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Analysis of the industrial companies' ecological impact within the scope of stable growth

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ABSTRACT: The article examines the ecological footprint of industrial enterprises within the framework of sustainable development, viewing it as a key indicator of anthropogenic pressure on the environment. The assessment of the ecological footprint allows for a comprehensive understanding of the imbalance between resource consumption and the biocapacity of territories. It reflects not only the scale of energy use and emissions but also the effects of water withdrawal, material flows, and spatial infrastructure on ecosystem sustainability. The study employs an integrated five-component model including energy, water, material, waste, and infrastructure components. All indicators are converted into global hectares according to the Global Footprint Network's methodology. Based on official statistics for six central regions of Ukraine during 2021–2024, the analysis reproduces the dynamics of resource consumption and pollution by industrial enterprises. Results show that the energy component dominates the ecological footprint structure (over 90%), confirming the industry's strong dependence on fossil fuels. Other components, such as water, materials, waste, and infrastructure, contribute less but remain significant. While 2021–2023 indicated a decline in resource intensity and emissions, a moderate rebound in 2024 revealed a persistent environmental imbalance. The proposed model supports eco-passporting of enterprises, regional monitoring, and modernization programs using the best available technologies.
Keywords: ecological footprint; industrial enterprises; sustainable development; biocapacity; carbon emissions; resource efficiency.

Análise do impacto ecológico das empresas industriais no âmbito do crescimento sustentável

RESUMO: O artigo analisa a pegada ecológica das empresas industriais no contexto do desenvolvimento sustentável, considerando-a um indicador-chave da pressão antrópica sobre o meio ambiente. A avaliação da pegada ecológica permite compreender, de forma abrangente, o desequilíbrio entre o consumo de recursos e a biocapacidade dos territórios. Ela reflete não apenas a escala do uso de energia e das emissões, mas também os efeitos da captação de água, dos fluxos de materiais e da infraestrutura espacial sobre a sustentabilidade dos ecossistemas. O estudo utiliza um modelo integrado de cinco componentes: energia, água, materiais, resíduos e infraestrutura. Todos os indicadores foram convertidos em hectares globais de acordo com a metodologia do Global Footprint Network. Com base em estatísticas oficiais de seis regiões centrais da Ucrânia, referentes ao período de 2021 a 2024, a análise reproduz a dinâmica do consumo de recursos e da poluição gerada pelas empresas industriais. Os resultados mostram que o componente energético domina a estrutura da pegada ecológica (mais de 90%), o que confirma a forte dependência do setor industrial de combustíveis fósseis. Embora 2021-2023 indiquem redução na intensidade de recursos e de emissões, uma recuperação moderada em 2024 revela um desequilíbrio ambiental persistente. O modelo proposto apoia a elaboração de eco-passaportes empresariais, o monitoramento regional e a implementação de programas de modernização com base nas melhores tecnologias disponíveis.
Palavras-chave: pegada ecológica; empresas industriais; desenvolvimento sustentável; biocapacidade; emissões de carbono; eficiência dos recursos.

1. INTRODUCTION

The global model of economic development, which has long been based on the idea of continuous growth in the production of goods and services, increasingly contributes to the deepening of anthropogenic environmental degradation, as its implementation is accompanied by the destruction of biodiversity, disruption of ecosystem integrity, climate change and a decrease in the ability of natural systems to perform vital ecosystem functions. As early as the second half of the twentieth century, the limitations of this model became apparent, as evidenced by the work "Limits to Growth" (1972), prepared for the Club of Rome by D. Meadows and co-authors, which substantiated the need to move to the paradigm of sustainable development (MUTHU, 2024).

The concept of sustainable development is to ensure a balanced interaction between the society-environment system, taking into account the needs of modern generations and guaranteeing the preservation of the resource base for the future. To identify key sustainability issues and risks, a wide range of methods have been developed that cover different scales, from local business facilities to global processes. The central task of the scientific and applied debate has been to identify integral indicators that can reflect the relationship between economic growth and environmental constraints (KHEZRI; MAMKHEZRI, 2025).

One of the most common and well-founded indicators in this context is the Ecological Footprint (EF), which can correlate the actual consumption of natural resources by industrial enterprises with the renewable potential of the biosphere or the biocapacity of the territory. It is from these principles that the relevance of the study is formed, since the actual use of the EF indicator in combination with the assessment of biocapacity forms a new system of environmental accounting that will provide a comparison of demand for resources and their supply, and therefore will help to more clearly and deeply determine whether our natural environment can support the current level of industrial consumption in the conditions of the desired and targeted sustainable development.

The purpose of the article is to study the methodological and applied framework and to develop and test an integrated methodology for assessing the size of the ecological footprint of industrial enterprises in the context of sustainable development.

2. LITERATURE REVIEW

In the base of scientific papers related to the research topic, considerable attention was paid to the search for effective methodological tools aimed at taking into account both economic and socio-environmental factors of production systems. Researchers such as Budihardjo et al. (2013) and Li; Zhang (2025) emphasize that penalties for environmental damage in many cases do not correspond to the scale of real environmental damage and environmental consequences, which reduces the incentives of enterprises to green production. A significant contribution to the development of this topic was made by Kupalova et al. (2025), Makedon et al. (2025), and Sheng et al. (2024), who described internal environmental control systems and showed that environmental activity of an enterprise can be associated with optimizing compliance costs and avoiding fines. At the same time, the areas of measuring the real impact of such measures on the integrated environmental footprint remain insufficiently developed, as most studies are limited to analyzing individual processes and do not form a holistic assessment of the environmental footprint of industry.

A significant role in the formation of scientific approaches to the identification of the issue of "ecological footprint" was played by Hess (2024), Li et al. (2024), and Petrova (2023). The results of the research of this group of scientists demonstrated that enterprises that consistently go through the stages of environmental transformation increase their competitiveness and reduce the burden on the environment. At the same time, the authors note that the pace of adaptation to the new standards remains an issue, especially in countries with a less developed industrial base, where lack of adequate funding and technological support makes it difficult to implement green economy concepts and assess the formation of an environmental footprint.

