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CARBON FOOTPRINT THROUGH THE LENS OF INFORMATION AND COMMUNICATION TECHNOLOGY

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ABSTRACT

The carbon footprint is one of the key indicators used to evaluate the environmental impacts of human activities and to guide sustainability policies. It refers to the total amount of greenhouse gases emitted into the atmosphere by individuals, institutions, or products. The carbon footprint encompasses not only direct emissions such as those resulting from energy production but also indirect sources, including manufacturing processes, logistics operations, and waste management. Today, these measurements are carried out based on various standards and methodologies. In particular, advancements in sensor technologies, the widespread adoption of cloud-based systems, and increased computational capacity have made it possible to monitor carbon footprints dynamically and in real time. These technological developments enable more precise tracking of environmental impacts over time and contribute to raising public awareness by providing personalized recommendations based on individual consumption habits. This study provides a comprehensive examination of the definition and significance of the carbon footprint, relevant standards, calculation methods, pricing mechanisms, and innovative technological approaches.

Keywords: Carbon footprint, Information and communication technology, Carbon footprint calculation, Emission reduction

BİLGİ VE İLETİŞİM TEKNOLOJİLERİ PERSPEKTİFİNDEN KARBON AYAK İZİ

ÖZ

Karbon ayak izi, insan faaliyetlerinin çevresel etkilerini değerlendirmek ve sürdürülebilirlik politikalarını yönlendirmek amacıyla kullanılan temel göstergelerden biridir. Bu gösterge, bireyler, kurumlar veya ürünler tarafından atmosfere salınan toplam sera gazı miktarını ifade eder. Karbon ayak izi yalnızca enerji üretimi gibi doğrudan emisyonları değil, aynı zamanda üretim süreçleri, lojistik faaliyetler ve atık yönetimi gibi dolaylı emisyon kaynaklarını da kapsamaktadır. Günümüzde bu ölçümler çeşitli standartlar ve metodolojiler temelinde gerçekleştirilmektedir. Özellikle sensör teknolojilerindeki ilerlemeler, bulut tabanlı sistemlerin yaygınlaşması ve artan hesaplama kapasitesi sayesinde karbon ayak izinin dinamik ve gerçek zamanlı olarak izlenmesi mümkün hale gelmiştir. Bu teknolojik gelişmeler, çevresel etkilerin zaman içinde daha hassas bir şekilde takip edilmesini sağlamakta; bireysel tüketim alışkanlıklarına yönelik öneriler sunarak toplumsal farkındalığın artmasına katkıda bulunmaktadır. Bu çalışmada karbon ayak izinin tanımı, önemi, ilgili standartlar, hesaplama yöntemleri, fiyatlandırma mekanizmaları ve yenilikçi teknolojik yaklaşımlar kapsamlı bir biçimde ele alınmaktadır.
Anahtar kelimeler: Karbon ayak izi, Bilgi ve iletişim teknolojileri, Karbon ayak izi hesaplama, Emisyon azaltma

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1. Introduction

The atmosphere absorbs a portion of the solar radiation emitted by the Earth's surface and cools by reflecting some of it back into space. However, a significant part of this radiation is absorbed by greenhouse gases in the atmosphere, causing both the atmosphere and the Earth's surface to warm. If the atmosphere lacked this property, the Earth's average temperature of 15°C would drop to approximately -18°C [1]. Increased atmospheric concentrations of carbon dioxide, chlorofluorocarbons, methane, and nitrogen oxides further amplify the greenhouse effect, which is considered the primary driver of global climate change. According to the Intergovernmental Panel on Climate Change (IPCC), the average global temperature on land and in the oceans increased by 0.85°C between 1880 and 2012 [2]. As a consequence of this temperature rise, glaciers are melting rapidly, sea levels are rising, and shifts in evaporation and precipitation patterns are leading to more frequent droughts and floods. Among these cascading effects, the depletion of water resources stands out as one of the most critical threats to sustainable living and environmental balance [3,4].

The primary gases contributing to the greenhouse effect are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and fluorinated gases. These gases originate from both natural processes and human activities, and their atmospheric concentrations have increased significantly since 1750 [2]. As of 2011, the concentrations of CO_2, CH_4, and N_2O had risen by 40%, 150%, and 20%, respectively, compared to pre-industrial levels, reaching 391 ppm, 1,803 ppb, and 324 ppb [2]. In response to these rising levels, numerous international discussions and initiatives have emerged to address greenhouse gas emissions. Efforts began with the First World Climate Conference in 1979 and continued with the establishment of the IPCC in 1988. In 1992, the United Nations Conference on Environment and Development was held, during which the United Nations Framework Convention on Climate Change (UNFCCC) was signed and adopted. The Kyoto Protocol, signed by 160 countries in 1997, emphasized the measurement and reporting of emissions, along with the implementation of mitigation strategies. It came into force in 2005. Later, in 2015, the 21st Conference of the Parties (COP21) convened in Paris, resulting in the adoption of the Paris Agreement, which entered into force in 2016 [4,5].

