



Madencilik Faaliyetlerinde Karbon Ayak İzi: Kavramsal Bir Çerçeve

Carbon Footprint in Mining Activities: A Conceptual Framework

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ÖZET

Küresel ısınma ve iklim değişikliği bu yüzyılda çözülmesi gereken en acil çevresel sorunlardan biridir. Küresel ısınma, insan faaliyetleri nedeniyle atmosferdeki sera gazı konsantrasyonlarının hızla artmasından kaynaklanmaktadır. Daha önceleri üretim süreçlerinin bir sonucu olarak karbon salınımı makul karşılanırken, günümüzde neden olduğu çevresel etkilerden dolayı mücadele edilmesi gereken bir kavram haline gelmiştir. Dünyanın geleceği karbon salınımının ne kadar kontrollü olduğu ile orantılı hale gelmiştir. Bu çalışmada literatürde yer alan bilgilere dayanılarak karbon ayak izinin Türkiye'deki durumu ve öncelikli sektörler analiz edilmiştir. Karbon salınımı deyince ilk alan sektörlerden biri olan madencilik sektörü özelinde ise karbon kaynakları ve karbon ayak izinin azaltılması hususunda izlenecek yöntemler yorumlanmaya çalışılmıştır. Ayrıca karbon ayak izi hesaplama yöntemlerinin madencilik sektörüne uygunluğu analiz edilmiştir.

Türkiye'de karbon ayak izi, verilerin tutulmaya başlandığı 1990 yılından itibaren sistematik olarak artmış, 2021 yılından devreye alınan karbon ayak izi azaltma politikaları sonucunda yavaş da olsa azalmaya başlamıştır. Türkiye'de karbon ayak izi en yüksek sektörlerin enerji ve endüstriyel üretim sektörleri olduğu görülmüştür. Madencilik sektörü özelinde ise fosil yakıt kullanılan operasyonel faaliyetlerin karbon ayak izinin ana kaynağı olduğu belirlenmiştir. Madencilik faaliyetlerinden kaynaklı sera gazı salınımı azaltmada elektrifikasyon, yenilenebilir enerji entegrasyonu ve enerji verimli teknolojilerin kullanımı başlıca alınacak önlemler olarak önerilmiştir. Karbon ayak izi yöntemlerinin ise madencilik faaliyeti kaynaklı karbon ayak izini hesaplamada tek başına yeterli olmayacağı, birden fazla yöntemin birlikte kullanılması gerekliliği görülmüştür.

Anahtar Kelimeler: Karbon ayak izi, sera gazı emisyonları, iklim değişikliği, sürdürülebilir madencilik.

ABSTRACT

Global warming and climate change are among the most urgent environmental issues that need to be addressed in this century. Global warming is caused by the rapid increase in greenhouse gas concentrations in the atmosphere due to human activities. While carbon emissions were previously considered reasonable as a result of production processes, today they have become a concept that must be combated due to their environmental impact. The future of the world has become proportional to how well carbon emissions are controlled. In this study, based on information in the literature, the carbon footprint in Turkey and priority sectors were analyzed. Specifically for the mining sector, one of the first sectors that comes to mind when talking about carbon emissions, methods to be followed in terms of carbon sources and reducing the carbon footprint have been interpreted. In addition, the suitability of carbon footprint calculation methods for the mining sector has been analyzed.

Turkey's carbon footprint has increased systematically since 1990, when data collection began, but has started to decline, albeit slowly, as a result of carbon footprint reduction policies implemented since 2021. The energy and industrial production

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sectors have been identified as the sectors with the highest carbon footprint in Turkey. In the mining sector specifically, operational activities using fossil fuels have been identified as the main source of carbon footprint. Electrification, renewable energy integration, and the use of energy-efficient technologies have been recommended as the main measures to reduce greenhouse gas emissions from mining activities. It has been observed that carbon footprint methods alone are not sufficient for calculating the carbon footprint from mining activities, and that multiple methods must be used together.

