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Assessment of the technological efficiency of production and consumption of EU countries in the context of circular economy

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Abstract. The intensive use of non-renewable production resources and the associated growing environmental pollution forces us to look for new methods of halting these negative trends. Circular economy is one such method. This phenomenon is the subject of numerous studies attempting to assess its condition at both the micro and macro levels, the implementation of circular economy strategies, its environmental impact, the context of waste generation, etc. On the other hand, little attention is paid to assessing its efficiency. Technological efficiency, i.e., the relationship between material footprint and waste generation, is of particular importance, since the amount of waste generated primarily depends on the technology used at the time of production. Thus, this paper aims to analyse and assess the development of technological efficiency over a certain period of time. Further, it is necessary not only to build on the results of development at the end of this period, but also to assess the extent of the changes that have taken place during it in order to reflect the actual state of affairs. Thus, the final result takes into account both the intensity of the development of technological efficiency and the importance of its current state to the overall development process.

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1. INTRODUCTION

Circular economy (CE) is a systemic response to a deteriorating global ecological situation characterised by the overexploitation of natural resources and increasing environmental pollution. It is no coincidence that the United Nations Sustainable Development Goal 12 concerns sustainable production and responsible consumption (Sustainable Development Goals, 2023). Today, the world is dominated by a linear economic system characterised by the intensive use of natural resources and large amounts of waste being generated. These trends threatening humanity can be localised in the transition to a CE. The Eurostat database provides a system of CE indicators consisting of five blocks: production and consumption, waste management, secondary raw materials, competitiveness and innovation, and global sustainability and resilience. Of these, the first block – production and consumption – is crucial, as it serves almost as a foundation for the other blocks. It contains eight indicators, among which material footprint and waste generation are crucial since the former reflects the raw materials needed for production and the latter reflects the total amount of waste generated in the country. The other six indicators are essentially derived from these two. The development of CE in different countries is largely reflected by the changes in material footprint and waste generation over a certain period of time. In the context of CE, these two phenomena must be considered in their interaction to estimate the effectiveness of this process. There are questions regarding how this interaction can be expressed and how effective it will be. In the context of CE, efficient production can only be achieved when the volumes of waste decrease. Literary sources distinguish between different types of efficiency, among which the three most frequently mentioned are: allocated, dynamic and technological (Bagdonavičius et al., 1999; Lukosevičius et al. 2005; Tareck, 2023). Of these, the emphasis is on two: accommodative and technological (Zofio et al., 2013; Susaeta et al., 2016), where the former determines the return of a company using limited resources (AGPC, 2013) – in other words, its ability to produce and realise its products or services at the lowest possible price (Nabradi et al., 2009; Kudinova & Verba, 2014; Rabe et al., 2023). In the context of the CE, it is logical to speak about and calculate technological efficiency as representing the presence of the smallest possible amount of waste at the same or increasing production volumes. This can only be achieved through increasingly advanced technologies. There are two main challenges in this context: first, to establish an indicator reflecting the overall process of production and waste generation; secondly, to quantify trends in this process in the countries concerned.

The purpose of this article is to calculate the technological efficiency of the overall material footprint and waste generation process, as well as to present and approve a methodology for the quantification of the technological efficiency of the CE.

2. LITERATURE REVIEW

The CE phenomenon is studied in the scientific literature in a broad and diverse manner. A significant part of such research is devoted to the importance and environ-mental impact of the CE. It is said that the CE contributes to the reduction of waste generation by shifting from the traditional 'take-make-discard' linear production model towards one of recycling and reuse. This reduces the scale of waste generation and incineration, as well as easing the burden of landfills (Androniceanu et al., 2021; Ginevicius, 2022; Nandi et al., 2023; Zielińska et al., 2023). At the same time, the CE reduces environmental impacts and mitigates climate change (Cui & Zhang, 2022; Pao & Chen, 2022). It also contributes to reducing carbon dioxide emissions into the atmosphere by reducing the impact of the extraction and production of energy-intensive raw materials (Cui & Zhang, 2022; Hailemariam & Erdiaw -Kwasie, 2022; Aguilar-Hernandez et al., 2021). The impact of the CE on a country's social situation is also highlighted, as it can create new jobs – especially in areas such as waste recycling and the development of renewable energy sources (Padilla-Rinera et al., 2020, Zhidebekkyzy et al., 2022a,b). A key feature of the CE is that it promotes the development of innovative technologies and new business models by creating favourable conditions for cooperation between industry and research institutions (Xu et al., 2021). The essential goal of the CE, which is declared by the UN, is to achieve sustainable development by addressing issues of importance to humanity, such as production and consumption (Kharlamova et al., 2021, Zhidebekkyzy et al., 2023), and combating climate change (Knable et al., 2022).

