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RESEARCH ARTICLE

Towards achieving net zero emission targets and sustainable development goals, can long-term material footprint strategies be a useful tool?

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Abstract
This study analyzes material footprint (MF), which can be essential in achieving net zero emission targets and sustainable development goals for EURO-26 countries. Increasing the efficiency of MF rather than domestic material consumption is more effective in reducing emissions. Therefore, this study examines the relationship between MF, economic growth, and CO_2 emissions for EURO-26 countries. For empirical analysis, second-generation panel cointegration tests and long-term coefficient estimators, which consider the cross-sectional dependence, are employed. The empirical results indicate that (i) there is a long-term relationship between the variables and (ii) MF increases the CO_2 emissions. However, the positive relationship between economic growth and CO_2 emissions is statistically insignificant. According to the individual results, while the impact of MF on CO_2 emissions is negative in developed countries, MF increases CO_2 emissions in developing countries in general. Overall findings reveal that long-term material footprint strategies should be implemented in EURO-26 countries and material footprint policies can be used as a strategic tool to achieve net zero emission targets and sustainable development goals (SDGs).

Keywords Material footprint strategies · Material footprint · CO_2 emissions · Sustainable development goals

Introduction

One of the primary issues that the entire globe is closely watching is the fact of climate change. Since the 1980s, environmental pollution has started to become evident. Therefore, the countries organized under the United Nations' umbrella have discussed policies to solve this problem at the Conference of the Parties (COP). At the 26th UN Climate Change Conference (COP26) held in Glasgow in 2021, countries signed an agreement that includes a series of measures to be taken against climate change. The agreement includes important decisions such as a commitment to phase out coal, a regular review of emission reduction plans, and more financial support to developing countries (United Nations 2021a). The Paris Agreement, signed in 2015, is the strongest agreement among the international climate change negotiations. This agreement is aimed at building zero-emission and climate-resilient societies (Karakaya 2016). Following the Paris Agreement, long-term climate targets were set and countries' emission reduction has been monitored through the INDC (intended nationally determined contribution) mechanism. Implementing the national net zero policies set in the Paris Agreement will play a critical role in limiting global warming to 1.5 °C (Runsen et al. 2022; Soest et al. 2021). The net zero emission concept has been defined as reducing society's impact on the climate and the environment (Worth 2005; United Nations Environment Program 2008). It is expected that global temperatures will become stable if these targets are met (Intergovernmental Panel on Climate Change 2021; Lee et al. 2021). However,

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for the 1.5 °C target to be achieved, CO_2 and greenhouse gas emissions (GHG) must fall to zero by 2050 and 2070 (Climate Action Tracker 2021).

MF is mentioned in the 8th[1] and 12th[2] sustainable development goals prepared by the United Nations. The United Nations (2019) defines MF as "*the total amount of raw materials extracted to meet final consumption demands. The total material footprint is the sum of the material footprint for biomass, fossil fuels, metal ores, and non-metal ores*." Together with reducing emissions from fossil fuels, sustainability and efficiency in the field of MF are essential tools that can be used to achieve the net zero targets and SDGs.

In order to achieve the net zero emission targets set for 2050 and 2070, it will not be enough to focus only on reducing energy-related emissions. In particular, developed countries have already made significant progress in this area. Reducing MF and energy efficiency will significantly contribute to sustainable development. According to the UNEP (2020), although energy efficiency and low carbon resources increase in countries with ongoing development processes, energy demand and CO_2 emissions have increased. Although materials and products are crucial determinants of industrial emissions (Scott et al. 2018), this fact is neglected, and climate change strategies generally focus on low-carbon energy technologies and energy efficiency (Pauliuk et al. 2017). The lack of a firm plan for material efficiency and cyclical economics limits the fight against climate change (Pauliuk et al. 2017). In this regard, it is necessary to consider different instruments. As the paper's framework, MF is one of these essential tools.