In addition to the studies and discussions conducted, technical committees within the International Organization for Standardization (ISO) have published three key standards: ISO 14064-1, ISO 14064-2 and ISO 14064-3 to provide standardized methods for tracking and managing greenhouse gas emissions. ISO 14064-1 outlines the principles and requirements for quantifying and reporting greenhouse gas emissions and removals at the organizational level [6]. ISO 14064-2 focuses on project-level activities, providing guidance for calculating, monitoring, and reporting efforts aimed at reducing or eliminating emissions [7]. ISO 14064-3 defines the criteria and processes for validating or verifying greenhouse gas declarations and managing assurance activities [8].

Although systematic efforts to monitor greenhouse gas emissions in Turkey began relatively recently, an official inventory has been maintained since 1990. In 1990, total greenhouse gas emissions were 228.4 million tons of CO_2e, and this figure rose to 558.3 million tons by 2022 [9]. While per capita CO_2e emissions were calculated as 4.1 tons/person in 1990, this value increased to 6.5 tons/person by 2023 [10]. The total greenhouse gas emissions for the Republic of Turkey are projected to reach 1,244.13 million tonnes of CO_2e by 2030, based on estimates derived from an artificial neural network model. This result significantly exceeds Turkey's commitment of 929 Mt CO_2e emissions for the year 2030, as declared at the Paris Climate Summit [11].

Carbon dioxide (CO_2) constitutes 76% of anthropogenic greenhouse gas emissions, followed by methane (CH_4) at 16%, nitrogen oxides (NO_x) at 6%, and fluorinated gases at 2%. The total amount of greenhouse gases emitted directly or indirectly by individuals, organizations, activities, or products is referred to as the carbon footprint [12]. Figure 1 illustrates the direct and indirect sources contributing to the carbon footprint, along with associated mitigation strategies.

In this context, the carbon footprint has emerged as a widely recognized indicator of greenhouse gas emissions. It has played a significant role in raising public awareness of climate change and the environmental impacts of global warming, and is expected to continue doing so in the future [13].

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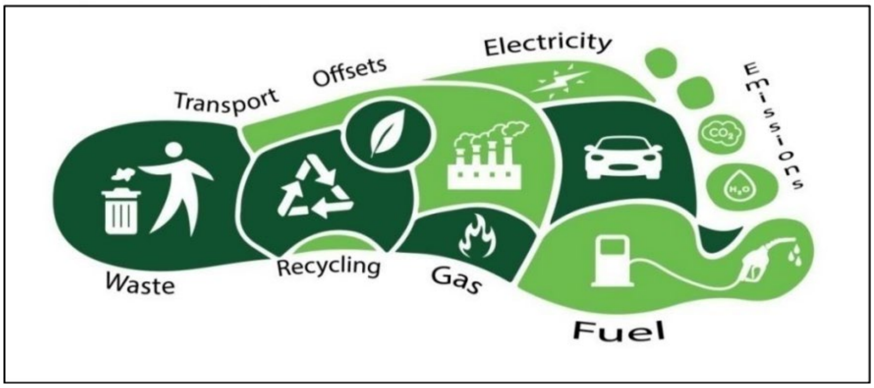

Figure 1. Overview of carbon footprint drivers and mitigation strategies

This study aims not only to examine the concept of the carbon footprint from technical and methodological perspectives, but also to investigate the role of information and communication technologies (ICT) from an interdisciplinary perspective. It offers a comparative evaluation of existing calculation methods, technological advancements, and emission mitigation strategies discussed in the literature, while also highlighting the innovative opportunities enabled by ICT-based systems. Accordingly, the primary objective of the study is to demonstrate how digital technologies can be more effectively leveraged to monitor and manage carbon footprints in alignment with sustainability goals.

2. Carbon Footprint Calculation Methodology

Determining carbon footprints is critically important for guiding sustainability initiatives, evaluating and enhancing the effectiveness of emission reduction strategies, mitigating global climate change, and understanding environmental impacts. To support these objectives, a variety of approaches, methodologies, and tools have been developed from simple online calculators for individuals and businesses to advanced, life cycle-based scientific models. These methods allow carbon footprint assessments to be conducted across multiple levels, including countries, cities, organizations, companies, households, and individuals [13]. However, despite the availability of sophisticated tools, different carbon calculators may yield inconsistent results when using similar inputs [14]. In some cases, the estimated values can differ by several metric tons per activity [15].

According to the EN ISO 14064-1 standard, greenhouse gas emissions that constitute a carbon footprint are categorized into three main scopes. Scope 1 (direct emissions) refers to emissions from sources owned or directly controlled by the organization, such as on-site fuel combustion. Scope 2 (indirect energy-related emissions) includes emissions generated during the production of electricity, heat, or steam purchased from external providers. Scope 3 (other indirect emissions) covers emissions indirectly resulting from the organization’s activities but occurring from sources not owned or controlled by the organization. This includes upstream and downstream processes such as supply chain operations, product use, and waste management [4,6].

In this context, a review of existing studies shows that carbon footprint calculations typically begin by identifying the relevant activities, products, and processes. Next, the scopes and their contents are defined. Once the scopes are established, data related to the selected activities are collected. These data are then converted into carbon dioxide equivalents (CO_2e) using appropriate unit conversions. Calculations are performed by applying emission factors corresponding to the type of energy or resource consumed. Finally, the total carbon footprint is obtained by aggregating the calculated emission values.