The development of a CE can only be managed in a targeted manner if it is possible to quantify its condition at the desired point in time. Literary sources offer a variety of solutions to this task, with methods that help to measure resource efficiency, waste reduction, and overall sustainability. Commonly used CE assessment methods include: Life Cycle Assessment (LCA), Multi-Criteria Decision Methods (MCDMs) and Circularity Indicators. According to Sassanelli et al. (2019), the most commonly used methodology for CE evaluation is LCA, which assesses the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to end-of-life disposal or recycling. LCA considers resource use, energy consumption, emissions, and potential environmental harm.

The CE is, by its very nature, a complex phenomenon that manifests itself in many different aspects of reality, and it is therefore widely covered by MCDMs (Sassanelli et al., 2019; Gonsalves & Campos, 2022). These methods involve evaluating CE strategies based on multiple criteria, including economic, environmental, social, and technological factors. This helps decision-makers to consider the trade-offs and synergies between different aspects of the CE. In practice, MCDMs such as PROMETHEE, TOPSIS, MOORA, etc., are applied. (Table 1).

Table 1

The literary sources that address different aspects of the CE and their assessment methods.

Authors	**Method**	**CE aspects**
Fetanat et al. 2021; Tariq et al. 2021; Tonini et al. 2020; Lee et al. 2021	fuzzy DEMATEL, fuzzy MULTIMOORA, TOPSIS, ELECTRE II	Waste management
Mi et al. 2021; Ramirez & George, 2019	POWA	Healthcare waste management
Kocak et al. 2022	ANP, VIKOR	Recycling of composite waste
Sharma et al. 2021	SWARA, WASPAS	Electronic waste
Zhang et al. 2021	AHP, TOPSIS	Remanufacturing reverse logistics
Krstic et al. 2023	ADAM	Agri-food production and consumption
Stevic et al. 2021	fuzzy MARCOS	Forestry industry

Source: own compilation

From Table 1, we can see that most research in this area is focused on the environmental dimension, as well as on green logistics and production and consumption.

A significant part of this research is devoted to the assessment of the state of the CE in countries, again using MCDMs and various indicator systems. For example, the CE Development Indicator System used in three provinces in China consists of 16 indicators divided into four blocks: resource consumption, environmental disturbance, recycling and social development (Jiang, 2011). The importance of these indicators was determined by the AHP method, and their development was assessed using the Fuzzy Comprehensive Evaluation Method.

The literature has a strong focus on assessing the state of the CE in EU countries. Ūsas et al. (2021) examined the development of CEs in EU countries in 2016 using three different MCDM approaches (TOPSIS, PROMETHEE II and ELECTRE I). The author only used indicators for recycling and the CE of materials, and concluded that Germany performed best. Mazur-Wierzbicka (2021) measured the CE performance of EU countries using 13 indicators proposed by the European Commission. A synthetic variable index was used to classify countries. Candan & Toklu (2022) evaluated 27 EU Member States' data from 2014, 2016 and 2018. Countries were assessed according to 4 main criteria (production and consumption, C1; waste management, C2; secondary raw materials, C3; competitiveness and innovation, C4) and the sub-criteria associated with each main criterion. As a result of this evaluation, the countries that demonstrated CE performance improvements were identified. The authors claim that their country level CE evaluation differs from previous studies in several respects. These differences include established endpoints, the inclusion of criteria in the calculation, the evaluation method, and the weighting of criteria, which was determined based on expert opinions. The same indicators were also evaluated by Garcia-Bernabeu et al. (2020) for 28 EU countries. Additionally, Cautisanu et al. (2018) conducted a quantitative evaluation of the CE in OECD countries. They used the same indicators as previous researchers and added several sustainable development indicators, such as demographic changes, quality of life, GDP growth, employment rate, and others. However, none of these studies provide explanations for the inclusion of certain indicators, typically relying on indicator and data availability instead.

