*): TCOE: Total carbon dioxide emissions (ktCO<sub>2</sub>), SpFC: Specific fuel consumption (g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>), SpCE: Specific carbon dioxide consumption (gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>)

Table 7 shows the projection coefficients calculated in the projection calculations of TCOE, SpFC, and SpCE values for sugar beet production in Türkiye are found to be 2.584 for TCOE and -1.736 for SpFC and SpCE. In the 2025-2034 projection estimates, TCOE values are projected to increase by 13. SpFC values are projected to increase by 0.13% between 1.524

and 1.526, and SpCE values are projected to increase by 0.13% between 5.210 and 5.217. It is projected that in 2034, the TCOE, SpFC, and SpCE values for potato production in Türkiye will be 137.66 ktCO<sub>2</sub>, 1.53 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>, and 5.22 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>, respectively.

**Table 7.** Projected estimates of TCOE, SpFC, and SpC values for sugar beet production in Türkiye for the years 2025-2034 based on the years 2015-2024.

Years	TCOE (*)	SpFC	SpCE
2015	101.29	1.85	6.322
2016	118.99	1.78	6.073
2017	125.20	1.73	5.920
2018	107.79	1.81	6.182
2019	115.79	1.88	6.414
2020	124.77	1.59	5.419
2021	112.70	1.86	6.343
2022	109.79	1.67	5.70
2023	134.35	1.56	5.32
2024	119.81	1.52	5.21
<b>Projection coefficient</b>	2.58	-1.74	-1.74
2025	121.48	1.52	5.21
2026	123.18	1.52	5.21
2027	124.90	1.52	5.21
2028	126.65	1.53	5.21
2029	128.42	1.53	5.21
2030	130.22	1.53	5.21
2031	132.04	1.53	5.22
2032	133.88	1.53	5.22
2033	135.76	1.53	5.22
2034	137.66	1.53	5.22

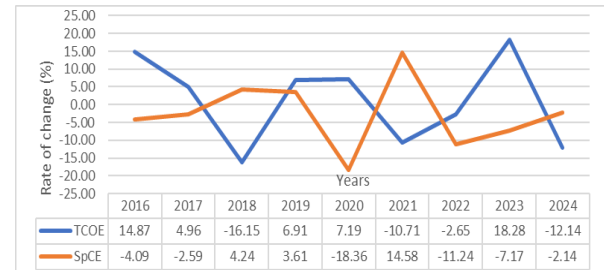
(\*): TCOE: Total carbon dioxide emissions (ktCO<sub>2</sub>), SpFC: Specific fuel consumption (g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>), SpCE: Specific carbon dioxide consumption (gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>).

### 3.3. Carbon dioxide emission results and projection estimates based on fuel consumption for potato production

The changes in planting area, production quantity, and yield values for the years 2015-2024, which were taken into account in the calculations of carbon dioxide emissions from potato production across Türkiye, are shown in Figure 5.

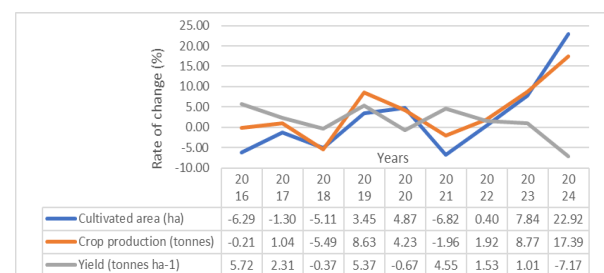
TCOE, SpFC, and SpCE calculations for potato production in Türkiye for 2015-2024 are presented in Table 8. The average TCOE for potato production in Türkiye between 2015 and 2024 is determined to be 20.81 ktCO<sub>2</sub>, the average SpFC is 1.28 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>, and the average SpCE is 4.37 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>. The lowest values for TCOE, SpFC, and SpCE between 2015 and 2024 were calculated as 18.39 ktCO<sub>2</sub> in 2018, 1.05 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup> in 2023,

and 3.58 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup> in 2023, respectively. In potato production, the highest TCOE, SpFC, and SpCE values between 2015 and 2024 were calculated as 26.48 ktCO<sub>2</sub> in 2024, 1.28 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup> in 2015, and 4.37 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup> in 2015, respectively (Table 8).



**Figure 4.** The changes of the total CO<sub>2</sub> emissions and specific CO<sub>2</sub> emissions of sugar beet production over time in Türkiye

Altuntaş (2024) reported that the average fossil fuel-based TCOE value for potato production in the TR71 Region between 2014 and 2023 was 3.650 ktCO<sub>2</sub>, the average SpFC value was 0.841 g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>, and the average SpCE value was 2.877 gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>. Pishgar-Komleh et al. (2012) reported that energy consumption and CO<sub>2</sub> emissions in potato production in the Isfahan region of Iran were 47 GJ ha<sup>-1</sup> and 992.88 kgCO<sub>2</sub> ha<sup>-1</sup>, respectively, while Bakhtiari et al. (2015) calculated the total average energy input consumption and greenhouse gas emissions in potato production in Iran's East Azerbaijan province to be 131 608.14 MJ ha<sup>-1</sup> and 4.542 kgCO<sub>2</sub> ha<sup>-1</sup>, respectively. In this study, the average fuel-based carbon dioxide emission value for potato production in Türkiye between 2015 and 2024 was 20.81 ktCO<sub>2</sub>.