Economic and industrial development can help countries by dematerializing and decarbonizing production systems (Steinberger et al. 2013). In this sense, developed countries are more successful in the field of material efficiency thanks to their technology, infrastructure, and environmental regulations. The advantages of these countries can be listed as follows: (i) structural changes in production and consumption patterns toward the service sector (Kander 2005; Wiedmann et al. 2015), (ii) technological development (Dinda 2004), (iii) technical capacity (Steinberger et al. 2013), (iv) strict environmental regulations and technical innovation (Stern 2004), (iv) outsourcing of contaminated material-intensive productions to less-developed countries (Stern et al. 1994; Suri and Chapman 1998), (v) high institutional quality (Muradian and Martinez-Alier 2001), and (vi) resource efficiency (Wiedmann et al. 2015). Developed countries can maintain economic growth and increase environmental quality thanks to technological capacity and human capital. Many studies have found that developed countries have decoupled economic growth from emissions (Raupach et al. 2007; Naqvi and Zwickl 2017; Wu et al. 2018; Mikayilov et al. 2018; Wang and Su 2020). Decoupling targets are also discussed for the new sustainable development goals (Bizikova et al. 2014).

On the other hand, Wiedmann et al. (2015) disagree that while economic growth increases in some developed countries, the use of natural resources decreases. They assert that there is no relative decoupling between the variables. Accordingly, governments generally use the findings obtained from domestic material consumption. However, the domestic material consumption is limited data since it is based on the amount of material consumed directly within the country. MF analysis is based on a production chain's process from the beginning to the end. In this context, Wiedman et al. (2015) used MF analysis to claim that the decouplings seen in many countries are actually less or even not valid. Wang et al. (2013), on the other hand, found that developed countries are more successful than developing countries in decoupling and this is attributed to the differences in their economic development levels. Although the European Union is seen as successful thanks to the environmental policies it implemented, Giljum et al. (2008) assert that MF results demonstrate the contrary. In addition, some studies indicate that these observations become problematic when trade (Krausmann et al. 2017; Schaffartzik et al. 2014) and population (Bithas and Kalimeris 2018) are taken into account.

The motivation of this study is to investigate whether the success of EURO-26 countries in emission reduction and energy efficiency is also valid for MF. According to the European Environment Agency (2019) report, only 10% of the material used in Europe is recovered and reused. Therefore, the circular economy in Europe is still in its developmental stage. This paper contributes to the literature in the following areas. (i) There are few studies in the current literature on MF. The MF issue is thought to be neglected since studies generally focus on the relationship between domestic material consumption and economic growth. Domestic material consumption is generally based on domestic consumption of the material. However, the MF comprises energy consumption caused by the material from production to consumption which is more realistic regarding environmental policies (Razzaq et al. 2021). In this sense, many studies have focused on the MF results to fill this gap (Giljum et al. 2016; López et al. 2017; Greiff et al. 2017; Ma et al. 2018; Schandl et al. 2018; Jiang et al. 2019; Ansari et al. 2020; Karakaya et al. 2021; Wang et al. 2022). To the best of the authors' knowledge, this paper is the first attempt to estimate the relationship between MF, gross domestic product (GDP), and CO_2 via second-generation panel data approaches. (ii) The study proposes emission reduction strategies to policymakers for MF strategies within the context of SDGs. In this context, in addition to energy-based emission reduction, MF policies are thought to be effective in closing the emission gap for the net zero targets. Before the empirical analysis, preliminary tests were carried out and it was seen that cross-sectional dependence and heterogeneity should be considered for EURO-26 countries. Therefore, the Westerlund panel cointegration test, which considers cross section and heterogeneity and gives more unbiased and robust results, was used. (iii) Focusing on the EURO-26 countries, the study examines whether the success of European countries at domestic material consumption is also valid for the MF. In this regard, the importance of material efficiency is discussed. Based on all these, the study investigated the post-financial crisis period of 2008 (2008–2019). (iv) The reason why we examine the EURO-26 countries is that it is recently claimed that there is a decoupling between economic growth and environmental pollution in many European countries. Therefore, we aim to analyze whether there is a decoupling between MF and economic growth. The plan of the study is as follows. The first part presents the theoretical background of MF. The second part gives a literature summary. The third part introduces the methodology and reports empirical findings. In conclusion, empirical results are discussed, and some policy recommendations are presented.