Circularity indicators are also used to assess the state and development of the CE. These indicators are metrics used to measure the circularity of a product, process, or system. Indicators could include, for example, the percentage of recycled content, the share of remanufactured or refurbished products, or the reduction in virgin material use. These indicators are used at the micro level because they can measure the circularity of a product or system – i.e., the ability to preserve both the quantity and the quality of the material (Rigamonti & Manccini, 2021). At the product level, these metrics prove valuable when designing new products, creating internal reports, and setting sourcing targets. On the other hand, company level metrics can be employed internally to compare or track the progress of different product lines. Additionally, circularity metrics can be used externally to compare the level of circularity across a larger number of companies. By establishing specific goals based on these metrics, companies can monitor their progress in implementing CE strategies.

This literature review shows that a large part of the research is devoted to assessing the state of the CE at different levels (macro, micro), the implementation of its strategies, and its environmental impact and waste generation. There are few studies dedicated to assessing CE efficiency, and they typically employ two concepts that are closely interconnected: efficiency as productivity, and efficiency as effectiveness. An analysis of their differences shows that the notion of efficiency more accurately reflects labour productivity, while effectiveness encompasses the overall quality of the production process. In the context of the CE, this means that the more efficient the technology that is applied, the more production is generated, and the less waste is produced. Therefore, the higher overall quality of the production process, and thus efficiency, is achieved. Quality is dependent on the technologies employed, so the ratio of costs to results (and waste) reflects technological efficiency.

3. METHODOLOGY

To adequately reflect the development of technological efficiency within a country's CE, it is necessary to establish an appropriate connection between its two fundamental values: material footprint and waste generation. When considering the types of efficiency discussed, it becomes evident that in all cases efficiency involves the ratio of inputs to production and the resulting outcome (Bagdonavičius et al., 1999; Zofio et al., 2013; Suseata et al., 2016). In the context of the CE, inputs encompass the raw materials, technologies, and labour required for production, while the outcome is the waste generated. Technological efficiency can be reflected in the relationship between these factors, as the application of more advanced technologies in production leads to reduced resource usage, including energy. This consequently leads to less waste generation, resulting in reduced environmental impact. Technological efficiency can be determined as follows:

$$E_j = \frac{Q_j^M}{Q_j^W} \tag{1}$$

where E_j is the technological efficiency of the CE of country *j*; Q_j^M the quantity of the material footprint of country *j* in the year in question; and Q_j^W the amount of waste generated in country *j* in the year in question.

The state of development of this phenomenon can be assessed in two ways: either based on the actual results at the end of the period under review, or by considering the dynamics of its development and its characteristics during this period (Ginevičius et al., 2018). Currently, the first approach is predominant, and this situation could have arisen for several reasons. Firstly, information from international databases on the development of phenomena is typically provided as the result for the specific year in question. Secondly, there is a lack of universally accepted methodologies for quantifying development as an ongoing process.

Considering that enlargement, in its essence, is a process, conducting such an assessment is methodologically flawed as it is one-sided. The phenomenon of development encompasses two aspects: action, movement, and change; and the outcomes derived from them. When solely evaluating the state of enlargement at the conclusion of the review period, the other half of the equation remains overlooked – the changes that occurred throughout the entire period under examination. These changes can exhibit both positive and negative trends during individual intervals within the reference period. The end result of enlargement at the conclusion of the reference period is contingent upon the extent and proportion of these changes. The enlargement result may be high, but its intensity may be low; conversely, it may produce low development results but occur intensely (see Figure 1).