Researchers such as Huang et al. (2025), Wang et al. (2024), Wojciechowski. Domański (2024), Mia et al. (2022), and Voronina et al. (2024) have developed alternative strategies for greener production, including environmental monitoring, identification of pollution factors, verification of compliance with international standards, and implementation of self-assessment of ecological footprint and burden. However, in the end, the authors do not see any conclusions that state the need for deeper integration of such assessment practices into national and regional sustainable development policies, as well as the need to develop universal indicators that can compare the results of different industrial enterprises to compare the size of the environmental footprint.

Interesting are the works of Mammadova et al. (2025), Pacana et al. (2024) and Sun et al. (2024), which focus on the development of environmental sustainability indices that include a system of indicators for emissions, waste, water and air quality. Their use allows assessing not only the state of the environment at the city level, but also the environmental footprint of industrial enterprises. At the same time, existing indices are often characterized by a high dependence on specific statistical sources and do not take into account the regional specifics of industrial loads, which limits their versatility.

Madjidova et al. (2021) and Odrekhivskyi et al. (2025), who developed methods for predicting environmental risks and economic losses due to emergencies, propose grouping factors according to different projections, including technological characteristics of production, quality of management, and the impact of external risks. The results of the tests showed the ability of the methods to predict the likelihood of negative consequences and determine the extent of damage. At the same time, a small amount of research was carried out in relation to the further integration of the methods into the ecological footprint management system under normal conditions of enterprise operation, when emergencies are not the only source of negative impact.

The development of algorithms and integral indices for assessing environmental impact has taken its place in scientific research, as it can be seen in the published research of Caetano et al. (2024), Khezri et al. (2023), Wang and Xu (2025), and Sumets et al. (2022a, 2022b). All of these tools identify numerous pollution factors, classify them by level of significance, and calculate generalized indicators of environmental hazard. However, the problem remains their complexity for practical use by enterprises and authorities, as they require significant amounts of reliable data that are not always quickly available for calculation. Thus, the authors have obtained a review result that scientists have indeed made a significant contribution to the development and testing of methodological approaches, indicators and models for managing the ecological footprint of industrial enterprises. However, there is still no single integrated system that would simultaneously take into account global standards, national characteristics and industry specifics.

3. RESEARCH METHODS

The study used an adapted methodology for assessing the ecological footprint of industrial enterprises in the Central regions of Ukraine (Kyiv, Cherkasy, Poltava, Kirovohrad, Dnipro, Vinnytsia) based on the international practice of assessment by the Global Footprint Network. The basic premise of the integrated industrial environmental impact assessment was to measure the area of biologically productive land and water areas required to restore used resources and absorb pollution. Unlike classical approaches that are focused mainly on the agricultural sector, the developed model takes into account the specifics of industry, such as energy intensity of production, high emissions, infrastructure space, and waste. The total environmental footprint of industrial enterprises is defined as the sum of five components:

$$EF = EF_{en} + EF_{wat} + EF_{mat} + EF_{wst} + EF_{inf} \quad (01)$$

where: EF_{en} – is the energy footprint calculated by converting energy consumption into the area of forest ecosystems; EF_{wat} – is the water footprint, which takes into account industrial freshwater intake; EF_{mat} – is a material and raw material footprint based on the consumption of metals, cement and other resources; EF_{wst} – is the waste and emissions footprint, which is determined by the amount of CO_2 and solid industrial waste; EF_{inf} – is the infrastructure footprint, which reflects the area of land occupied by industrial zones.

The statistical base of the study was formed on the basis of official data from the State Statistics Service of Ukraine, annual environmental reports of regional state administrations, and sectoral fuel and energy balances for 2021-2024. For each year, the indicators of energy consumption, water intake, use of basic raw materials, waste generation and industrial land area are collected and presented in Appendix A.

4. RESULTS

4.1. Global trends in the formation of the ecological footprint and the growth of the anthropogenic burden of industry

Over the past five decades, the size of humanity's ecological footprint has increased by almost 190%, indicating a dangerous increase in the imbalance in the interaction between society and the natural environment, when the rate of resource use and the pace of industrial expansion far exceed the capacity of the biosphere to regenerate itself, accompanied not only by profound environmental transformations but also by significant socio-economic changes (EUROPEAN COMMISSION, 2021). According to Global Footprint Network analytics, sustainable development is possible only when humanity meets basic needs without critical depletion of the planet, which is scientifically expressed through two key indicators: first, the ecological footprint, which, in the case of a stable ratio of population and available resource area, should not exceed 1.7 global hectares per person, and second, the Human Development Index (HDI), whose value above 0.7 is defined as an indicator of a high level of well-being and social progress. The combination of these criteria allows us to state the minimum conditions for achieving a balance between economic growth and the preservation of natural capital, because true sustainability means ensuring a decent standard of living within the ecological capacity of the planet (GLOBAL FOOTPRINT NETWORK, 2025). The dynamics of the HDI growth – from 0.55 in 1990 to 0.7 in 2024 – demonstrates the improvement of social parameters, but at the same time emphasizes the aggravation of the environmental crisis, as since 1970 the growth rate of the ecological footprint has consistently exceeded the growth of global biocapacity, which has led to a deficit of ecological capital of more than 8.3 billion global hectares. The authors emphasize that the root cause of these consequences was the large-scale excess and overuse of fossil fuels, which are the basis for the work of the world's industries (OECD, 2025).

During this period, the proven biocapacity of the planet has decreased by almost three times. Since the early 1970s, the ecological footprint has systematically exceeded the regenerative potential of the biosphere, which actually means the constant use of more environmental resources than nature is able to reproduce within one generation. The authors define the main structural component of the ecological footprint as the carbon footprint, which estimates the total amount of greenhouse gas emissions that are directly or indirectly caused by the production and economic activities of enterprises or are formed at different stages of the life cycle of industrial products (Figure 1) (GU et al., 2014).