Literature

Climate change and environmental problems continue to pose problems for current and future generations. While countries are struggling with these problems, they are also trying to increase their welfare by maintaining economic growth. Therefore, it leads to a decrease in environmental quality while economic growth rises. However, it has recently been argued that European countries are achieving sustainable economic growth and diverging from emissions. Many studies detect successful decomposition between domestic material consumption and emissions. However, similar success cannot be seen in MF analyses, because domestic material consumption is based only on local consumption, while MF is based on consumption throughout the supply chain (Razzaq et al. 2021). For this reason, most developed countries that outsource material-incentive products have failed in terms of MF. Therefore, sustainable policies in MF will be more realistic than the domestic material consumption decomposition and help achieve net zero emission targets and SDGs. This study investigates the achievement SDGs through the material footprint. As it is known, there are 17 sustainable development goals. Recently, some studies have investigated the role of environmental factors in achieving sustainable development goals and net zero targets (Adebayo et al. 2022a, b; Ibrahim et al. 2022; Zhang et al. 2022; Akadiri et al. 2022; Wu et al. 2022; Wang et al. 2023). The section includes studies examining the relationship between material use, emissions, and economic growth. In this context, studies in the literature are categorized as global, regional, and national. Zhong et al. (2010) stated that the main concerns about decoupling stem from method measurements and decoupling have different definitions. Accordingly, there are eight measurement methods for decoupling, and there are some differences among these methods. Therefore, decoupling findings might be disputable.

First of all, most of the studies examining the environment-economic growth interaction investigate the validity of the Environmental Kuznets Curve (EKC) hypothesis (Sharif et al. 2019, 2020a, b; Suki et al. 2020; Godil et al. 2021; Ahmed et al. 2022a, b; Ali et al. 2022; Adebayo et al. 2022a).

Haberl et al. (2020) conducted an extensive literature review on whether there is a decoupling between GDP, resource use, and GHG emissions. In this regard, they said that absolute long-term decoupling is rare; however, recently, some industrialized countries have succeeded in decoupling their GDP and CO_2 emissions based on production and consumption. According to the researchers, effective resource use or emissions reduction is necessary for green growth. However, degrowth will occur if resource use or emission reduction is preferred to GDP. Another literature review was carried out by Vaden et al. (2020). According to this study, researchers mostly found a decoupling between CO_2 and GDP, but they could not find any findings on national/international net resource decoupling as part of the economy.

Bithas and Kalimeris (2022) found an increasing decoupling between total and per capita resource use and material density at global and national levels. This decoupling arises from faster growth in total and per capita resources rather than the decrease in the resources per unit of GDP. Ward et al. (2016) compared the results from the past (1980–2010) and future projections (2015–2050–2150). The results determined that GDP growth cannot be decoupled with material and energy use in the world. For this reason, they disagree with developing a growth-oriented policy within the decoupling framework. In parallel with this, Hickel and Kallis (2020) stated that there is no decoupling between economic growth and resource use on a global scale in the ongoing economic growth process. The authors note that even under optimistic policy conditions, the reduction of emissions required to limit global warming to 1.5 °C or 2 °C is not feasible. They suggest to policymakers that green growth is probably a misguided goal and alternative strategies should be considered. Frodyma et al. (2020) investigated whether there is a decoupling between GDP and fossil fuel consumption in 141 countries with both domestic material consumption and MF analysis. Results vary by method. While domestic material consumption results show a relative decoupling, MF analysis results indicate that there is no decoupling in many countries.