Keywords: Carbon footprint, greenhouse gas emissions, climate change, sustainable mining.

1. INTRODUCTION

Global warming and climate change are widely recognized as some of the most pressing environmental challenges facing humanity today. Global warming results from the rapid increase in atmospheric concentrations of greenhouse gases due to human activities. While a portion of incoming shortwave solar radiation is directly reflected back into space by the atmosphere, another portion is absorbed by the Earth's surface. Much of the longwave radiation emitted from the warmed surface is subsequently reabsorbed by the atmosphere. Because atmospheric gases are highly transparent to shortwave solar radiation but less so to longwave radiation-owing to the accumulation of greenhouse gases-the near-surface layers of the atmosphere experience greater warming than would otherwise occur. This process is known as the atmospheric greenhouse effect (Figure 1) (Öztürk, 2002; Seymenler & Yamankaradeniz, 2025).

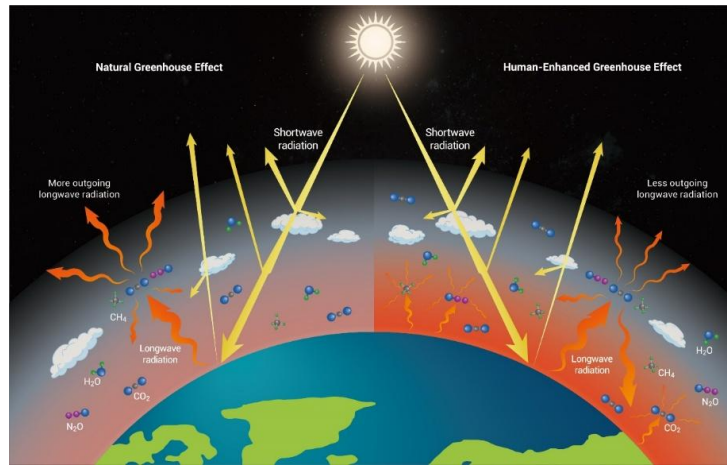


Figure 1. *Natural (left) and human-induced (right) greenhouse gas effect mechanisms (Wang et al., 2023)*

Greenhouse gases generate a greenhouse effect in the atmosphere by trapping incoming solar radiation and limiting the re-emission of heat from the Earth's surface. This leads to an increase in surface temperatures and triggers a range of adverse environmental impacts collectively referred to as climate change (Demir, 2025). The rise in human activities since the Industrial Revolution, coupled with the rapid proliferation of technology and efforts to improve living standards, has resulted in an excessive increase in the concentration of greenhouse gases. Particularly from the second half of the 20th century onward, the rapid accumulation of these gases has led to global warming and a series of natural disasters threatening the survival of humans, plants, and animal species (Bozoğlu et al., 2003).

In this context, mining activities-including exploration and production, ore processing and beneficiation, and transportation-constitute a significant source of greenhouse gas emissions due to their intensive consumption of fossil energy. Within the scope of this study, a comprehensive literature review was conducted on the carbon footprint of the mining sector and the methodologies used to calculate sector-related carbon emissions, and several recommendations are proposed.

There is a significant body of research analyzing the relationship between carbon footprint reduction and climate policies, as well as the additional burdens this may impose on national and corporate economies. Recent studies have also been conducted on sectors subject to the Carbon Border Adjustment Mechanism (CBAM) (aluminum, iron and steel, cement, electricity, fertilizer, and hydrogen). The mining sector has not been included in these studies because it is not among the sectors covered by the CBAM. However, the mining sector supplies raw materials to almost all of the sectors subject to the CBAM (aluminum, iron and steel, cement, electricity, fertilizer, and hydrogen). This study will attempt to analyze the relationship between the mining sector and carbon footprint in conceptual terms.