Although general steps for carbon footprint calculation are commonly applied in the literature, there is still no universally accepted method, standard, or consensus on how to calculate personal carbon footprints [16,17]. In most cases, carbon footprint is calculated by multiplying the activity data that cause emissions with the relevant emission factor (see Equation 1).

$$E_S = AD_S \ x \ EF_S \quad (1)$$

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Greenhouse gas emissions from a specific source (Es) are calculated by multiplying the activity data (ADs) associated with that source by the relevant emission factor (EFs). Activity data represent a quantifiable measure of resource use, such as liters of gasoline or kilowatt-hours of electricity, while emission factors are coefficients used to convert activity data into greenhouse gas emissions.

Once the total greenhouse gas emissions (CO_2, CH_4, NO_x) from all sources are calculated, they are aggregated and expressed as carbon dioxide equivalents (CO_2e) (see Equation 2). CO_2e is a standardized unit commonly used to represent greenhouse gas emissions. It quantifies the global warming potential of different gases by converting them into the equivalent amount of CO_2 [18].

$$E_s = \sum_{fuels} \left(E_{s,fuels}\right) \tag{2}$$

The emission factor and oxidation factor values used in carbon footprint calculations may vary depending on the specific methodology, standard, or guideline employed. In most studies, commonly referenced sources include IPCC Tier methods [12,19–21], the GHG Protocol developed by WRI/WBCSD [22], Annexes of relevant international agreements [23], and the UK Department for Environment, Food and Rural Affairs (DEFRA) [12]. Table 1 presents selected DEFRA conversion factors for 2024 for illustrative purposes [24].

Table 1. DEFRA 2024-based greenhouse gas conversion factors by fuel type for scope 1 and scope 2 emissions

	Fuel Type	**Unit**	**kg CO_2e**	**kg CO_2**	**kg CH_4**	**kg N_2O**
Scope 1	Natural Gas	m^3	2.04542	2.04140	0.00307	0.00095
	Coal	tonnes	2904.95234	2632	240.352	32.60034
	Gasoline	litres	2.0844	2.07047	0.00806	0.00587
	Diesel	litres	2.51279	2.47960	0.00029	0.0329
Scope 2	Electricity	kWh	0.20705	0.20493	0.0009	0.00122

The DEFRA conversion factors, which are widely used in organizational carbon footprint assessments in the UK, calculate emissions by multiplying activity data with the corresponding emission factors. Similarly, the IPCC 2006 methodology, developed as part of international greenhouse gas reporting standards, uses an emission factor-based approach to quantify emissions from energy use and industrial processes. The IPCC 2006 guidelines define three calculation tiers, namely Tier 1, Tier 2, and Tier 3, which represent different levels of methodological complexity and data specificity for estimating greenhouse gas emissions [25].

The Tier-1 method is easier to apply than the others. In this method, the emission value is calculated by multiplying the amount of fuel consumed by the emission factor and the oxidation factor (see Equation 3). The emission factor is a coefficient that varies by fuel type and is typically expressed in kilograms of gas per terajoule (kg/TJ). It represents the amount of greenhouse gases released into the atmosphere as a result of fuel combustion. In Tier 1 calculations, the oxidation factor is taken as 1 [19].

$$Emission = Fuel\ Amount\ x\ Emission\ Factor\ x\ Oxidation\ Factor \tag{3}$$

In the Tier 2 method, country-specific or region-specific emission factors and fuel properties are used to improve accuracy. The emission value is calculated as shown in Equation 4. In this equation, the calorific value refers to the lower heating value of the fuel and is expressed in kilocalories (kcal). MW represents the molar mass of carbon and carbon dioxide, expressed in grams per mole (g/mol). The symbol C denotes the carbon content percentage of the fuel by mass.

$$\begin{aligned} &Emission \\ &= Fuel\ Amount\ x\ Calorific\ Value\ x\ Carbon\ Content\ x\ Oxidation\ Factor\ x\ \frac{MWco_2}{MWc}\ x\ C \end{aligned} \tag{4}$$

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The Tier 3 method is a facility-level approach that incorporates country-specific methodologies and typically requires more detailed input data. This approach accounts for various parameters such as the type of fuel used, combustion technology, emission control methods, and maintenance practices. It also considers fuel characterization and operating conditions, all of which must be specifically determined for each facility [19].

The scope and depth of calculations vary significantly across carbon footprint assessment studies. Developed carbon calculators are designed to estimate not only individual carbon footprints but also those of organizations and products. Mulrow et al. [26] evaluated 31 publicly accessible calculators capable of estimating personal carbon footprints. Their analysis showed that simpler tools generally calculate emissions based solely on energy-related activities. In contrast, more comprehensive calculators also incorporate lifestyle and consumption factors such as diet and travel behavior. Some applications further provide tailored recommendations to help users reduce their carbon emissions. The authors emphasized that input parameters vary widely among personal carbon footprint calculators, and that no standardized framework has yet been established.