In this part, the findings for developed and developing countries are compared. First of all, Wang et al. (2013) examined the relationship between environmental indicators and economic growth in the USA, Japan, China, and Russia. According to the results, decoupling is higher in the USA and Japan since these countries are at different levels in terms of economic development. Wang et al. (2018a) reached similar findings. They found that developed countries have better decoupling condition than developing countries at the domestic material consumption level. Still, there is not much difference between developed and developing countries at the MF level. In addition, the decoupling of developing countries is better than developed countries, according to the MF analysis. These results are valid for three BRICS countries (China, India, and Brazil) and three OECD countries (USA, Australia, and Japan). As seen in many studies, the results of the domestic material consumption analysis show that there is decoupling for developed countries. In contrast, these divergences are more limited or sometimes even absent, according to MF analyses. Wang et al. (2018b) compared the results of decomposition and decoupling in their study, examining the two most polluting countries in the world, China and the USA. They detected decoupling for each country. Wiedmann et al. (2015) claim that OECD economies have a significant potential to reduce their material production and carbon emissions, and they stated that their impact on the economy is limited. They argue that emerging economies like China could grow at much lower environmental costs. Finally, if global efforts on resource efficiency increase, they assert that decarbonization and dematerialization can be achieved without harming the economy. Lonca et al. (2019) investigated decoupling in the framework of circularity. Accordingly, three types of circularity measures are required in the EU to reduce greenhouse gas emissions from the steel, plastics, aluminum, and cement industries by 2050. These are material circulation, material efficiency, and new circular business models. The authors determined that to achieve the required GHG emission reductions, global environmental efficiency must be 67% for the steel industry, 57% for plastics, 56% for aluminum, and 44% for cement. Sanyé-Mengual et al. (2019) determine an absolute divergence between the environmental impacts of consumption and GDP for 2005–2014 in the EU-28. According to Vavrek and Chovancova (2016), there is a strong decoupling of economic growth and greenhouse gas emissions in V4 countries (Czech Republic, Hungary, Slovakia, and Poland). Nevertheless, countries should create new and rapidly implemented energy demand policies to reduce greenhouse gas emissions in the context of 2050 targets.

Some studies were also conducted for countries. Martinico-Perez et al. (2018) found a relative decoupling between economic growth and material density for the Philippines. The reason is the increasing service sector in the Philippines. A similar study was conducted by Yu et al. (2013) using domestic material consumption analysis for China. Accordingly, a decoupling occurred in China during the 1978–2010 period through material energy efficiency. However, a relevant decoupling level decreased considerably due to high consumption and mineral extraction for 2001–2010. Yu et al. (2017) examined the decoupling relationship between environmental pressure and GDP at the city level. According to the results, there was an absolute decoupling of SO_2, soot, and wastewater emissions in Chongqing between 1999 and 2010. Technological changes are the main reason for the decoupling. Brizga (2019) examined Latvia; results reveal that resource extraction and consumption are increasing steadily and are not decoupled from economic growth since material productivity is low.

Table 1 Data (EURO-26 countries)

Belgium	Bulgaria	Czechia	Slovenia
Denmark	Germany	Estonia	Slovakia
Ireland	Greece	Finland	Spain
Croatia	Cyprus	Latvia	Sweden
Lithuania	Luxembourg	Hungary	Switzerland
Malta	Netherlands	Austria	
Poland	Portugal	Romania	
Data	**Unit**	**Data source**	
LNCO2	Kilo tonnes	Our World in Data, Ritchie et al. (2020)	
LNGDP	Constant (2015, US$)	World Bank (2022)	
LNMF	Tonnes	Eurostat (2022)	

In this study, studies on MF are presented comparatively. The literature review shows that MF studies are generally focused on decoupling. However, there is a gap in the literature regarding the relationship between MF and sustainable development. In this context, studies examining the relationship between the MF and the sustainable development index and its sub-components will contribute to the literature.

Model and data set

This study investigates the relationship between MF, economic growth, and CO_2 emissions for EURO-26 countries by panel data method. Table 1 provides information about the sample and variables used in the empirical analysis.

In the empirical model, CO_2 emissions represent environmental degradation. In addition, the GDP represents economic growth. Many studies in the literature associate environmental degradation with economic growth

(Al-Mulali 2012; Borhan et al. 2012; Mitić et al. 2017; Bekhet and Othman 2018; Li et al. 2020; Awan and Azam 2021; Shah et al. 2022). The primary variable MF was added to the model to determine how it relates to CO_2 emissions. MF does not focus on extracting raw materials at home or abroad; it refers to how much material extraction is required throughout the production chain to produce the product (Eurostat 2021). Eurostat (2021) generates raw material consumption (RMC) data it represents MF in this study. It is formulated as follows.

$$\mathrm{RMC} = (\mathrm{RMI} - \mathrm{EXP\_RME}) \tag{1}$$

where RMI represents the sum of domestic extraction and total imports in raw material equivalents and EXP_RME represents total exports in raw material equivalents. Therefore, we see that MF considers not only the domestic consumption of the material but also all the stages it goes through.