2. CARBON FOOTPRINT

The corporate carbon footprint, or organizational-level carbon footprint, refers to the total greenhouse gas emissions-expressed in CO₂ equivalents-generated by all activities of an organization or company, including production, services, and processing, that contribute to climate change (Figure 2) (Ulusal, 2021; Çolak & Atılğan Türkmen, 2023; Seymenler & Yamankaradeniz, 2025). In other words, according to the Kyoto Protocol, it is defined as the CO₂ equivalent of greenhouse gas emissions resulting from activities such as production and services (Dindar, 2021). The carbon footprint is a measure of the total greenhouse gas emissions (CO₂ and equivalents) caused by an activity, product, or organization. It is generally expressed in tons of CO₂ equivalent and can encompass all direct and indirect emission sources throughout the life cycle (Wiedmann and Minx, 2008). The concept of carbon footprint has become a widely accepted sustainability indicator because it quantitatively demonstrates the impact of activities on climate change. Carbon footprint has become an important tool used to manage and reduce greenhouse gas emissions (Wright et al., 2011; Pandey et al., 2011).



Figure 2. Carbon footprint (Dell, 2023)

The importance of carbon footprint becomes even more significant when considering the climate change crisis and water scarcity experienced on a global scale. The higher the amount of greenhouse gases emitted into the atmosphere as a result of an activity, the greater its contribution to global warming. Indeed, climate change has become a problem that threatens the future of humanity (Rockström et al., 2009). In order to limit global warming caused by greenhouse gas accumulation to between 1.5 and 2 °C, many countries have made commitments to reduce their carbon footprints through international agreements such as the 2015 Paris Agreement. The mining sector is estimated to contribute a significant share of around 4–7% to global greenhouse gas emissions (Enemuo & Ogunmodimu, 2025). The concept of carbon footprint is a crucial tool for quantifying environmental sustainability performance. By ensuring that environmental impacts are transparently disclosed in energy-intensive sectors such as mining, carbon footprint helps facilitate the implementation of corrective measures (Azapagic, 2004; Mudd, 2010).

3. GREENHOUSE GAS CLASSIFICATION

The assessment of carbon footprints is conducted by classifying emission sources into three scopes- Scope 1, Scope 2, and Scope 3-based on whether the emissions are direct or indirect (Lombardi et al., 2017; Kircher, 2021). The greenhouse gas emissions are organized into three primary categories. Scope 1 encompasses direct emissions from activities such as fossil fuel combustion, waste management, industrial processes and product use, as well as agriculture, forestry, and other land-use practices. Scope 2 refers to indirect, energy-related emissions resulting from the consumption of electricity, heat, steam, and/or cooling purchased from the national grid, generated beyond the city boundaries. Scope 3 includes all remaining indirect emissions associated with upstream and downstream activities occurring outside city limits, such as waste and wastewater management, maritime and aviation transport, and traded goods including food, water, and construction materials (Vásquez et al., 2015; Fenner et al., 2018; Hertwich & Wood, 2018; Erol, 2025).

According to data provided by the Global Atmospheric Research Emissions Database (EDGAR) and developed by the European Commission's Joint Research Centre (Crippa et al., 2018), the primary sources of these emissions are concentrated in several key sectors and each contributes to total greenhouse gas emissions in varying proportions. Table 1 shows the shares of these sectors in total greenhouse gas emissions. It is observed that approximately 75%

of total greenhouse gas emissions originate from the (1) Thermal power plants, (2) Land, air, and sea transportation, and (3) Chemical industry. The impact of improvements in greenhouse gas emissions from just these three sectors alone would be felt very quickly and effectively. It is observed that the mining sector, which includes oil and natural gas operations, ranks sixth among the eight sectors with a share of 6.6%. Research has shown that each sector has greenhouse gas emissions specific to its own activities (Lamb et al., 2021; Liu et al., 2023; Hong et al., 2021; Nayak et al., 2015; Kim et al., 2016; Menegat et al., 2022; Zhong et al., 2021a, 2021b). When examining greenhouse gas sources, it is observed that CO₂ and N₂O typically result from the combustion of fossil fuels, while CH₄ arises as a product of various processes (Filonchyk et al., 2024).