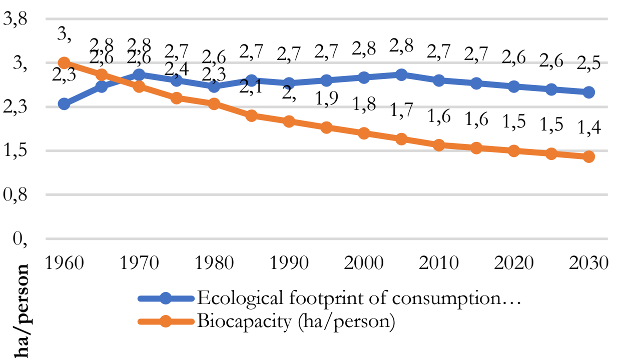

Figure 1. Dynamics of the ecological footprint of consumption and biocapacity per capita in the world (1960-2030).
Figura 1. Dinâmica da pegada ecológica de consumo e da biocapacidade per capita no mundo (1960–2030).
Source: built by the author based on Global Footprint Network (2025)

This indicator is the most dynamic and fastest growing. While in 1961 its share was about 44% in the structure of the global ecological footprint, in 2014 it exceeded 60%, indicating an increased dependence of the world economy on fossil fuels and energy-intensive technologies. Globally, as of 2020, more than 32% of greenhouse gas emissions were accounted for by electricity generation, 15.5% by transportation, 13.2% by manufacturing and construction, and 12.5% by agriculture. In the European Union in 2022, the largest sources of emissions were the energy sector (26.6%), domestic transportation (23%), and industrial production (19.6%), which confirms the growing role of industrial enterprises in shaping the carbon component of the ecological footprint (UNIDO, 2022; GLOBAL FOOTPRINT NETWORK, 2025).

Significant greenhouse gas emissions, especially carbon dioxide, have become the main source of environmental debt, as their volumes exceed the absorption capacity of natural ecosystems. Recent statistics show that in 2024, the total global biocapacity was about 1.62 global hectares per person, while the ecological footprint reached 2.85 global hectares per person, which means a deficit of more than 1.23 global hectares. The carbon footprint, formed mainly by industry and the energy sector, increased to 1.75 global hectares per person, which is more than 60% of the total environmental burden (Table 1).

Table 1. Environmental debt and biocapacity of the world in 2024 (global hectares per person).
Tabela 1. Dívida ambiental e biocapacidade do mundo em 2024 (em hectares por pessoa).

Category	Biocapacity	Ecological footprint	Deficit/ Surplus
Built-up land	0.06	0.07	-0.01
CO_2 emissions	0.00	1.75	-1.75
Arable land	0.52	0.54	-0.02
Fishing grounds	0.14	0.10	+0.04
Forest lands	0.70	0.26	+0.44
Pastures	0.20	0.13	+0.07
In total	1.62	2.85	-1.23

Source: compiled by the author based on Global Footprint Network (2025).
Fonte: compilado pelo autor com base no Global Footprint Network (2025).

The biocapacity of arable land and pastures remains relatively stable, but fishing and forest lands are declining, which increases the vulnerability of the ecological balance. The situation in industry and construction is aggravated by the fact that these sectors generate a significant portion of emissions and waste that are not compensated for by natural mechanisms. Developed countries have managed to reduce emissions growth rates to some extent due to the development of renewable energy sources, the transition from coal to natural gas, and increased nuclear power production. However, these positive changes are offset by an increase in energy consumption in developing countries, where industrial growth is often not accompanied by proper control over the level of environmental burden. As a result, although there was a temporary decline in emissions in 2020 during the pandemic recession, they stabilized at a high level again in the following years.

4.2. Methodological approaches to assessing the environmental footprint of industrial enterprises in the context of sustainable development

There are several approaches to assessing the environmental footprint of industrial enterprises in the world, which differ in their impact on decision-making. The marginal approach is the most formalized and focuses on creating reports with general recommendations that rarely affect management processes. Nevertheless, even such assessments are of some importance, as they allow accumulating data on the state of the environment, testing analysis methods, and creating a basis for further research (MAKEDON et al., 20220; SHMATKOVSKA et al., 2022). The compliance approach has clearer outlines, as it involves verifying compliance with environmental legislation and standards by enterprises, which effectively reduces it to the functions of state environmental expertise or environmental impact assessment. The constructive approach, which is considered the most promising in modern science and practice, is aimed at actually integrating the assessment results into strategic decision-making processes. Its peculiar feature is the ability to take into account not only the regulated parameters, but also global challenges, trends in resource exhaustion, climate risks, and the requirements of the concept of sustainable development, so that the ecological footprint is used as a basic indicator for developing scenarios for industrial modernization (Table 2) (FENG; BAO, 2024).

Table 2. Approaches to assessing the ecological footprint of industrial enterprises
Tabela 2. Abordagens para a avaliação da pegada ecológica das empresas industriais

Methodological approach	Characteristics of the impact	Level of integration into sustainable development
Marginal approach	It is limited to the preparation of formal reports on the state of the environment and social sphere with minimal recommendations; it has little impact on management decision-making, but contributes to the accumulation of statistics and testing of methods.	A very low environmental footprint is considered only as a background indicator.
Compliance approach	The main function is to verify compliance with environmental legislation and standards; it is used in the form of environmental impact assessment or environmental impact assessment; it is useful for preventing negative consequences of projects.	Medium ensures environmental safety of projects, but is limited by regulatory criteria.
Constructive approach	Aimed at integrating ecological footprint assessment into strategic management decisions, it takes into account global challenges, sustainable development goals and climate risks; used to develop scenarios for industrial modernization.	High ecological footprint becomes a key indicator of the sustainable development of enterprises.

Source: compiled by the author based on Oprea et al. (2024) and Hess (2024).
Fonte: compilado pelo autor com base em Oprea et al. (2024) e Hess (2024).