Based on the information above, we created the model in Eq. 2 for the study.

$$\mathrm{LNCO}_{2\mathrm{it}} = \gamma_0 + \gamma_1 \mathrm{LNGDP}_{\mathrm{it}} + \gamma_2 \mathrm{LNMF}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{2}$$

where $LNCO_2$ denotes CO_2 emissions, LN GDP economic growth, LNMF material footprint, and $\varepsilon_{\mathrm{it}}$ error term. All variables are in log terms.

Empirical strategy

This section includes the methodology for empirical analysis and the results. To avoid the spurious regression problem, it is necessary to determine the stationary level of the series. However, unlike time series analysis, cross-sectional dependence and homogeneity tests must be applied in panel data analysis. For this reason, before starting the analysis, it is necessary to check whether the variables contain cross-sectional dependence and to decide which unit root and cointegration tests will be applied to the variables (first or second-generation tests). Based on the test results, we applied second-generation unit root and cointegration approaches that consider the cross section and heterogeneity for empirical analysis.

CADF (Cross-sectional Augmented Dickey-Fuller) unit root test developed by Pesaran (2007) is used in this study to test the stationarity. First, CADF test statistic values are calculated for all units forming the panel. Then, the arithmetic average of these tests is taken and CIPS (Cross-sectional Augmented IPS) statistic values are obtained for the whole panel. The CADF test results deliver a stationarity test for countries, while the CIPS test provides for the entire panel. The CADF and CIPS test calculations are shown in Eqs. (3)–(9):

$$t(N,T) = \frac{\Delta y'_i \overline{M}_i y_{i-1}}{\tilde{\sigma}^2 \left(\Delta y'_{i-1} \overline{M}_i, \Delta y_{i-1} \right)^{1/2}}, \tag{3}$$

$$\overline{M} = \left(\tau, \Delta \overline{y}, \overline{y}_{t-1} \right), \tag{4}$$

$$\tau = (1, 1, \dots)', \tag{5}$$

$$\Delta \overline{y} = \left(\Delta \overline{y}_1, \Delta \overline{y}_2, \dots \Delta \overline{y}_t \right)', \tag{6}$$

$$\overline{y}_{t-1} = \left(\overline{y}_0, \overline{y}_1, \overline{y}_{t-1} \right)', \tag{7}$$

$$\overline{\sigma}^2 = \frac{\Delta y'_i \overline{M}_i, \Delta y_i}{T-4}, \tag{8}$$

$$\mathrm{CIPS} = N^{-1} \sum\nolimits_{i=1}^{n} t(N,T). \tag{9}$$

"The cross-sectional dependence is based on the assumption that a shock occurring in any of the units forming the panel affects the other units. Globalization has reached a particular stage, and this process has been continuing rapidly. Many countries establish economic relations regardless of geography and work on systems based on mutual trade. Therefore, an economic shock in one country can influence others directly and indirectly" (Sofuoğlu and Ay 2020). Consequently, it is necessary to test the presence of cross-sectional dependence among the variables before the analysis and decide on the appropriate approach (Menyah et al. 2014).

The panel cointegration method developed by Westerlund (2007) is based on the error correction model, and this test takes into account the cross-sectional dependence. According to this approach, four separate test statistics are used to determine the existence of a long-term relationship between variables (Pτ, Pα, Gτ, and Gα). Accordingly, Pτ and Pα statistics are based on combining information about the error correction model. However, this information is not considered by Gτ and Gα statistics. According to the results from the Pτ, Pα, Gτ, and Gα tests, the cointegration relationship is tested with the null hypothesis (there is no cointegration). Equation (10) shows the model used by Westerlund (2007).

$$\Delta y_{it} = \delta_i d_+ + a_i y_{i\lambda-1} + \sum\nolimits_{j=1}^{P_i} a_{ij} \Delta y_{it-j} + \sum\nolimits_{j=0}^{P_i} \gamma_{ij} \Delta x_{it-j}, \tag{10}$$

where d_t and λ_i represent the deterministic components and long-term coefficients, respectively. Besides, α_{ij} and γ_{ij} show short-term parameters. The null hypothesis, defined as H0: pi = 0 for all i, is tested against the alternative hypothesis as H1: pi < 0 for all I through Pα and Pτ tests. These test statistics are shown in Eqs. (11) and (12).