Carbon footprint calculators are also used at the organizational level. In a study conducted by Harangozo and Szigeti [27], the carbon footprint of a hypothetical company was evaluated under three scenarios involving varying energy consumption levels and supplier activity characteristics. To assess the consistency of the results, the researchers examined whether the calculators produced similar outputs when provided with identical input data. The findings revealed that the reliability of the calculators was insufficient. The authors attributed this inconsistency primarily to variations in calculation methods and emission factors [13].

Product-based carbon footprint assessments differ from individual or organizational assessments in both scope and methodology. These calculations are more complex, as they account for greenhouse gas emissions generated throughout the entire life cycle of a product. Due to the dependence on supply chain structures and life cycle stages, it is not feasible to develop a universal product-based calculator that accommodates the wide variety of product types and categories [13]. Kim and Neff [28] analyzed eight carbon calculators designed to estimate and communicate indirect emissions from food consumption in the United States of America (USA). Their study revealed that most calculators tend to overlook diet-related emissions. Moreover, they highlighted that dietary choices significantly contribute to indirect greenhouse gas emissions, underscoring the need for more robust and comprehensive calculation methodologies.

3. Carbon Emission Pricing Methods

There are two primary methods for pricing carbon emissions: carbon taxation and carbon trading. Carbon trading is a market-based approach to reducing emissions, and the Emissions Trading System (ETS) is its most widely implemented regulatory form. The carbon tax imposes a fixed price on greenhouse gas emissions for all emitters, providing a direct economic incentive to reduce emissions. In contrast, carbon trading involves setting an overall emissions cap and allowing participants who exceed their allocated limits to purchase additional emission allowances. This system requires the establishment of a functioning market for the trading of emission permits [29,30].

Although both carbon taxation and carbon trading aim to reduce emissions, they differ significantly in terms of policy design, implementation mechanisms, and potential economic impacts. These differences are summarized in Table 2 [30,31].

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Table 2. Comparative overview of carbon tax and carbon trading: key features and implementation characteristics

Feature	Carbon Tax	Carbon Trading
Emission Reduction Potential	Emission reduction is not guaranteed due to the “polluter pays” approach.	More likely to reduce emissions as it involves emission caps.
Regulatory Integration	Easier to implement as it can be integrated into the existing tax system.	Requires detailed design as it introduces a new trading mechanism.
Applicability	Can be applied to all sectors and companies emitting carbon.	Requires differentiation among sectors.
Pricing Mechanism	Prices are clear and transparent.	May create a market prone to manipulation.
Cost Impact	Creates additional costs for firms.	Offers trading opportunities that may offset costs.

Carbon prices vary significantly across countries. As of April 2024, carbon taxes and ETSs have been adopted in 75 countries worldwide. Together, these instruments cover approximately 24% of global greenhouse gas emissions. Revenues from carbon pricing mechanisms surpassed $100 billion in 2023, marking a notable increase compared to 2022. Carbon pricing is implemented through a range of policy frameworks, either at the national level or within subnational jurisdictions. As of April 1, 2024, direct carbon prices under existing tax and trading schemes range from as low as $1 to over $160 per tonne of CO_2e. In countries such as Ukraine, Argentina, and Indonesia, carbon prices remain at the lower end of the scale (approximately $1 to 5/tCO_2e$). In contrast, Switzerland, Norway, Finland, and the Netherlands report prices ranging from $90 to $120/tCO_2e$. However, most existing prices remain well below the levels required to align with the Paris Agreement targets, which are estimated to be at least $226 to 385/tCO_2e$ for 2024. According to the World Bank’s 2024 report, countries with operational carbon pricing schemes are illustrated in Figure 2 [32].

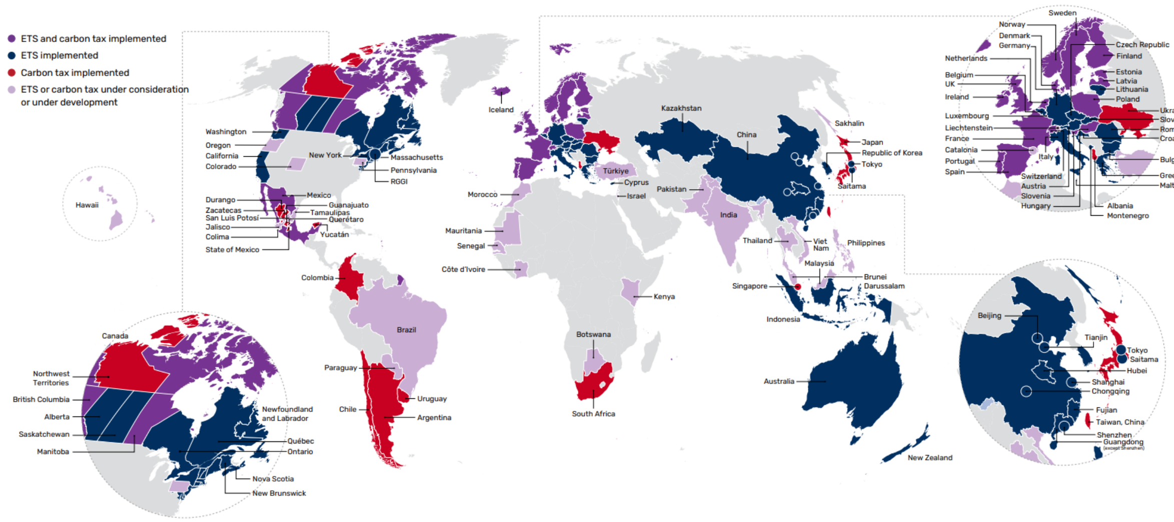

Figure 2. Worldwide Implementation of Carbon Pricing Mechanisms in 2024: ETS and Carbon Taxes