The integration of the assessment of the ecological footprint of industrial enterprises into the concept of sustainable development is of crucial theoretical, methodological and practical importance, as it allows to correlate economic, social and environmental priorities in the long term (MAKEDON et al., 2024b). In this context, international documents play a special role, primarily the UN Agenda 2030, which sets guidelines for countries to adapt the Sustainable Development Goals (SDGs) to national conditions and to develop strategies, programs, and plans that take into account environmental risks. The importance of the SDGs lies not only in the development of new policies at the global and national levels, but also in the development of tools to assess their effectiveness, including through the analysis of the environmental footprint of industrial enterprises that directly affect emissions, natural resource use, and biocapacity (OPREA et al., 2024; PETRUKHA, 2021). The experience of leading countries demonstrates that modern industrial policy is increasingly based on the principles of best available technologies (BAT), which are considered regulatory benchmarks for regulators and industry. It is the application of BAT that allows combining economic benefits with environmental safety, stimulates innovation, and creates conditions for modernizing production in a low-carbon direction. At the same time, the SDGs form a system of integrated indicators, among which the ecological footprint occupies a key position as a universal indicator of anthropogenic pressure on the environment (CHAURASIA et al., 2024). For industrial enterprises, this indicator is of particular importance, as it allows assessing the balance between resource consumption and the ability of ecosystems to recover (Table 3).

Table 3. Interrelation of sustainable development goals and assessment of the ecological footprint of industrial enterprises (2024).
Tabela 3. Inter-relação entre os Objetivos de Desenvolvimento Sustentável e a avaliação da pegada ecológica das empresas industriais (2024).

UN SDGs	National priority	Context for the ecological footprint	Format of active actions and implementation policies	Expected environmental impact
Goal 8: Sustainable economic growth and decent work	New environmental industrial policy	Reduction of resource intensity and emissions	Transition to BAT, modernization of production facilities, introduction of energy-efficient technologies	Reducing the environmental footprint per unit of production
Objective 9: Innovations and infrastructure	Industrial modernization	Minimize the environmental impact of industrial infrastructure	Development of green industrial parks, environmental certification of enterprises	Reducing the infrastructure footprint
Objective 12: Responsible consumption and production	Rational use of resources	Optimization of the material and raw material cycle	Implementation of circular economy principles and waste management	Reducing the material and raw material footprint
Objective 13: Combating climate change	Climate policy	Reducing the carbon footprint of industry	Fulfillment of the Paris Agreement commitments, implementation of corporate climate strategies	Reducing the global environmental deficit
Goal 15: Protect terrestrial ecosystems	Forest and land policy	Control over land and forest degradation	Reclamation of industrial areas, environmental compensation	Balancing land and forest components of the footprint

Source: compiled by the author based on Impact Fund Denmark (2024).
Fonte: compilado pelo autor com base em Impact Fund Denmark (2024).

Statistics show that the greatest pressure on the biosphere is created by greenhouse gas emissions of industrial origin, which exceed 60% of the global ecological footprint (KHAKIMOVNA; OGLU, 2025). At the same time, the authors note that industrial enterprises also affect other components of the ecological footprint through the use of land, forests, water and minerals, which form a negative range of expected environmental risks.

4.3. Methodological support for assessing the size of the ecological footprint of industrial enterprises (case of the Central regions of Ukraine)

Ukraine's current industrial activity is accompanied by a significant anthropogenic burden on the natural environment, which creates a demand for the development of effective and practically applicable indicators for assessing the level of sustainability of regional ecosystems. The authors' opinion should be based on a visual integral indicator – the ecological footprint – which will reflect the amount of resources and the area of biologically productive land and water areas required to compensate for production costs and waste disposal (PETRUKHA et al., 2024). In the format of the Ukrainian industry, it will cover energy costs, water and material resources, waste generation, and spatial infrastructure needs. For the practical application of the methodology, the authors used aggregate data from the State Statistics Committee of Ukraine and a number of regional environmental reports.

1. Energy footprint:

$$EF_{en} = \frac{E}{Y_{for}} \cdot f_y \cdot f_{eq} \quad (02)$$

where: E – annual energy consumption by enterprises (in kcal or MWh, converted to wood weight); Y_{for} – is the average global forest productivity (m³ ha^{-1}); f_y – is a yield factor; f_{eq} – equivalent factor (for forests = 1.365).

2. The water footprint is proposed to be calculated as follows:

$$EF_{wat} = \frac{W}{Y_{wat}} \cdot f_w \cdot f_{eq} \quad (03)$$

where: W – annual water intake by industry (m^3); Y_{wat} – average productivity of aquatic ecosystems (m³ ha^{-1}); f_w – is the water use efficiency factor; f_{eq} – is the equivalent factor for inland waters (0.36).

3. The formula will determine the material and raw material footprint:

$$EF_{mat} = \sum_{i=1}^{n} \frac{C_i}{Y_i} \cdot f_{y,i} \cdot f_{eq,i} \quad (04)$$

where: C_i – domestic consumption of resource iii (metals, cement, coal, etc.); Y_i – productivity of the respective resource base (tons ha^{-1}); $f_{y,i}$ – yield factor for resource iii; $f_{eq,i}$ – equivalent factor.

4. The authors propose to calculate the waste and emissions footprint as follows:

$$EF_{wst} = \frac{Q_{CO_2}}{Y_{abs}} + \frac{Q_{sol}}{Y_{dis}} \quad (05)$$

where: Q_{CO2} – is the volume of CO_2 emissions (tons $year^{-1}$); Y_{abs} – is the average capacity of forests to absorb CO_2 (tons $year^{-1}$); Q_{sol} – solid waste generation (tons $year^{-1}$); Y_{dis} – is the productivity of landfills or disposal systems (tons ha^{-1}).

5. The infrastructure footprint is formed in the following formulaic form:

$$\mathrm{EF_{inf}} = \mathrm{A} \cdot \mathrm{f_{inf}} \cdot \mathrm{f_{eq}} \qquad (06)$$

where: A – is the area of land occupied by industry and industrial infrastructure (ha); f_{inf} – is the area utilization factor; f_{eq} – is the equivalent factor for built-up land.

Table 4 shows the averages for the industrial systems of Kyiv, Cherkasy, Poltava, Kirovohrad, Dnipro, and Vinnytsia regions of Ukraine. All data are based on Annex A, which is a sample of the required indicators and data from the annual reports of the State Statistics Committee of Ukraine.