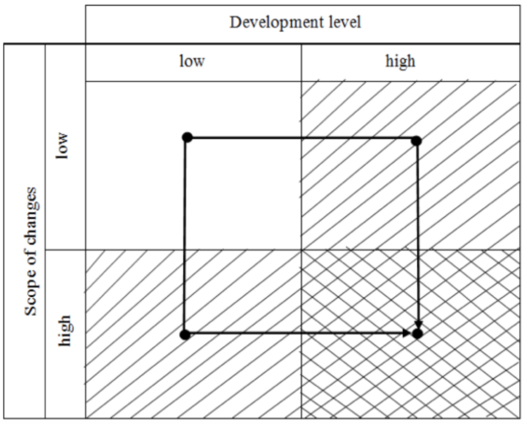

Figure 1. Potential scenarios for the development of the phenomenon under consideration
Source: compiled by the author according to Ginevičius et al. 2018

The scenarios depicted in Figure 1 are characteristic of the development of many socio-economic processes. For instance, an analysis of developments in the index reflecting the growth of the sharing economy between 2011 and 2018 in EU countries revealed that Bulgaria ranked last in terms of its overall level, but it exhibited one of the highest growth rates during this period (Grybaitė, 2023). However, the present study does not propose a quantitative method for assessing this conflicting situation, i.e., considering both the enlargement result and its intensity simultaneously.

The possible causes of such a situation can be both systemic and incidental. Systemic factors encompass the conditions of enlargement that have evolved within a country – including economic, legal, political, cultural, and labour-related factors. Meanwhile, incidental factors may involve sudden (particularly recent) changes in the climate situation and other unexpected events. Nevertheless, in the broader context, the overall result of enlargement must be determined by taking into account both the positive and negative developments that occurred during the period under consideration.

There have been limited attempts to address this issue. For example, one comprehensive assessment of economic development in a country's region (Ginevičius et al. 2018) considered not only the level of development achieved, but also its changes over the past 2 years as follows:

$$\mathrm{K_{kpi}} = \mathrm{k_{pfi}} \times \frac{\mathrm{k_{pfi}}}{\mathrm{k_{pbi}}} = \frac{\mathrm{k_{pfi}^2}}{\mathrm{k_{pbi}}} \quad (2)$$

where K_{kpi} is the importance of the complex assessment of the economic development of the region, i.e., the country; k_{pfi} the significance of the economic development of the country's region *i* at the end of the reference period; and k_{pbi} the significance of the economic development of the country's region *i* at the beginning of the period under review.

Formula 2 shows that K_{kpi} does not take into account the development trend over the whole period considered.

Studies that attempt to quantify the dynamics of the development of socio-economic processes can also be attributed to this direction of research (Ginevičius, 2019). Their essence is that the indicator of dynamics is determined by combining two sub-indicators into a single aggregate, where one reflects the evenness of development and the other its intensity. Here, the equilibrium is defined as the ratio between the ideal and actual lengths of the trajectories during the period under consideration. According to formula (3), the intensity of development is determined in this way (Ginevičius et al., 2018):

$$K_j = \frac{Q_{fj} - Q_{bj}}{Q_{fj}} \quad (3)$$

where K_j is the indicator of the intensity of the development of country *j* throughout the time frame under consideration; $Q_{fj}$the material footprint volumes of country *j* at the end of the considered period; and Q_{bj} the material footprint volumes of country *j* at the beginning of the period considered.

In order to obtain an adequate assessment of the situation on the basis of formula (3), it is necessary to take a closer look at Q_f. As stated above, Q_f can be taken as the actual value of the material footprint at the end of the period under consideration, or can be transformed in an appropriate way depending on the context – i.e., the developmental changes that occurred during the period under consideration. The first approach is perhaps too simplistic – or even wrong. This claim is supported by the example of two countries, Latvia and Romania (Figure 2).