The unit cost of carbon pricing varies significantly across countries worldwide. A carbon tax is a policy instrument that imposes a fee on entities based on the amount of carbon dioxide they emit, aiming to reduce overall greenhouse gas emissions [33]. It is a widely recognized pricing mechanism and may be implemented independently or alongside emissions trading schemes. This approach offers emission-reducing entities several mitigation strategies, such as switching to low-carbon fuels, improving energy efficiency, or altering production processes and input sources. The concept of a carbon tax was first

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introduced in academic and policy discussions during the 1970s and was initially implemented by Northern European countries in the 1990s. Finland became the first country to apply a national carbon tax in 1990, targeting fossil fuel consumption in sectors such as transportation, electricity generation, and heating [30].

In addition to carbon taxation, carbon trading is a market-based mechanism designed to lower the overall cost of reducing greenhouse gas emissions from human activities [5]. It contributes to both air quality improvement and climate change mitigation, which are essential goals in addressing global warming. The carbon trading system requires companies to limit their greenhouse gas emissions to predefined thresholds and to verify their emissions through certifiable units that can be traded in the market. Within this system, emission allowances can be bought and sold among regulated entities. These certificates represent a quantifiable amount of emissions; for example, one allowance may correspond to one metric ton of carbon dioxide equivalent (CO_2e) [5,34].

Historically, the first emissions trading scheme originated from the Acid Rain Program, which was established under the Clean Air Act Amendments of 1990 to reduce sulfur dioxide (SO_2) emissions, especially within the electricity generation sector [35]. Subsequently, the European Union Emissions Trading System (EU ETS), recognized as the world's largest carbon market, was launched in 2005 [30,36].

Expanding beyond internal market mechanisms, the European Green Deal proposes the implementation of carbon border adjustment mechanisms to extend carbon taxation to products imported into the European Union (EU). It outlines targets across key sectors, including clean energy transition, biodiversity, sustainable industrial and food systems, construction and renovation, and zero pollution. Among the instruments developed to meet these objectives, the carbon border adjustment mechanism is designed to impose a carbon price on imports from non-EU countries in order to prevent carbon leakage and reduce global emissions [37]. This mechanism introduces a carbon levy on specific imported product groups, such as cement, fertilizers, aluminum, electricity, and iron and steel products. Over time, the list has expanded to include raw materials like agglomerated iron ore, ferrochrome, ferromanganese, and kaolin. In addition, manufactured goods such as hydrogen, screws, and bolts, which fall under the iron and steel category, have also been added to the scope. The implementation of this mechanism is expected to negatively impact the export competitiveness of carbon-intensive products and sectors, particularly in countries that trade extensively with the EU. However, during the transitional phase of the mechanism, which will run from 2023 to 2026, no financial payments are expected [38].

4. Literature Review

According to IPCC's Sixth Assessment Report published in 2023, as of 2019, 34% of global greenhouse gas emissions originated from the energy sector, 24% from industry, 22% from agriculture, forestry, and land use, 15% from transportation, and 6% from buildings [39]. These findings underscore the critical importance of transitioning to low-carbon technologies, particularly within the energy sector, which is the largest source of emissions. For instance, while coal-fired power plants are estimated to emit between 675 and 1689 gCO_2e/kWh over their life cycle [40], renewable sources such as offshore wind energy can reduce this figure to as low as 5.3-13 gCO_2e/kWh [41]. Furthermore, life cycle assessments of solar and wind systems demonstrate that improvements in the design and deployment phases of these technologies can play a decisive role in reducing emissions [42]. Comparative analyses covering all stages of energy production reveal that fossil fuels have the highest life cycle emissions, whereas nuclear, hydroelectric, and wind power exhibit the lowest emission levels [43].

As digitalization accelerates, the share of the ICT sector in global greenhouse gas emissions is increasing significantly, and its long-term impact is expected to become even more substantial. Indeed, some projections indicate that the ICT sector's contribution to global greenhouse gas emissions could reach as high as 23% by 2030 [44]. Freitag et al. [45] report that the ICT sector currently accounts for between 1.8% and 2.8% of global emissions. However, when the full upstream supply chain and life-cycle emissions are considered, this estimate may increase to between 2.1% and 3.9%. At this stage, selecting regions and time periods with lower carbon intensity becomes essential for minimizing emissions. Dodge et al. [46] propose a framework for evaluating the carbon intensity of software on cloud platforms and emphasize that the environmental impact of computing operations varies depending on when and

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where they are executed. Accordingly, users are encouraged to utilize cloud resources during times and in locations with lower carbon intensity to minimize their environmental impact.