Table 1. Distribution of greenhouse gas emissions by source (Filonchyk et al., 2024)

No	Greenhouse gas source	%
1	Thermal power plants	38.07
2	Land, air, and sea transportation	20.69
3	Chemical industry	16.97
4	Energy consumption and heating in buildings	8.88
5	Cement production, iron and steel industry	8.38
6	Mining operations and oil - gas extraction	6.57
7	Agriculture, livestock	0.39
8	Waste disposal, wastewater treatment	0.05

4. TURKEY GREENHOUSE GAS EMISSIONS

According to the greenhouse gas inventory results published by the Turkish Statistical Institute (TURKSTAT), Figure 3 shows that Turkey's greenhouse gas emissions were significantly high until 2017. In 2016, they were first calculated at approximately 505 million tons (Mt) of CO₂ equivalent (CO₂ eq.) and have not fallen below this limit since. They remained approximately at this value until 2020, reaching their highest level in 2021 at 574 Mt CO₂ eq.. Total greenhouse gas emissions for 2022 decreased by 2.41% compared to the previous year, reaching 560 Mt CO₂ eq., and total greenhouse gas emissions for 2023 decreased by 1.39% compared to the previous year, reaching 552.2 Mt CO₂ eq. (TURKSTAT, 2025).

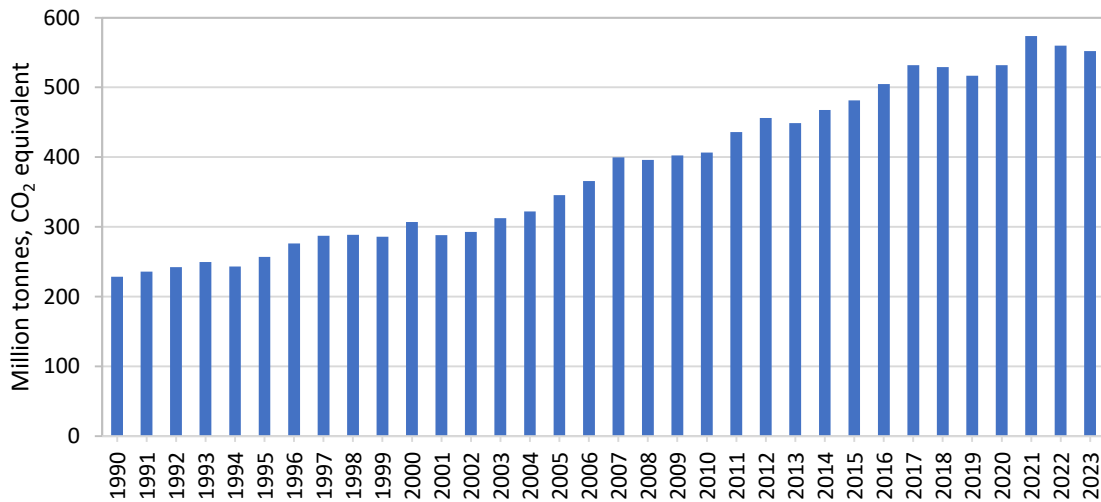


Figure 3. Turkey's carbon footprint over the years (1990–2023)

The total carbon footprint shows a steady increase from 1990 to 2021, followed by a slight downward trend after 2022 (Table 2) (TURKSTAT, 2025). Figure 4 shows the change in the share of sectors in the total carbon footprint over the years. The energy sector has always had the largest share in the total carbon footprint, while the waste sector has had the smallest share. Within the total carbon footprint for 2023, the energy sector accounts for the largest share 71.6% in terms of CO₂ equivalent emissions. It is followed by agriculture at 13.0%, industrial processes and product use at 12.8%, and the waste sector at 2.5%. The decline that began after 2021 can be attributed to the transition to clean energy sources and increased energy efficiency.