Table 4. Dynamics of resource consumption and waste generation by industrial enterprises in the Central regions of Ukraine (Kyiv, Cherkasy, Poltava, Kirovohrad, Dnipro, and Vinnytsia regions) (2021–2024)
Tabela 4. Dinâmica do consumo de recursos e da geração de resíduos pelas empresas industriais nas regiões centrais da Ucrânia (regiões de Kyiv, Cherkasy, Poltava, Kirovohrad, Dnipro e Vinnytsia) (2021–2024)

Indicator	Years			
	2021	2022	2023	2024
Energy consumption, billion kWh	62.1	59.4	55.8	57.3
Water intake by industry, mln m^3	1520	1430	1390	1415
Metal consumption (steel, cast iron), mln tons	4.2	3.9	3.5	3.7
Use of cement and construction materials, million tons	2.1	1.8	1.7	1.9
CO_2 emissions, million tons	21.4	20.2	18.7	19.1
Solid waste, million tons	9.6	8.8	8.4	8.7
Industrial land, thousand hectares	482	482	482	482

Source: compiled by the author based on Annex A.
Fonte: compilada pelo autor com base no Anexo A.

The above analytical data show us a steady downward trend in most resource intensity indicators of industrial enterprises in the Central regions of Ukraine in 2021–2023, which is partly due to the overall decline in production activity. In particular, energy consumption decreased from 62.1 billion kWh in 2021 to 55.8 billion kWh in 2023, water intake decreased from 1520 million m^3 to 1390 million m^3, and metal consumption decreased by almost 17%. Similar changes are observed in the cement industry, where the consumption of materials decreased by 0.4 million tons. CO_2emissions decreased by 12.6% and solid waste by 12.5% over three years. At the same time, in 2024, there was a partial recovery in production, when the format indicators of energy consumption, water intake, and metal use showed a slight increase, reflecting the transition from the recession to the gradual revival of the country's industry (STATE STATISTICS SERVICE OF UKRAINE, 2025).

Let's calculate the size of the integrated ecological footprint for a selected group of Ukrainian regions by applying the following formulas (1–6), which accumulate factors of both natural resource use and environmental impact. The initial step is to calculate the energy footprint, where energy consumption is converted into the area of forested land required to restore the same energy potential. The water footprint is calculated by comparing industrial water consumption with the average productivity of aquatic ecosystems using special equivalence factors (MAKEDON et al., 2024a).

The authors calculate the material and raw material footprint based on the total consumption of metals, cement, and other materials, taking into account the productivity of the respective natural resources. The waste and emissions footprint is calculated by relating *CO_2* emissions and solid waste volumes to the absorption capacity of natural ecosystems. The calculation is completed by the infrastructure footprint, which is determined by the area of industrial facilities, taking into account the building coefficients. The final ecological footprint (*EF*) (calculated based on Formula 1) is the sum of all types of ecological footprints (Table 5).

Table 5. Dynamics of the size of the ecological footprint of industrial enterprises in the Central regions of Ukraine by selected components (2021–2024)
Tabela 5. Dinâmica do tamanho da pegada ecológica das empresas industriais nas regiões centrais da Ucrânia por componentes selecionados (2021–2024)

Year	EF_{en} (ha)	EF_{wa} (ha)	EF_{mat} (ha)	EF_{wst} (ha)	EF_{inf} (ha)	Total EF (ha)
2021	$1.18–10^{8}$	$3.8–10^{4}$	$3.1–10^{6}$	$8.2–10^{6}$	$1.07–10^{6}$	$1.29–10^{8}$
2022	$1.14–10^{8}$	$3.5–10^{4}$	$2.9–10^{6}$	$7.9–10^{6}$	$1.07–10^{6}$	$1.22–10^{8}$
2023	$1.07–10^{8}$	$3.4–10^{4}$	$2.7–10^{6}$	$7.6–10^{6}$	$1.07–10^{6}$	$1.16–10^{8}$
2024	$1.09–10^{8}$	$3.4–10^{4}$	$2.8–10^{6}$	$7.5–10^{6}$	$1.07–10^{6}$	$1.18–10^{8}$

Source: calculated by the author.
Fonte: calculada pelo autor.

The modeling data for the regions of Ukraine presented in Table 3 demonstrate the predominance of the energy component in the structure of the environmental load of industrial enterprises in the central regions of Ukraine. In 2021, the energy footprint reached $1.18–10^{8}$ hectares, which was more than 90% of the total. Even with the reduction in production capacity in 2022–2023, this component remained dominant. The minimum value of the total footprint was recorded in 2023 – $1.16–10^{8}$ ha, which is due to a decrease in energy, water and material resources consumption by the industry. In 2024, there was a gradual increase in the EF_{en} and EF_{mat} indicators, indicating a recovery in industrial activity.

The water footprint is characterized by relatively small values – 3.4-$3.8–10^{4}$ ha, but is of significant environmental importance due to local resource constraints. The waste and emissions footprint shows a positive trend of decrease from $8.2–10^{6}$ ha (2021) to $7.5–10^{6}$ ha (2024), which reflects the effectiveness of technological modernization and strengthening of environmental protection measures. The infrastructure component remains unchanged at $1.07–10^{6}$ ha. The obtained results confirm the crucial role of the energy and waste components in the subsequent formation of the environmental load from industrial facilities (PELYUKH et al., 2025).

The developed methodology for assessing the ecological footprint should become the basis for creating a system for continuous monitoring of the anthropogenic load of industrial facilities at the regional level. Its comprehensiveness is ensured by simultaneously taking into account energy consumption, water use, material flows, waste generation, and infrastructure load. The practical implementation of the methodology in the future will help to create environmental passports of enterprises as tools for assessing the sustainable development of production.

5. DISCUSSION

The results of the study confirm the global trends highlighted by Muthu (2024) and Pelyukh et al. (2025) regarding the critical excess of the human ecological footprint over the planet's biocapacity. Our calculations for industrial enterprises in the central regions of Ukraine correlate with international data on the dominance of the carbon component (over 60%) in the structure of the global ecological footprint. These positions are in full agreement with the findings of Li et al. (2024) and Wang et al. (2024) on the leading role of the energy sector in shaping the anthropogenic burden on the environment.