The environmental footprint of artificial intelligence (AI) systems has emerged as an increasingly critical issue. Kirkpatrick [47] highlights that both the training and deployment of large-scale AI models entail substantial energy consumption, consequently resulting in significant CO_2 emissions. This impact is further exacerbated when data centers are powered by fossil fuel-based energy sources. Similarly, Yu et al. [48] estimate that the cumulative annual carbon footprint of 79 AI systems released between 2020 and 2024 may reach 102.6 $MtCO_2e$, highlighting the necessity of regulatory interventions in the sector. The environmental implications of AI-assisted software development have also become a key area of investigation. Cheung et al. [49] show that software development using large language models (LLMs) produces, on average, 32.72% more carbon emissions than conventional manual development approaches.

Blockchain technologies and bioinformatics have become increasingly scrutinized due to their high energy demands. Bitcoin's annual electricity consumption is reported to be approximately 45.8 TWh, with corresponding carbon emissions ranging from 22.0 to 22.9 $MtCO_2e$ [50]. These levels are comparable to the annual greenhouse gas emissions of certain nations. In bioinformatics, computationally intensive tasks such as genetic analyses and biological simulations have been shown to consume substantial amounts of energy, which in turn generates a considerable carbon footprint. To address this issue, Grealey et al. [51] suggest various mitigation strategies, including software optimization, careful hardware selection, and enhancements in data center efficiency.

While ICT is an emissions-intensive sector, it also holds substantial potential to serve as a tool for emissions mitigation. This duality is evident across sectors and applications, typically supported by empirical research and field implementations. In particular, AI and machine learning (ML) have been applied in industries such as manufacturing, agriculture, and logistics to reduce carbon emissions.

In a large-scale empirical study, Lu and Liau [52] found that a 1% increase in AI adoption across industrial enterprises resulted in a 0.0395% reduction in sectoral carbon emission intensity. Likewise, Rajendiran et al. [53] showed that ML-based forecasting and logistics optimization algorithms, such as Random Forest and Gradient Boosted Machines, can effectively reduce transport-related emissions in the e-commerce sector.

Ji et al. [54] highlighted the potential of digital agriculture for both direct and indirect emission mitigation. By integrating IoT, big data, blockchain, and modular greenhouse systems, the study demonstrated how agricultural productivity can be enhanced while enabling the quantification and trading of carbon sinks. Their proposed architecture combines renewable energy systems with green production and finance modules. Nonetheless, infrastructural disparities and limited digital access in rural areas remain key barriers to implementation.

In a field-based case study, Andrae et al. [55] proposed a practical energy-saving model for the ICT supply chain. Accelerated life cycle assessments were conducted on four ICT products (one modem and three access modules), identifying high-impact components. On-site energy audits were then carried out in accordance with the International Performance Measurement and Verification Protocol (IPMVP), followed by the implementation of energy conservation measures. These efforts led to annual savings of 27,000 MWh of energy and 25,700 tons of CO_2e, amounting to a 1% reduction in the operator's Scope 3 emissions.

In addition to these applications, it has been demonstrated that artificial intelligence can, in certain domains, have a lower carbon footprint than human labor. Tomlinson et al. [56] report that AI systems emit 130 to 2,900 times less CO_2 than humans when performing tasks such as writing and image generation. However, these findings do not account for broader dimensions such as social implications and transformations in the labor market.

Personal carbon footprint analysis is regarded as an effective tool for shaping individual decision-making and enhancing environmental awareness. Nevertheless, estimates based on static methodologies have shown limited effectiveness in influencing behavioral change [26]. In this context, Rahman et al.

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[15] proposed a specialized framework called the Open Carbon Footprint Framework, which could serve as a foundation for the development of carbon footprint calculation applications. This framework provides developers with access to a cloud-based information infrastructure that supports the integration of real-time sensor data, offering a dynamic and responsive resource for emissions estimation. Based on this framework, an application named the Ubiquitous Carbon Footprint Calculator was developed, enabling users to calculate their carbon footprints. This application allows users to monitor their emissions regardless of location and supports conscious decision-making related to environmental impact. Furthermore, the design and features of a mobile Global Positioning System (GPS) application, developed specifically for the iPhone platform, are detailed. This GPS-based application is capable of suggesting the most environmentally friendly route to the user, thereby enhancing fuel efficiency and reducing emissions. The functionality and applicability of the study are demonstrated through two example scenarios. In the first scenario, a graduate student working in a laboratory equipped with smart sensors is shown to reduce their carbon footprint by optimizing indoor heating. Temperature and humidity data obtained from the student's smartphone are combined with environmental data from external sensors to calculate real-time emissions. The application provides instant feedback and recommends actionable strategies, such as adjusting the ambient temperature, to lower energy-related carbon output. The second scenario focuses on the behavior of a sales representative who is frequently on the move. The system tracks the representative's travel routes via GPS, generates speed profiles to evaluate driving efficiency, and proposes alternative, lower-emission routes. In addition, the application encourages emission reduction by enabling users to carpool with others who share similar travel paths, further contributing to sustainable mobility.