Table 2. Sectoral carbon footprints (million tons of CO₂ equivalent) (TURKSTAT, 2025)

Year	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023
Energy	143.2	170.0	219.8	247.7	290.9	344.1	369.6	406.5	400.5	395.4
Industrial processes and product use	23.1	25.9	26.6	34.7	49.7	60.3	68.9	76.5	71.9	70.9
Agriculture	51.8	49.0	46.0	46.3	47.7	59.2	76.4	75.4	71.5	71.8
Waste	10.3	12.1	14.5	16.9	18.1	17.7	17.0	15.4	16.0	14.1
Total	228.4	257.0	307.0	345.5	406.4	481.3	531.9	573.8	560.0	552.2

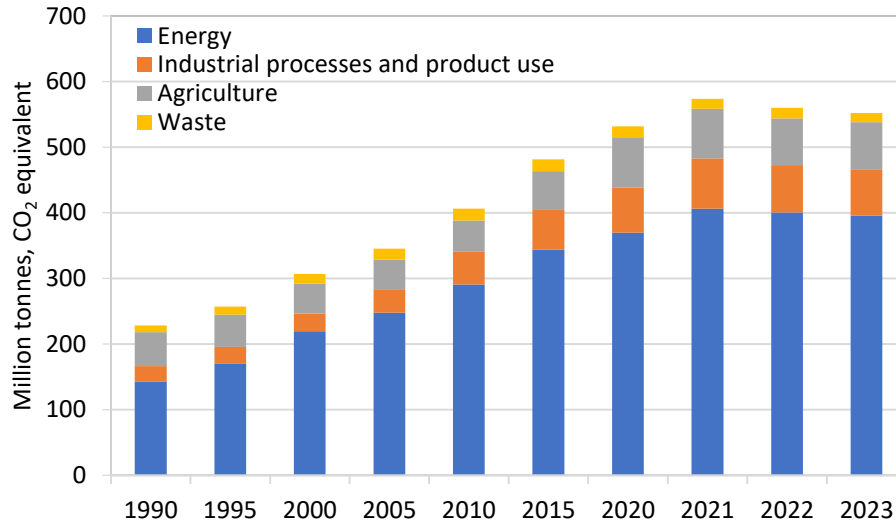


Figure 4. Change over the years in the share of sectors' carbon footprints within the total carbon footprint

Figure 5 shows the change in carbon footprint over the years by sector. Except for the agriculture sector, all sectors show a steady increase until 2021, after which a downward trend in carbon footprint began as a result of climate policy agreements signed globally. It can be said that, especially after 2000, the carbon footprint for all sectors increased by more than 100% due to the rapid change in consumption habits and the impact of growth in societies.