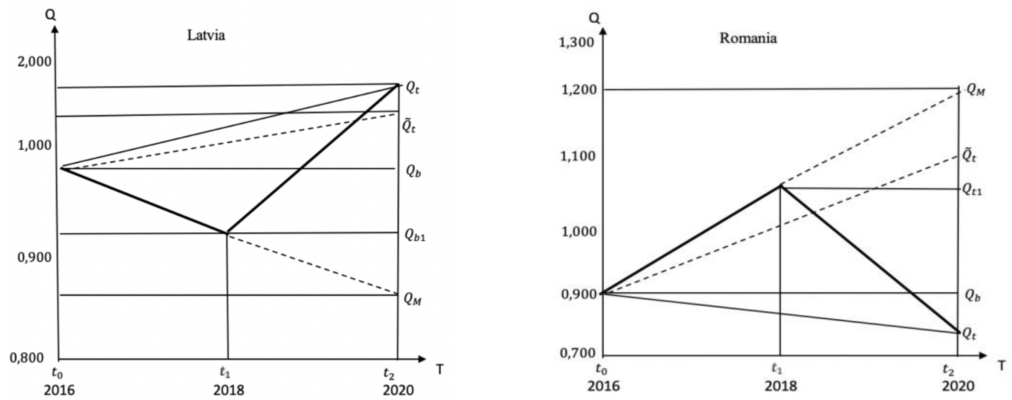

Figure 2. Waste generation in Latvia and Romania in 2016–2018 (kilograms per capita)

Source: own compilation

In Figure 2, we observe the opposite scenario: In Latvia, the amount of waste increased by 1.54 times in 2020 compared to 2016, while in Romania, it decreased by 1.23 times. In either case, we cannot assess the overall situation solely based on the 2020 indicator. Instead, it is necessary to evaluate the changes that occurred over the entire reference period from 2016 to 2020. For this purpose, it is necessary to identify E_j^T – changes in size over the reference period, i.e., in 2016, 2018, and 2020. These changes will be reflected in a corresponding transformation – $\tilde{Q}_t$ (Fig. 2). The desired size must assess the development during the time period t_0–t_1, as well as the time period t_1–t_2. In order to find this value, first of all, the difference – Δq – is calculated.

$$\Delta q_{t1} = Q_b - Q_{t1} \tag{4}$$

where Δq_{t1} is the value of the development of the material footprint and waste generation in the time period t_0–t_1; and Q_{t1} is the value of phenomenon under consideration at the end of the time period t_0–t_1.

Based on formula (4), the size Q_M is derived as follows:

$$Q_M = Q_b + 2\Delta q_{t1} \tag{5}$$

or

$$Q_M = Q_b - 2\Delta q_{t1} \tag{6}$$

The size of Q_M reflects the trajectory of the expansion that took place during the time period t_0–t_1.

The Q_t value transformed from formulas (5) and (6) shall be calculated as follows:

$$\tilde{Q}_f^M = \frac{Q_M^M + Q_f^M}{2} \tag{7}$$

$$\tilde{Q}_f^W = \frac{Q_M^W + Q_f^W}{2} \tag{8}$$

where $\tilde{Q}_f^M$, $\tilde{Q}_f^W$ are the values of the material footprint, Q_t^M, and waste generation, Q_t^W, at the end of the period under consideration.

Formula (7) makes it possible to determine the value of the technology efficiency ratio of the CE at the end of the reference period.

$$E_{fj}^{MW} = \frac{\tilde{Q}_{fj}^M - \tilde{Q}_{fj}^W}{\tilde{Q}_{fj}^M} \tag{9}$$

where E_{fj} is the importance of the technological efficiency of the CE of country *j* at the end of the period under review.

Similarly, on the basis of formula (8), the value of technological efficiency at the beginning of the period considered is determined:

$$E_{bj}^{MW} = \frac{\tilde{Q}_{bj}^M - \tilde{Q}_{bj}^W}{\tilde{Q}_{bj}^M} \tag{10}$$

where E_{bj} is the importance of the technological efficiency of the CE of the country at the beginning of the period under review.