Andersson [16] developed a mobile application in Sweden that estimates users' greenhouse gas emissions through a hybrid approach combining user-provided data, official government records, and financial transaction data. The system utilized these three data sources to generate individualized carbon footprint estimates. In particular, users could link their private bank accounts and credit cards to the app, allowing financial transactions to be analyzed and matched with Sweden-specific multi-regional environmental input-output data. By categorizing spending across different consumption domains, the system enabled the estimation of emissions associated with various activities. All data transmissions were encrypted and stored on secure servers in compliance with Swedish and European Union regulations. Users' expenditures were classified based on financial transaction data, allowing for detailed insights into their carbon profiles. Depending on the policies of individual banks, the system could access transaction histories ranging from three months to five years. This historical data allowed users to monitor the evolution of their carbon footprints over time. Emission estimates were calculated using GWP100 (Global Warming Potential over 100 years) conversion factors integrated into the application.

One of the key components of a carbon footprint is emissions generated by transportation activities. Therefore, accurately tracking and monitoring transportation-related emissions through carbon footprint calculators is essential for reducing global greenhouse gas outputs. In this context, Ajufo and Bekaroo [57] developed a personal, transportation-based carbon footprint calculator called TCTracker, which eliminates the need for manual data entry. The mobile application leverages GPS functionality and built-in artificial intelligence to monitor user behavior and estimate emissions. In a related effort, Wang et al. [58], addressed carbon reduction in the petroleum distribution network by formulating and solving a low-carbon inventory routing problem. Their model aims to minimize total costs while accounting for carbon emissions. To solve the model, they proposed a hybrid approach that combines an adaptive genetic algorithm with a greedy algorithm, and they validated its performance using a practical case study. The study was structured in two parts: the first part examined model effectiveness under varying carbon tax scenarios, and the second part applied the model to optimize routing for petroleum tankers with different loading capacities. Similarly, Jabali et al. [59], investigated the trade-offs among carbon emissions, travel time, and fuel consumption in time-dependent vehicle routing problems using a tabu search algorithm. Their study also discussed the implications of setting carbon emission thresholds in transportation planning. In the aviation sector, Tsai et al. [60], introduced a mixed activity-based costing decision model for green fleet planning. They evaluated how carbon emissions affect the operating costs of airline logistics under the regulatory constraints of the European Union Emissions Trading Scheme.

In addition to academic research, many companies also engage in efforts to reduce their carbon footprints by providing consumers with sustainability ratings or certifications for the services and

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products they offer. Such initiatives not only promote consumer awareness but also help influence user preferences by offering environmental information about the purchased product or service. For example, Booking.com [61] has classified the sustainability ratings of many hotels listed in its database into four levels, based on 29 criteria related to waste management, water consumption, energy and greenhouse gas emissions, location and community impact, and nature conservation. This categorization enables consumers to make informed decisions regarding the environmental performance of their accommodation choices. In the aviation sector, Travalyst [62], in collaboration with Google, has developed the "Travel Impact Model" (TIM), a framework that calculates the life cycle emissions of flights. Similarly, platforms such as Skyscanner [63] and Google Flights [64] provide users with estimated carbon emission data for selected flights. These calculations are based on several criteria, including travel distance, cabin class, baggage allowance, and aircraft type. These examples illustrate how environmental transparency in consumer services contributes to the foundation of individual carbon emission tracking and management. While the number of such implementations continues to grow, their common objective is to empower individuals to make environmentally responsible decisions in daily life.

5. Results and Discussion

This section provides a multidimensional analysis of the methodological diversity in carbon footprint assessment approaches and the current trends shaping this field. In addition to the dominant traditional, static calculation methods in the literature, newer models supported by real-time data and emerging technologies are comparatively examined. The potential of user-centered applications designed to influence daily lifestyle choices, the contribution of corporate transparency in product and service-level emission data to decision-making processes, and the dual role of ICT in both increasing and reducing carbon emissions are also discussed. Throughout the section, ICT-based solutions developed across different sectors are evaluated to explore their contribution to environmental sustainability from a broad and integrated perspective.

The concept of carbon footprinting remains fundamental to assessing the environmental impact of individuals, organizations, and products. Conventional carbon footprint calculation methods typically aim to quantify this impact by measuring greenhouse gas emissions arising from energy consumption, transportation, production, and related activities. In addition to these traditional approaches, recent studies have introduced dynamic models and analytical techniques that consider temporal variability in environmental impacts and emissions to obtain more precise results [16,57]. These contemporary approaches emphasize the use of real-time data enabled by emerging technologies, including sensor systems and smart devices. As a result, research in carbon footprinting is advancing significantly, offering deeper insights into environmental effects, supporting the achievement of sustainability goals, and contributing to the development of more effective strategies to mitigate global climate change. This dual function of ICT highlights the necessity for balanced strategies that can simultaneously leverage its monitoring and optimization capabilities while minimizing its environmental costs.