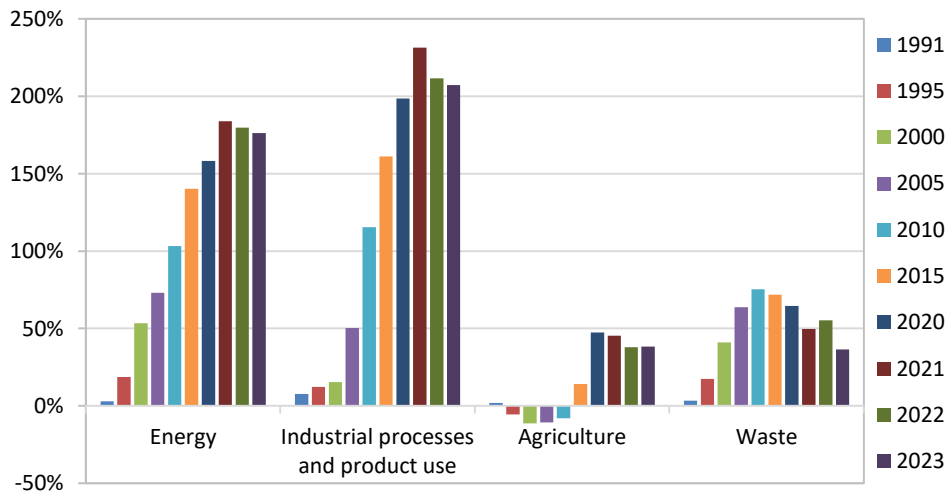


Figure 5. Changes in carbon footprint over the years by sector

When Figures 4 and 5 are considered together, the downward trend emerging from 2021 can be seen as evidence that the measures taken as a result of the climate policies developed are beginning to bear fruit, and it can be concluded that energy and industrial production processes should be at the center of these climate policies.

The mining sector is part of the supply chain for all sectors except agriculture, meaning it is a supplier of raw materials. A policy that does not include mining is inconceivable in Turkey's pursuit of its carbon neutrality goal.

5. MINING SECTOR AND CARBON FOOTPRINT

The mining industry has been undertaking various initiatives since the 1980s to reduce its environmental impacts and has continuously improved the technology it uses. Towards the end of the 20th century, although the environmental problems caused by mining activities were concentrated on issues such as acid mine drainage, particulate matter pollution, and the destruction of natural habitats, mining activities have always been seen as the prime suspect in terms of climate change and the pollution and consumption of water resources (Mudd, 2010). Following the signing of the Kyoto Protocol in 1997, mining companies also began monitoring and reporting greenhouse gas emissions. In the early 2000s, major mining companies began sharing greenhouse gas emissions and water resource usage as separate performance indicators in their sustainability reports (Mudd, 2010). In countries with intensive mining activities, such as Australia and Canada, declining ore grades and increasing tailings volumes have been accompanied by rising energy and water consumption; this situation has accelerated efficiency and improvement efforts in the sector (Mudd, 2010).

Azapagic (2004) developed sustainable development indicators for the mining sector and introduced an approach for monitoring the environmental impacts of industrial activities. In his work, he made it possible to measure and compare the carbon emissions and water usage of mining activities, significantly raising awareness within the sector.

Efforts to reduce the carbon footprint of the mining sector have largely focused on increasing energy efficiency and reducing fossil fuel use. Since the early 2000s, the life cycle assessment (LCA) method has been used to analyze the contribution of mining activities to carbon emissions. Norgate and Haque (2010) examined the extraction and ore processing stages for metallic mineral production in detail and found that loading, transportation, and grinding processes accounted for a large portion of total greenhouse gas emissions. Such studies have shed light on which processes should be prioritized for improvement in order to reduce the carbon footprint.

Mining operations traditionally cause significant greenhouse gas emissions due to their high dependence on fossil fuels (coal, oil, natural gas). In regions with high solar radiation, such as Australia and Chile, large-scale solar power plants have been established near open-pit mines. A study by Feio et al. (2024) showed that solar panels integrated into an isolated mining facility significantly reduced the use of diesel-fueled generators, lowering operating costs and annual carbon emissions. Wind turbines installed at a mining operation in Canada have substantially reduced fossil fuel consumption in the region and resulted in noticeable decreases in annual carbon emissions (CANWEA, 2013).

Some studies have shown that if more than 50% of the energy used in mining operations is supplied by renewable energy sources, the sector's carbon footprint could be reduced by nearly 50% by 2050 (Enemuo and Ogunmodimu, 2025).

The most significant carbon emissions in mining activities typically originate from heavy-duty trucks, excavators, and generators equipped with diesel engines. Today, the use of electric loaders and trucks is rapidly increasing, particularly in underground mining. Tokac et al. (2025) stated in their study that replacing diesel trucks used in open-pit mining with electric trucks would completely eliminate direct emissions (Scope 1) and reduce carbon emissions from mining activities by 50% to 90%. They also found that the use of electric trucks could reduce operating costs by 40–60%.