Formulas (9) and (10) allow the intensity of changes in the technological efficiency of the CE over the reference period t_0–t_2 (Figure 2) to be determined:

$$I_j = \frac{E_{fi} - E_{bj}}{E_{fi}} \quad (11)$$

where I_j is an indicator of the intensity of the changes in the technological efficiency of the CE of the country.

In order to obtain an integrated assessment of the technological efficiency of the CE, it is necessary to combine two indicators, which reflect both the intensity and the state of development, into a single aggregate. The value of the first indicator should be higher for developing EU countries, as they can develop rapidly by tapping into the EU's powerful potential. It is much more difficult for highly developed countries to continue to develop at a high pace. On the other hand, the final result is important and is reflected in the state of development achieved. It follows that the state of the development of technological efficiency is more important than its intensity. In this case, the desired indicator of technological efficiency development will be formed as follows:

$$E_j = w_1 E_{fj} + w_2 I_j \quad (12)$$

where E_j is a composite indicator of the technological efficiency of the CE within the country; and w_1, w_2 are the weights of development efficiency and intensity ($\sum w_1 + w_2 = 1$).

Based on the proposed methodology, calculations were performed for the development of the technological efficiency of the CE of the EU countries over the 2016–2020 period.

4. EMPIRICAL RESULTS AND DISCUSSION

The Eurostat database provides data on indicators related to the CE production and consumption of the EU countries from various years and using different measurement units, including material footprint and waste generation (Eurostat, 2023). The values for the material footprint indicator are provided annually for the years 2016–2020 (measured in tonnes per capita), while the waste generation indicator is reported every 2 years, specifically for 2016, 2018, and 2020 (measured in kilograms per capita). To validate the proposed methodology, data for both indicators were collected in tonnes per capita for 2016, 2018, and 2020 (see Table 2).

Firstly, based on equations (5–8), the values of Q_M and $\tilde{Q}_f$ were calculated for both indicators – material footprint and waste generation (Table 3). Then, utilising equations (9) and (10), the efficiency of CE development was determined for the beginning and end of the analysed period, namely the values of E_{bj}^{MW} and E_{fj}^{MW} (Table 3). Using formula (11), the intensity of technological efficiency development, denoted as I_j, was calculated (Table 3). At the end of the calculations, a summarised result of the development of the technological efficiency of the CE in EU countries was obtained. This is denoted as E_j, which is expressed both numerically and in rank order (Table 3).

Table 2

Indicators for the technological development of the CE in EU countries

No	**Country**	**Indicators**					
		Material footprint (tonnes per capita)			Waste generation (tonnes per capita)		
		2016	2018	2020	2016	2018	2020
1.	Belgium	13.062	14.678	13.049	5.899	5.967	5.573
2.	Bulgaria	17.478	21.199	20.671	16.785	18.470	16.907
3.	Czechia	15.685	16.807	15.597	3.598	3.560	2.402
4.	Denmark	22.661	23.029	25.603	0.353	3.702	3.663
5.	Germany	15.744	15.961	14.959	4.824	4.891	4.858
6.	Estonia	24.05	30.321	27.87	12.163	17.539	18.451
7.	Ireland	12.363	12.944	10.758	3.248	2.874	3.207
8.	Greece	12.971	12.119	11.095	2.651	4.215	6.712
9.	Spain	9.62	11.016	9.922	2.230	2.945	2.774
10.	France	12.639	13.844	10.901	4.593	5.112	4.836
11.	Croatia	12.465	13.681	13.085	1.483	1.355	1.286
12.	Italy	10.923	11.597	9.846	2.942	2.855	2.702
13.	Cyprus	18.23	20.181	21.979	2.491	2.646	2.897
14.	Latvia	14.355	17.518	18.04	1.501	0.920	0.975
15.	Lithuania	17.985	20.229	22.681	2.396	2.527	2.327
16.	Luxembourg	29.062	28.705	28.587	14.618	14.828	17.217
17.	Hungary	11.719	14.818	14.741	1.759	1.879	1.624
18.	Malta	11.745	10.587	18.095	6.847	5.173	4.287
19.	Netherlands	7.9	7.391	7.745	7.175	8.429	8.281
20.	Austria	25.373	24.866	21.267	7.728	7.428	7.008
21.	Poland	16.65	19.039	17.615	4.492	4.621	4.793
22.	Portugal	14.959	16.808	17.097	1.612	1.546	1.427
23.	Romania	23.154	23.695	29.616	7.338	10.425	9.012
24.	Slovenia	14.976	16.511	16.908	3.576	3.964	2.661
25.	Slovakia	13.416	14.625	13.278	2.340	2.277	1.953
26.	Finland	31.419	35.258	33.617	20.993	23.253	22.359
27.	Sweden	25.317	25.79	24.932	14.664	13.628	14.272