At the same time, our results contradict the optimistic forecasts of Sheng et al. (2024) regarding the rapid reduction of the environmental impact of industry due to the introduction of green technologies. The analysis of the dynamics of the ecological footprint for Ukrainian enterprises showed that even in the face of a significant reduction in production capacity, the total footprint remained at a critically high level, indicating the structural inertia of industrial systems to environmental transformations.

The methodological approach developed in this study extends the scientific basis laid down by Caetano et al. (2024) and Khezri et al. (2023) by integrating the five components of the ecological footprint into a single model. In contrast to previous studies that focused mainly on individual aspects of industrial impacts, our methodology provides a comprehensive assessment of all forms of resource consumption and waste generation. This is in line with the recommendations of the European Commission (2021) on the need to standardize methods for assessing the environmental footprint factor for all industrial enterprises.

The novelty of the study lies in the development of a methodology adapted for post-Soviet industrial regions, which takes into account the specifics of energy-intensive industries and outdated technologies. Unlike the Western European studies of Oprea et al. (2024), which are based on data from high-tech economies, our approach takes into account the realities of transition economies with a high level of resource intensity of production. The practical significance of the developed methodology is confirmed by the possibility of its application to create environmental passports of enterprises, which is in line with the recommendations of UNIDO (2022) on the integration of environmental criteria into industrial policy. Our approach has formed the basis for the transition from formal reporting to the constructive use of ecological footprint indicators in strategic planning, which is consistent with the concept of best available technologies substantiated by Huang et al. (2025).

At the same time, the study has certain methodological limitations. The use of averaged ecosystem productivity coefficients can lead to inaccuracies in regional calculations, which confirms the criticism of Pacana et al. (2024) about the need to localize biocapacity indicators. In addition, the proposed methodology does not fully take into account dynamic changes in the technological processes of enterprises, which may limit the accuracy of forecast estimates. Comparison with the studies by Mammadova et al. (2025) and Sun et al. (2024) shows that the integrated model developed by us provides a more comprehensive approach to assessing industrial environmental impact, but requires significant amounts of statistical data.

The results of the study make a tangible contribution to the scientific debate on methods of integrating environmental criteria into industrial policy. The developed methodology can become the basis for creating a system of environmental monitoring of industrial regions of Ukraine and other countries with similar economic conditions.

6. CONCLUSIONS

The study has shown that the anthropogenic burden of industry continues to grow, creating a sustainable imbalance in natural ecosystems. The scientific result was the establishment of the leading role of carbon emissions as the main factor in exceeding the ecological limits of the planet, which is associated with the high energy intensity of modern production and dependence on traditional energy sources.

To address the identified problems, a comprehensive transformation of industrial policy is proposed. The main directions include the transition to low-carbon technologies, systemic improvement of energy efficiency, development of alternative energy sources, and strengthening of environmental control.

The scientific novelty is the definition of the ecological footprint as a universal indicator for scenario analysis and evaluation of the effectiveness of management decisions in the context of sustainable development. It is proposed to introduce the best available technologies at the institutional level, develop the principles of the circular economy, create environmentally friendly industrial zones and coordinate government and corporate decarbonization programs.

The calculations of the ecological footprint (EF) for industrial enterprises in the Central regions of Ukraine (2021–2024) showed a reasonable dominance of the energy component (EFen), the share of which exceeded 90% of the total EF (in the range from $1.07–10^8$ ha in 2023 to $1.18–10^8$ ha in 2021), which correlates with the global structure, where the carbon footprint is more than 60% of the anthropogenic load. A quantitative determination of the reduction of the total EF by 10% during 2022–2023 (to $1.16–10^8$ ha) due to a decrease in energy consumption (by 10.1%), water intake (by 8.6%) and CO_2 emissions (by 12.6%), which represents adaptation processes in crisis conditions, has been determined. At the same time, the recovery of indicators in 2024 (EF = $1.18–10^8$ ha) indicates the risk of regressive dynamics in the absence of structural transformations.

A methodological toolkit for assessing the ecological footprint of industrial enterprises in the central regions of Ukraine has been developed and tested in practice. The testing identified the current structural features of the impact and confirmed the dominance of the energy component in the overall environmental load.

The scientific significance of the work lies in the creation of a single integrated model that combines the accounting of energy consumption, water resources, material flows, waste generation, and infrastructure load. The modeling has formed the critical importance of constructive use of EF as an indicator of sustainable development: the implementation of the best available technologies (BAT) and the principles of the circular economy can reduce EF by 15–20% by optimizing the coefficients $f_{(eq)}$ and Y_i.

For Ukraine, this implies a priority modernization of energy-intensive industries, aligned with the UN Sustainable

Development Goals (SDGs), to prevent a biological carrying capacity deficit of 1.23 global hectares/person. The model is suitable for regional comparisons and practical application in industrial environmental management.

Practical suggestions include creating a system of environmental passports for enterprises, organizing regular monitoring by standardized indicators, developing mechanisms for predicting environmental risks, and integrating assessment results into regional development and environmental safety programs.

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Appendix A

Statistical data on resource consumption and waste generation by industrial enterprises in regions of Ukraine (2021-2024).
Dados estatísticos sobre o consumo de recursos e a geração de resíduos por empresas industriais por região da Ucrânia (2021-2024).