Recent studies indicate that if green transformation occurs in the mining sector, significant improvements will be achieved in carbon emissions per unit of mining product (Tokac et al., 2025; Northey et al., 2016). Improvements in carbon footprint indicators will not only contribute to achieving environmental impact reduction targets but also generate economic benefits for companies by increasing process efficiency (Tokac et al., 2025).

A “green transformation” is inevitable for sustainable mining. Meeting the expected future increase in mining demand while keeping environmental impacts within certain limits is the most important task of sustainable mining. Current research and applications show that technologies aimed at reducing the carbon footprint are both accessible and applicable.

Table 3 shows that greenhouse gas emissions from mining activities originate from a wide variety of activities and cover all three emission categories. This highlights the difficulty and complexity of carbon footprint management in the mining sector. Activities associated with intensive energy use, particularly excavation-loading-transportation, crushing-grinding, underground ventilation, and the production of energy required on site using diesel generators, appear to be the operational activities with the highest carbon reduction potential. The carbon reduction potential of drilling-blasting, water drainage, and waste management activities is considered to be relatively lower. Electrification, renewable energy integration, and the use of energy-efficient technologies come to

mind as the main measures to be taken to reduce greenhouse gas emissions from mining activities. However, it should also be noted that there are no measures that mining companies can take directly for Scope 3 emissions.

Table 3. Greenhouse gas emissions from mining activities

Mining Activity	Description	Scope 1	Scope 2	Scope 3	Carbon Reduction Potential
Beneficiation/mineral processing	Separation processes (flotation, leaching, etc.)	CO ₂ from on-site fuel use and reagents	CO ₂ from electricity use in processing circuits	Emissions from reagent production	High (process optimization, clean energy)
Crushing and grinding	Size reduction of ore prior to beneficiation	CO ₂ from auxiliary fuel use	CO ₂ from high electricity consumption in crushers and mills	Emissions from equipment production	High (high power grinder machine, energy-efficient mills)
Drilling and blasting	Rock fragmentation using drilling rigs and explosives	CO ₂ from diesel-powered drilling equipment N ₂ O from explosive detonation	CO ₂ from electricity used by electric drills	Emissions from explosive manufacturing and transport	Medium (electrification, optimized blasting)
Excavating, loading and hauling	Material loading and transportation using trucks and loaders	CO ₂ , CH ₄ from diesel haul trucks and loaders	-	Emissions from fuel supply and vehicle manufacturing	High (battery-electric/hydrogen trucks)
Mine dewatering	Pumping of groundwater	-	CO ₂ from electricity for pumping systems	Emissions from infrastructure construction	Medium (efficient pumps, renewable power)
Power generation (on-site)	Diesel or gas generators at mine sites	CO ₂ , CH ₄ , N ₂ O from fuel combustion	-	Emissions from fuel transport	High (renewable energy integration)
Product transport (off-site)	Transport of ore/concentrate to markets	-	-	CO ₂ from road, rail, and shipping transport	High (rail, electrification, logistics optimization)
Ventilation (underground mining)	Air circulation for safety and gas control	-	CO ₂ from electricity used by ventilation fans	Emissions from power generation	High (ventilation-on-demand systems)
Waste rock and tailings management	Handling and storage of waste materials	Minor CH ₄ and CO ₂ emissions	CO ₂ from pumping and monitoring systems	Emissions from dam construction	Medium (limited direct mitigation potential)

Note: Compiled using relevant literature (McKinsey & Company, 2020; IEA, 2021; ICMM, 2021).

6. METHODS FOR CARBON FOOTPRINT CALCULATION

Mining involves complex processes where various field operations (excavation-loading-transportation, crushing-grinding, underground ventilation, drilling-blasting, water drainage, waste management, etc.) are carried out simultaneously. Therefore, in order to accurately calculate the carbon footprint caused by mining activities, it is very important to correctly define mining activities and quantitatively determine the contributions of the parameters affecting the carbon footprint (Li et al., 2025). A review of the literature shows that different approaches can be used to calculate the carbon footprint of the mining sector.