Source: Authors' results based on Eurostat data.

Table 3

Indicators for calculating the technological efficiency of the CE in EU countries in 2016–2020

No	Country	Indicators								
		size Q_f		size $\tilde{Q}_f$		Technological efficiency E^{MW}		Intensity of development	Indicator of technological efficiency development	
		Material footprint	Waste generation	Material footprint	Waste generation	E_{fj}^{MW}	E_{bj}^{MW}	I_j	Indicator value E_j	E_j rank
1.	Belgium	16.294	6.361	14.6715	6.13	0.582	0.015	0.9739	0.355	23
2.	Bulgaria	24.920	20.033	22.7955	18.409	0.192	0.830	−3.3145	0.447	14
3.	Czechia	17.929	4.718	16.763	4.158	0.752	−0.126	1.1678	0.401	20
4.	Denmark	23.397	3.741	24.5	3.597	0.853	0.017	0.9796	0.519	9
5.	Germany	16.178	4.924	15.5685	4.874	0.687	−0.007	1.0095	0.409	16
6.	Estonia	36.592	16.627	32.231	14.395	0.553	0.579	−0.0468	0.563	3
7.	Ireland	13.525	2.541	12.1415	2.8945	0.762	0.028	0.9638	0.468	13
8.	Greece	11.267	1.718	11.181	2.1845	0.805	0.400	0.5025	0.643	1
9.	Spain	12.412	3.116	11.167	2.673	0.761	0.064	0.9153	0.482	12
10.	France	15.049	5.388	12.975	4.9905	0.615	−0.003	1.0053	0.368	21
11.	Croatia	14.897	1.424	13.991	1.4535	0.896	−0.001	1.0009	0.537	7
12.	Italy	12.271	3.008	11.0585	2.975	0.731	−0.030	1.0405	0.427	15
13.	Cyprus	22.132	2.395	22.0555	2.443	0.889	0.054	0.9391	0.555	4
14.	Latvia	20.681	0.865	19.3605	1.183	0.939	0.007	0.9923	0.566	2
15.	Lithuania	22.473	2.727	22.577	2.5615	0.887	0.018	0.9797	0.539	6
16.	Luxembourg	28.348	12.439	28.4675	13.5285	0.525	0.223	0.5744	0.404	19
17.	Hungary	17.917	2.134	16.329	1.9465	0.881	0.022	0.9750	0.537	8
18.	Malta	9.429	6.059	13.762	6.453	0.531	−0.196	1.3683	0.240	26
19.	Netherlands	6.882	8.577	7.3135	7.876	−0.077	0.373	5.8490	0.103	27
20.	Austria	24.359	7.848	22.813	7.788	0.659	−0.099	1.1503	0.356	22
21.	Poland	21.428	4.449	19.5215	4.4705	0.771	0.076	0.9010	0.493	10
22.	Portugal	18.657	1.665	17.877	1.6385	0.908	0.004	0.9955	0.547	5
23.	Romania	24.236	11.838	26.926	9.588	0.644	0.051	0.9201	0.407	18
24.	Slovenia	18.046	5.267	17.477	4.4215	0.747	−0.101	1.1349	0.408	17
25.	Slovakia	15.834	2.601	14.556	2.4705	0.830	−0.029	1.0350	0.486	11
26.	Finland	39.097	24.147	36.357	22.57	0.379	0.240	0.3682	0.323	24
27.	Sweden	26.263	12.984	25.5975	13.824	0.460	0.051	0.8881	0.296	25