Region	Indicator	2021	2022	2023	2024
Vinnytsia	Energy consumption, billion kWh.	4.8	4.6	4.3	4.4
	Water intake by industry, mln m³	25.0	23.5	22.0	22.5
	Metal consumption (steel, cast iron), mln tons	0.3	0.3	0.2	0.3
	Use of cement and construction materials, million tons	0.2	0.2	0.1	0.2
	CO_2 emissions, million tons	1.5	1.4	1.3	1.3
	Solid waste, million tons	0.7	0.6	0.6	0.6
	Industrial land, thousand hectares	25	25	25	25
Volyn region	Energy consumption, billion kWh.	2.1	2.0	1.9	1.9
	Water intake by industry, mln m³	12.0	12.3	11.6	11.8
	Metal consumption (steel, cast iron), mln tons	0.1	0.1	0.1	0.1
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	0.6	0.6	0.5	0.5
	Solid waste, million tons	0.3	0.3	0.3	0.3
	Industrial land, thousand hectares	15	15	15	15
Dnipropetrovska	Energy consumption, billion kWh.	28.0	26.8	25.2	25.9
	Water intake by industry, mln m³	650.0	610.0	49.3	50.0
	Metal consumption (steel, cast iron), mln tons	2.5	2.3	2.1	2.2
	Use of cement and construction materials, million tons	1.0	0.9	0.8	0.9
	CO_2 emissions, million tons	12.0	11.3	10.5	10.7
	Solid waste, million tons	5.5	5.0	4.8	4.9
	Industrial land, thousand hectares	120	120	120	120
Donetsk	Energy consumption, billion kWh.	35.0	28.0	22.0	23.0
	Water intake by industry, mln m³	163.0	163.0	245.6	250.0
	Metal consumption (steel, cast iron), mln tons	10.0	2.0	2.0	2.5
	Use of cement and construction materials, million tons	0.5	0.4	0.3	0.4
	CO_2 emissions, million tons	15.0	8.0	7.0	7.5
	Solid waste, million tons	20.0	15.0	12.0	13.0
	Industrial land, thousand hectares	80	80	80	80
Zhytomyr region	Energy consumption, billion kWh.	3.2	3.0	2.8	2.9
	Water intake by industry, mln m³	6.0	5.5	5.9	6.0
	Metal consumption (steel, cast iron), mln tons	0.2	0.2	0.2	0.2
	Use of cement and construction materials, million tons	0.2	0.2	0.2	0.2
	CO_2 emissions, million tons	0.9	0.8	0.8	0.8
	Solid waste, million tons	0.4	0.4	0.4	0.4
	Industrial land, thousand ha	20	20	20	20
Zakarpattia region	Energy consumption, billion kWh.	1.8	1.7	1.6	1.7
	Water intake by industry, mln m³	9.5	9.5	9.3	9.4
	Metal consumption (steel, cast iron), mln tons	0.1	0.1	0.1	0.1
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	0.5	0.5	0.5	0.5
	Solid waste, million tons	0.2	0.2	0.2	0.2
	Industrial land, thousand ha	12	12	12	12
Zaporizhzhia	Energy consumption, billion kWh.	12.0	10.0	8.0	8.5
	Water intake by industry, mln m³	40.0	38.0	0.0	0.0
	Metal consumption (steel, cast iron), mln tons	1.5	1.0	0.8	1.0
	Use of cement and construction materials, million tons	0.3	0.3	0.2	0.3
	CO_2 emissions, million tons	4.0	3.0	2.5	2.7
	Solid waste, million tons	2.0	1.5	1.2	1.3
	Industrial land, thousand hectares	60	60	60	60
Ivano-Frankivsk	Energy consumption, billion kWh.	4.5	4.3	4.0	4.1
	Water intake by industry, mln m³	48.0	48.0	42.9	43.5
	Metal consumption (steel, cast iron), mln tons	0.2	0.2	0.2	0.2
	Use of cement and construction materials, million tons	0.5	0.4	0.4	0.4
	CO_2 emissions, million tons	1.2	1.1	1.0	1.0
	Solid waste, million tons	0.5	0.5	0.5	0.5
	Industrial land, thousand hectares	18	18	18	18
Kyiv	Energy consumption, billion kWh.	15.0	14.3	13.5	13.8
	Water intake by industry, mln m³	180.0	170.0	641.3	650.0
	Metal consumption (steel, cast iron), mln tons	0.8	0.7	0.6	0.7
	Use of cement and construction materials, million tons	0.5	0.4	0.4	0.4
	CO_2 emissions, million tons	4.5	4.2	3.9	4.0
	Solid waste, million tons	2.0	1.8	1.7	1.8
	Industrial land, thousand hectares	80	80	80	80
Kirovograd region	Energy consumption, billion kWh.	5.0	4.8	4.5	4.6
	Water intake by industry, mln m³	80.0	75.0	25.1	25.5
	Metal consumption (steel, cast iron), mln tons	0.2	0.2	0.2	0.2
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1