$$\text{Pa} = T\hat{a}, \tag{11}$$

$$\text{P}\tau = \frac{\hat{a}}{SE(\hat{a})}. \tag{12}$$

Alternatif hipotez için ise, Gα ve Gτ testleri için en azından bazı i için H1: pi < 0 olarak tanımlanmaktadır. For the alternative hypothesis, it is defined as H1: pi < 0 for some Gα and Gτ tests. These statistics are in Eqs. (13) and (14).

$$\text{Ga} = \frac{1}{N}\sum_{\text{i}=1}^{N}\frac{T\hat{a}\text{i}}{\hat{a}\text{i}(1)}, \tag{13}$$

$$\text{G}\tau = \frac{1}{N}\sum_{\text{i}=1}^{N}\frac{\hat{a}\text{i}}{SE(\hat{a}\text{i})}. \tag{14}$$

If a long-term relationship is determined between the variables, long-term coefficients can be calculated using appropriate econometric methodologies according to cross-sectional dependence findings. In this study, the Common Correlated Effects Mean Group estimator (CCEMG) (Pesaran 2006) and Augmented Mean Group (AMG) (Eberhardt and Bond 2009) estimators, which consider cross-sectional dependence and heterogeneity, are used.

$$y_{it} = \beta_i' x_{it} + u_{it}, \tag{15}$$

$$u_{it} a_i = a_i + \lambda_i' f_t + \varepsilon_{it} \tag{16}$$

In Eqs. (15) and (16), an Augmented Mean Group estimator is obtained by adding a "common dynamic effect" to each cross-sectional regression to calculate the cross-sectional dependence. The AMG estimator is obtained in two stages. First, the variables' first difference is taken, dummies are added to the model, and the model is estimated. Then, u_t^* obtained in the first step is added to Eq. (15) to expand the model to account for the cross-sectional dependence. Thus, Eq. (20) is obtained by including N in each standard country regression.

$$\Delta y_{it} = b_i x_{it} + y_{it-j} + \sum_{t=2}^{T} c_{it}\Delta D_t + e_{it}, \tag{17}$$

$$\hat{c}_t \equiv \hat{\mu}^*{}_t, \tag{18}$$

$$y_{it} = a_i + b_i' x_{it} + c_i t + d_i \hat{\mu}^*{}_t + e_{it}, \tag{19}$$

$$\hat{b}_{\text{AMG}} = N^{-1}\sum_{\text{i}}\hat{b}_i. \tag{20}$$

f_t, λ_i, Dt show the unobservable factor, factor loads, and dummies. And $\hat{\mu}^*{}_t$ indicates the new variable, which considers the cross-sectional dependence.

$$\hat{b}_{\text{CCEMG}} = \frac{1}{N}\sum_{\text{i}=1}^{N}\hat{b}_{\text{i}}. \tag{21}$$

AMG estimates the long-term cointegration coefficient for the whole panel by weighting the arithmetic mean of the long-term coefficients belonging to cross sections. In this aspect, it provides more robust results than the CCEMG estimator. In addition, the AMG estimator considers common factors and dynamic effects on variables and gives effective results in unbalanced panel analyses. In this regard, it can be said that the AMG estimator gives more robust results than the CCEMG estimator (Eberhardt and Bond 2009). Figure 1 shows the analysis flowchart of the present study.

Empirical results

According to Table 2, all the test results reject the null hypothesis "*H0: there is no cross-sectional dependence*." Based on this, we apply a second-generation unit root test to understand whether the variables are stationary. However, another problem at this point is determining which second-generation unit root test is appropriate for the analysis. For this purpose, we also apply homogeneity to the variables.

The Hsiao homogeneity test results in Table 3 reject all three hypotheses that accept homogeneity at the 10% significance level. In addition, H1 and H2 hypotheses are rejected, but their alternative is considered to be heterogeneous. Similarly, the Delta test results show that the panel has a heterogeneous structure. Finally, we conclude that the coefficients are heterogeneous.

According to the results obtained from Table 3, we use unit root and cointegration methods that consider cross-sectional dependence and heterogeneity for long-term analysis. For this purpose, Table 4 shows second-generation CADF test results.