**Figure 5.** Changes in potato production values in Türkiye over the years.

Figure 6 shows the change in total CO<sub>2</sub> emissions and specific CO<sub>2</sub> emissions from potato production in Türkiye between 2015 and 2024 compared to the previous year. Projections for the years 2024-2033 were calculated by considering the TCOE, SpFC, and

SpCE values for potato production in Türkiye for the years 2015-2024, and these are presented in Table 9.

**Table 8.** The changes of total CO<sub>2</sub> emissions, specific fuel consumption, and specific CO<sub>2</sub> emissions in wheat production of Türkiye between 2015 and 2024.

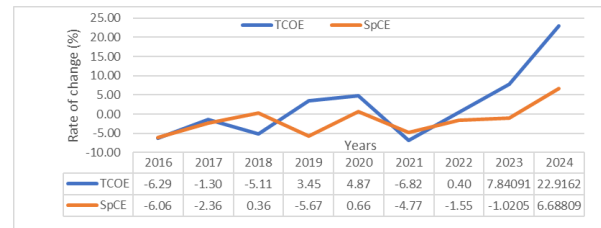
Years	TCOE (*)	SpFC	SpCE
2015	20.81	1.28	4.37
2016	19.58	1.21	4.12
2017	19.33	1.18	4.03
2018	18.39	1.18	4.04
2019	19.04	1.12	3.82
2020	20.02	1.13	3.85
2021	18.74	1.07	3.67
2022	18.81	1.06	3.62
2023	20.42	1.05	3.58
2024	26.48	1.12	3.84
Mean	20.81	1.28	4.37

(\*): TCOE: Total carbon dioxide emissions (ktCO<sub>2</sub>), SpFC: Specific fuel consumption (g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>), SpCE: Specific carbon dioxide consumption (gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>).

**Table 9.** Projected estimates of TCOE, SpFC ve SpCE values for potato production of Türkiye for the years 2025-2034 based on the years 2015-2024.

Years	TCOE (*)	SpFC	SpCE
2015	0.02	1.13	3.85
2016	0.03	1.14	3.90
2017	0.07	1.07	3.65
2018	0.05	1.21	4.15
2019	0.07	1.14	3.88
2020	0.09	1.11	3.80
2021	0.13	1.13	3.85
2022	0.16	1.07	3.65
2023	0.20	1.05	3.57
2024	0.22	1.06	3.62
<b>Projection coefficient</b>	<b>33.97</b>	<b>-0.51</b>	<b>-0.51</b>
2025	0.22	1.06	3.62
2026	0.23	1.06	3.62
2027	0.23	1.06	3.62
2028	0.23	1.06	3.62
2029	0.24	1.06	3.63
2030	0.24	1.06	3.63
2031	0.24	1.06	3.63
2032	0.25	1.06	3.63
2033	0.25	1.06	3.63
2034	0.25	1.06	3.63

(\*): TCOE: Total carbon dioxide emissions (ktCO<sub>2</sub>), SpFC: Specific fuel consumption (g<sub>fuel</sub> kg<sub>product</sub><sup>-1</sup>), SpCE: Specific carbon dioxide consumption (gCO<sub>2</sub> kg<sub>product</sub><sup>-1</sup>).



**Figure 6.** The changes in the total CO<sub>2</sub> emissions and specific CO<sub>2</sub> emissions of potato production over time in Türkiye.

#### 4. Conclusion

In this study, fuel-based carbon dioxide emissions from wheat, sugar beet, and potato production in Türkiye were determined, and projections for future years were estimated. For Türkiye, it is anticipated that total carbon dioxide emissions, specific fuel consumption, and specific carbon dioxide emissions for wheat, sugar beet, and potato production will show an upward trend in projections for the next 10 years (2025–2034). Therefore, to reduce total carbon dioxide emissions for wheat, sugar beet, and potato production in Türkiye, fuel consumption must be reduced. To this end, environmentally friendly alternative production techniques must be planned for soil tillage systems, planting, fertilization, maintenance, irrigation, pesticide application, harvesting, and post-harvest processing, and farmers must be educated on these techniques. For Türkiye, the use of renewable energy sources that could serve as alternatives to fuels causing carbon dioxide emissions in wheat, sugar beet, and potato production, along with restricting the use of chemical fertilizers and pesticides, which are significant input costs in production, to the extent possible, and ensuring the use of agricultural tools and machinery appropriate for the size of the land and needs, is important for sustainability and environmental protection.

#### Authorship contribution statement

E.A: Planning, data processing, article writing, editing.

#### Conflict of interest

The authors declare no conflicts of interest.

#### Ethical Statement

There is no need to obtain ethics committee approval for this study.

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