- I. Direct Measurement Method
- II. Mass Balance Method
- III. Input-Output Analysis (IOA)
- IV. Intergovernmental Panel on Climate Change (IPCC) Method
- V. Carbon Emissions Dataset (ODIAC)

Table 4 attempts to provide a comparative overview of the fundamental principles of carbon footprint calculation methods and their applicability in mining. Looking at Table 4, it is considered that the Direct Measurement and Mass Balance methods provide high accuracy and detailed process tracking, but as a result, they have limited applicability due to reasons such as high monitoring costs, extensive equipment requirements, and limited scalability for complex and diverse mining activities. The IOA and IPCC methods are considered highly suitable for assessments at the national, regional, and sectoral levels, but may be weak in providing outputs compatible with complex and diverse operational activities in the mining sector. The ODIAC method, being a hybrid method that combines measurement-based data with the strengths of the IPCC method, may enable the necessary quantitative analyses for the mining sector. It is believed that none of these methods alone can successfully calculate the carbon footprint of mining activities; instead, different methods can be used together in the calculation, and the limits of the desired outputs must be clearly defined.

Table 4. Comparison of carbon emission calculation methods

Method	Basic Principle	Main Advantages	Key Limitations	Typical Application Scale	Suitability for Mining Applications
Direct Measurement (Liu et al., 2015)	Direct monitoring of emissions at the source	High accuracy; minimal external interference	High monitoring cost; long observation periods; limited spatial representativeness	Site/ Process level	High
Mass Balance Method (Liu et al., 2024)	Decomposition of production processes into sub-components	Detailed process-level emission quantification	Stringent equipment requirements; limited practical applicability	Process/ Facility level	Medium
Input-Output Analysis (IOA) (Sheng et al., 2025)	Economic input-output relationships linked with emissions	Clear theoretical basis; holistic macro-scale assessment	Complex data collection; limited data timeliness; uncertainty in data accuracy	Regional/ National/ Macro scale	Low
IPCC Method (Shan et al., 2016)	Activity data multiplied by emission factors	Simple, fast, and standardized; widely applicable	Strong dependence on emission factors; low spatial and process resolution	Provincial/ National/ Global scale	High
ODIAC Dataset (Li et al., 2025)	Integration of measurement-based data and IPCC methodology	Accurate, comprehensive, and easily integrable datasets	Limited sectoral/process detail; reliance on secondary data	Regional/ National/ Global scale	High

7. CONCLUSIONS

Carbon footprint has become one of the most effective tools in reducing climate change and its associated consequences, the impact of which is increasingly being felt every day. While individuals concerned about this issue may take personal measures to reduce their carbon footprint, the real impact will come from efforts to reduce corporate carbon footprints. Within the scope of this study, assessments were made regarding the change in total greenhouse gas emissions in Turkey over the years and their sector-based distribution, as well as the causes, calculation, and reduction of the carbon footprint from mining activities.

According to data from the Turkish Statistical Institute (TURKSTAT), total greenhouse gas emissions in Turkey increased over the period from 1990 to 2023. However, following the adoption of clean energy use and technological transformations for energy efficiency after 2021, a slight decline has begun to be observed. The energy and industrial production sectors have the largest carbon footprints. It is clear that these two sectors must be at the center of carbon footprint reduction policies and that the results achieved in these sectors will rapidly change the big picture.

In the mining sector specifically, due to mining activities involving many different operations simultaneously, traditional methods alone are considered insufficient for carbon footprint calculations. It is believed that using several of these methods in a hybrid manner for these calculations would be more accurate. Future studies should focus on developing calculation methods specifically for the mining sector.

Conflict of Interest Statement

The authors declare that there is no conflict of interest between them.

Author Contribution Statement

The authors have contributed equally to all stages of preparing the article.

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