Source: Authors' results

From Table 3, it can be observed that the indicators of CE technological efficiency development for the most highly developed EU countries, based on GDP per capita, are nearly 1.5 times lower than the corresponding values in the remaining countries. Several factors may contribute to this situation. Firstly, the level and structure of economic development in these countries could play a role – whether they have well-developed industrial production that generates more waste or, for example, focus on sectors such as agriculture, tourism and the like, which may produce fewer waste materials. This fact is supported by a comparison between developed and developing countries (Table 4).

Table 4

The impact of the economic development of EU countries on waste generation in 2020

No	Country	GDP per capita (EUR)	Material footprint (tonnes per capita)	Waste generation (tonnes per capita)	$\frac{Q_f^W}{Q_f^M}$
1	Luxembourg	182,650	28.587	17.217	0.602
2	Sweden	46,420	24.932	14.272	0.572
3	Finland	43,440	33.617	22.359	0.665
4	Greece	15,460	11.095	6.712	0.605
5	Latvia	15,920	18.04	0.975	0.054
6	Spain	23,610	9.922	2.774	0.278

Source: Authors' results based on Eurostat data.

From Table 4, it is evident that in highly economically developed countries, 1 tonne of material footprint results in approximately twice as much waste generation.

Another reason for this disparity is the non-comprehensive nature of this study – due to a lack of information, it only covers the first two indicators of the CE production and consumption block (material footprint and waste generation). The third essential stage, i.e., the efficiency of waste recycling systems, remains unexamined. However, previous research indicates that the efficiency of this stage is significantly higher in developed countries compared to developing countries, where the majority of waste is not recycled but rather transported to landfills (Ginevičius, 2022). Therefore, the results obtained in this study should be viewed as representing the partial analysis and evaluation of production and consumption issues. To obtain a complete assessment of the situation, further research on this problem should encompass all three stages: production, waste, and recycling.

5. CONCLUSION

In the context of intensive natural resource use and increasing environmental pollution, the CE concept gains particular significance. The application of its principles in production helps to reduce both the amount of material resources required and the waste generated. The effective management of a CE can only be achieved if its state can be quantitatively assessed at a desired point in time. This assessment is based on a system of indicators provided in international databases, consisting of five blocks. The primary block is production and consumption, which comprises eight indicators, two of which are essential: material footprint and waste generation. The ratio between them can be analysed as representing technological efficiency in the context of the CE, helping decision-makers to understand how waste generation can be minimised while maintaining the same production volume.

Literature sources reveal that the CE phenomenon has been extensively studied from various perspectives. However, there are limited studies focusing on evaluating its efficiency. To determine technological efficiency, one needs to know the quantity of material footprint and waste generation in a country for the years under consideration. Adequately assessing the first variable requires not only considering its absolute value, but also assessing the development changes that occurred during the analysed period. This is because the value alone may not accurately reflect, or may even contradict, the trend of previous changes.

It is beneficial to examine the CE as a process. In this case, the index for the quantitative assessment of its development combines two indicators. The first is the transformed value, reflecting developmental changes at the end of the analysed period; the second represents the intensity of development during the observed time frame.

Calculations of the development of production efficiency in EU countries for the 2016–2020 period have shown that it is nearly 1.5 times lower in highly developed countries than in other states. Several key factors have contributed to this situation, first among which is the level and structure of economic development in these countries. In countries with advanced industrial production, 1 tonne of material footprint generates approximately twice as much waste. Another reason for this result is the nature of this study – due to a lack of information, certain issues remain unresolved, and the crucial stage of the CE, waste recycling, has not been examined. In developed countries, waste recycling is solved at an advanced technological level, minimising the amount of waste sent to landfills. In contrast, in other countries, a significant portion of waste is transported to landfills.

Further research on this issue should encompass all three stages: production, waste, and recycling.

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