Traditional studies on carbon footprint assessment lack the ability to dynamically update data in response to user actions due to their static structures. Although there are sector-based or scenario-specific dynamic applications such as route optimization for vehicles [55,58] and electricity consumption optimization[52,54] that consider the carbon footprint, comprehensive systems capable of guiding daily life remain insufficient. In this context, the development of a smart carbon optimization application that incorporates carbon footprint considerations and facilitates daily living, potentially even offering actionable recommendations, would be highly beneficial. By processing data collected through personal smartphones, smartwatches, or various sensors, a dynamic system can be developed that not only offers users novel and unconventional experiences but also contributes to reducing their carbon footprint. A multi-criteria application that provides guidance on topics such as public versus private transportation, fuel types like gasoline or diesel, route planning, accommodation and facilities, food choices, lighting, and heating, based on cost, carbon footprint, and time, could significantly enhance both awareness and the adoption of more environmentally friendly lifestyles at the individual level. Furthermore, environmentally conscious behaviors such as support for recycling should also be taken into consideration in reducing carbon footprints. For example, recyclable waste deposited in smart recycling machines should be recognized as a positive contributor to an individual's overall carbon reduction.

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In addition to behavior-responsive applications, infrastructure-level strategies play a critical role in reducing the environmental impact of digital systems. One promising solution is the broader adoption of edge computing architectures in place of centralized cloud systems. By enabling local data processing, edge computing minimizes the energy demands of large-scale data centers while also improving latency. This approach is particularly relevant in applications involving IoT, artificial intelligence, and mobile services, where both responsiveness and efficiency are key concerns. Reducing ICT-related emissions also requires a shift toward low-carbon energy sources. Data centers and digital platforms should prioritize the use of electricity generated from renewable energy. Moreover, geographical and temporal optimization—executing high-energy tasks in regions and at times with lower grid carbon intensity—can play a significant role in emission reduction. Encouraging cloud service providers to implement carbon-aware scheduling and infrastructure planning can help align digital growth with climate goals.

The implementation of environmentally friendly policies by businesses can pave the way for more comprehensive efforts and contribute to the development of emission reduction mechanisms. By transparently presenting sustainability assessments of their products and services or disclosing emission data obtained through product life cycle analyses, businesses can play an active role in decision-making processes. The data provided by companies may serve as a valuable resource for the learning mechanisms of intelligent systems. Furthermore, such data can help lay the groundwork for autonomous software that functions as an assistant by evaluating not only time and cost but also emission-related expenses. Moreover, integrating energy-efficient coding practices and carbon-aware software design into corporate digital services could enhance environmental performance across the software lifecycle. Carbon labeling of software products may also help users and institutions make more informed choices.

Another noteworthy point is that ICT has both increasing and decreasing effects on the carbon footprint across various sectors. For instance, the use of artificial intelligence systems can be considered a significant source of emissions [48,49]. However, these systems can also contribute to emission reduction by enhancing efficiency [58,59]. Similarly, while energy efficiency improvements in the manufacturing industry can help control carbon emissions [52], the high energy consumption of data centers may increase the environmental burden [47]. In the retail and e-commerce sectors, AI-supported supply chain planning and demand forecasting algorithms help prevent overstocking, thereby reducing emissions related to production and transportation [53]. In the transportation and logistics sector, GPS-based route optimization and fleet management systems reduce fuel consumption and thus contribute to lower emissions [59,60]. Nevertheless, the carbon footprint of ICT-based solutions themselves, particularly stemming from the hardware and infrastructure used in data processing, storage, and transmission, should not be overlooked [49,50]. This dual impact reveals that ICT can serve both as a means of promoting sustainability and as a potential source of environmental concern. Beyond infrastructure and corporate design, digital tools at the individual level should evolve from merely providing information to actively guiding low-carbon behavior. For instance, mobility apps can suggest routes based on minimal emissions rather than just cost or speed, while e-commerce platforms could display the carbon impact of products to support sustainable consumption.

6. Conclusion

This study examined the evolution of carbon footprint assessment approaches, focusing particularly on the integration of ICT into sustainability efforts. The findings emphasize a shift from conventional, static models to dynamic, user-responsive, and data-driven systems supported by real-time analytics. ICT-based tools have demonstrated significant potential in enhancing carbon monitoring, guiding behavioral changes, and optimizing resource usage across sectors.

Nevertheless, ICT itself is a contributor to global emissions due to the high energy demands of data centers, cloud infrastructures, and AI-based applications. This dual role of ICT as both an enabler and a driver of emissions calls for balanced strategies that simultaneously leverage its capabilities and minimize its environmental footprint. Key recommendations include the adoption of edge computing architectures, carbon-aware infrastructure planning, renewable energy integration, and energy-efficient software development practices. Furthermore, encouraging corporate transparency, carbon labeling of digital services, and behavior-oriented user interfaces are critical in aligning technological innovation with sustainability goals.

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Future research should evaluate the real-world feasibility, scalability, and cross-sector applicability of these approaches. It is essential to examine how ICT-driven systems can be effectively embedded into institutional, infrastructural, and behavioral frameworks. Policy incentives, regulatory support, and interdisciplinary collaboration will play a vital role in ensuring that these tools are not only technologically sound but also socially acceptable and ethically robust. Exploring how individuals respond to carbon-aware digital systems and how these influence long-term behavioral change also presents a valuable direction for further investigation.

In conclusion, the sustainable digital transformation of carbon footprint assessment requires more than technological advancement. It demands systemic thinking, collective responsibility, and alignment between digital innovation and environmental ethics. ICT should be seen not only as a source of impact but as an integral part of the solution in the transition toward a low-carbon future.

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