	CO_2 emissions, million tons	1.2	1.1	1.0	1.0
	Solid waste, million tons	0.6	0.6	0.5	0.6
	Industrial land, thousand hectares	30	30	30	30
Luhansk	Energy consumption, billion kWh.	20.0	15.0	12.0	13.0
	Water intake by industry, mln m^3	120.0	100.0	80.0	85.0
	Metal consumption (steel, cast iron), mln tons	3.0	1.0	0.8	1.0
	Use of cement and construction materials, million tons	0.2	0.1	0.1	0.1
	CO_2 emissions, million tons	8.0	5.0	4.0	4.5
	Solid waste, million tons	10.0	7.0	6.0	6.5
	Industrial land, thousand hectares	70	70	70	70
Lviv	Energy consumption, billion kWh.	5.5	5.2	4.9	5.0
	Water intake by industry, mln m^3	34.0	34.0	35.6	36.0
	Metal consumption (steel, cast iron), mln tons	0.3	0.3	0.3	0.3
	Use of cement and construction materials, million tons	0.2	0.1	0.2	0.2
	CO_2 emissions, million tons	1.5	1.4	1.3	1.4
	Solid waste, million tons	0.7	0.7	0.7	0.7
	Industrial land, thousand hectares	25	25	25	25
Mykolaivska	Energy consumption, billion kWh.	3.8	3.6	3.4	3.5
	Water intake by industry, mln m^3	70.0	70.0	68.0	69.0
	Metal consumption (steel, cast iron), mln tons	0.2	0.2	0.2	0.2
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	1.0	0.9	0.9	0.9
	Solid waste, million tons	0.4	0.4	0.4	0.4
	Industrial land, thousand ha	22	22	22	22
Odesa region	Energy consumption, billion kWh.	4.2	4.0	3.8	3.9
	Water intake by industry, mln m^3	32.0	32.0	29.3	29.8
	Metal consumption (steel, cast iron), mln tons	0.2	0.2	0.2	0.2
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	1.1	1.0	1.0	1.0
	Solid waste, million tons	0.5	0.5	0.5	0.5
	Industrial land, thousand hectares	35	35	35	35
Poltava region	Energy consumption, billion kWh.	6.5	6.2	5.8	6.0
	Water intake by industry, mln m^3	320.0	300.0	119.8	122.0
	Metal consumption (steel, cast iron), mln tons	0.8	0.7	0.6	0.7
	Use of cement and construction materials, million tons	0.2	0.2	0.2	0.2
	CO_2 emissions, million tons	1.8	1.7	1.6	1.6
	Solid waste, million tons	0.6	0.6	0.6	0.6
	Industrial land, thousand hectares	45	45	45	45
Rivne region	Energy consumption, billion kWh.	2.5	2.4	2.3	2.3
	Water intake by industry, mln m^3	25.0	24.0	24.8	25.0
	Metal consumption (steel, cast iron), mln tons	0.1	0.1	0.1	0.1
	Use of cement and construction materials, million tons	0.3	0.3	0.3	0.3
	CO_2 emissions, million tons	0.7	0.7	0.6	0.7
	Solid waste, million tons	0.3	0.3	0.3	0.3
	Industrial land, thousand hectares	16	16	16	16
Sumy region	Energy consumption, billion kWh.	3.0	2.9	2.7	2.8
	Water intake by industry, mln m^3	26.0	25.0	26.1	26.5
	Metal consumption (steel, cast iron), mln tons	0.2	0.2	0.2	0.2
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	0.8	0.8	0.7	0.8
	Solid waste, million tons	0.4	0.4	0.4	0.4
	Industrial land, thousand hectares	18	18	18	18
Ternopil region	Energy consumption, billion kWh.	2.0	1.9	1.8	1.8
	Water intake by industry, mln m^3	18.0	17.0	17.6	17.8
	Metal consumption (steel, cast iron), mln tons	0.1	0.1	0.1	0.1
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	0.6	0.5	0.5	0.5
	Solid waste, million tons	0.2	0.2	0.2	0.2
	Industrial land, thousand ha	14	14	14	14
Kharkiv region	Energy consumption, billion kWh.	10.0	8.0	7.0	7.5
	Water intake by industry, mln m^3	155.0	150.0	154.3	156.0
	Metal consumption (steel, cast iron), mln tons	0.5	0.4	0.4	0.5
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	3.0	2.5	2.2	2.3
	Solid waste, million tons	1.5	1.2	1.1	1.2
	Industrial land, thousand hectares	65	65	65	65
Kherson region	Energy consumption, billion kWh.	2.2	2.1	2.0	2.0
	Water intake by industry, mln m^3	18.0	17.0	18.1	18.3
	Metal consumption (steel, cast iron), mln tons	0.1	0.1	0.1	0.1
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	0.6	0.6	0.6	0.6
	Solid waste, million tons	0.3	0.3	0.3	0.3
	Industrial land, thousand hectares	20	20	20	20

Khmelnytsky	Energy consumption, billion kWh.	3.5	3.3	3.1	3.2
	Water intake by industry, mln m³	35.0	34.0	34.3	34.8
	Metal consumption (steel, cast iron), mln tons	0.2	0.2	0.2	0.2
	Use of cement and construction materials, million tons	0.2	0.2	0.2	0.2
	CO_2 emissions, million tons	1.0	0.9	0.9	0.9
	Solid waste, million tons	0.4	0.4	0.4	0.4
	Industrial land, thousand ha	22	22	22	22
Cherkasy region	Energy consumption, billion kWh.	2.8	2.7	2.5	2.6
	Water intake by industry, mln m³	100.0	95.0	37.6	38.2
	Metal consumption (steel, cast iron), mln tons	0.2	0.2	0.2	0.2
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	0.4	0.4	0.4	0.4
	Solid waste, million tons	0.2	0.2	0.2	0.2
	Industrial land, thousand hectares	30	30	30	30
Chernivtsi region	Energy consumption, billion kWh.	1.5	1.4	1.3	1.4
	Water intake by industry, mln m³	22.0	21.0	22.1	22.3
	Metal consumption (steel, cast iron), mln tons	0.1	0.1	0.1	0.1
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	0.4	0.4	0.4	0.4
	Solid waste, million tons	0.2	0.2	0.2	0.2
	Industrial land, thousand ha	10	10	10	10
Chernihiv region	Energy consumption, billion kWh.	2.8	2.7	2.5	2.6
	Water intake by industry, mln m³	22.0	21.0	22.1	22.3
	Metal consumption (steel, cast iron), mln tons	0.2	0.2	0.2	0.2
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	0.8	0.7	0.7	0.7
	Solid waste, million tons	0.3	0.3	0.3	0.3
	Industrial land, thousand hectares	16	16	16	16
м. Kyiv	Energy consumption, billion kWh.	8.0	7.6	7.2	7.4
	Water intake by industry, mln m³	220.0	210.0	219.1	221.0
	Metal consumption (steel, cast iron), mln tons	0.4	0.4	0.3	0.4
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	2.2	2.1	2.0	2.0
	Solid waste, million tons	1.0	0.9	0.9	0.9
	Industrial land, thousand hectares	62	62	62	62
Crimea	Energy consumption, billion kWh.	1.0	0.8	0.7	0.8
	Water intake by industry, mln m³	10.0	8.0	7.0	7.5
	Metal consumption (steel, cast iron), mln tons	0.1	0.1	0.1	0.1
	Use of cement and construction materials, million tons	0.1	0.1	0.1	0.1
	CO_2 emissions, million tons	0.3	0.2	0.2	0.2
	Solid waste, million tons	0.2	0.1	0.1	0.1
	Industrial land, thousand hectares	20	20	20	20

Source: State Statistics Service of Ukraine (2025)
Notes: Data for the occupied regions (Donetsk, Luhansk, Crimea) are adjusted for limited activity.
Fonte: Serviço Estatal de Estatísticas da Ucrânia (2025)
Notas: Os dados para as regiões ocupadas (Donetsk, Luhansk, Crimeia) foram ajustados para atividade limitada