Table 5 shows the unit root test results applied across the panel. Accordingly, while all variables have a unit root at the level, they are stationary at the first difference. These results allow us to test whether there is a long-term relationship between the variables. Table 6 indicates Westerlund's cointegration test results. This test considers cross-sectional dependence and allows heterogeneity.

Table 6 shows Westerlund (2007) panel cointegration test results. As seen, the null hypothesis of no cointegration is rejected by Gτ, Gα, Pτ, and Pα test statistics. Therefore, all test statistics present evidence in favor of a long-run cointegration relationship. With this result, examining the long-term coefficients will also bring more clarity to the analysis. For this purpose, long-term coefficient estimations can be applied using AMG and CCEMG estimators.

Fig. 1 Analysis flowchart

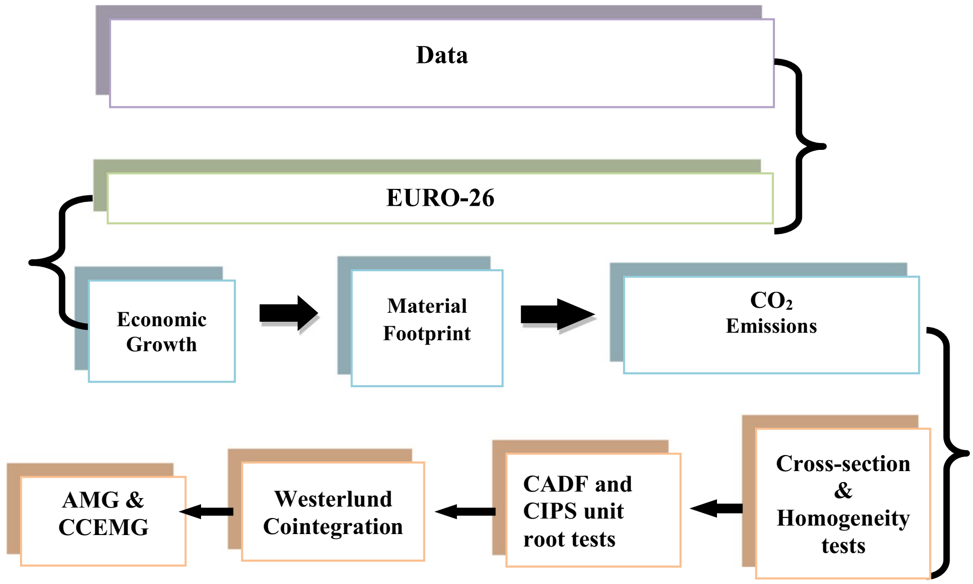

Table 2 Cross-sectional dependence test findings

Variables	LM	CD_{LM}	LM_{adj}	CD
LNCO2	2187.95***	65.83***	64.55***	44.14***
	(0.00)	(0.00)	(0.00)	(0.00)
LNGDP	3062.31***	97.63***	96.35***	48.55***
	(0.00)	(0.00)	(0.00)	(0.00)
LNMF	1043.64***	24.21***	22.94***	14.73***
	(0.00)	(0.00)	(0.00)	(0.00)

*, **, and *** indicate 10%, 5%, and 1% levels of significance. Figures in parentheses show probability values

Table 3 Hsiao and Delta homogeneity test

Hypothesis	f-statistics	Prob
H1	104.72	0.00*
H2	1.29	0.10*
H3	296.66	0.00***
Δ	– 1.35	0.17
Δ_{adj}	– 1.77	0.08***

*, **, and *** indicate 10%, 5%, and 1% levels of significance. Figures in parentheses show probability value

According to Table 7, it is seen that the MF variable is positive and statistically significant. Therefore, there is a positive relationship between MF and CO_2 emissions in the EURO-26 Region. In other words, MF increases environmental degradation. However, the variable of economic growth is positive but statistically insignificant. Both CCEMG and AMG test results are similar. Therefore, we might consider the results reliable. Finally, Table 8 presents individual AMG and CCEMG test results for EURO-26 Region. Energy consumption is one of the most critical reasons why MF increases CO_2 emissions. Many studies determined that energy consumption and energy intensity reduce environmental quality by increasing CO_2 emissions (Nejat et al. 2015; Adams et al. 2020; Alharthi et al. 2021; Amin and Dogan 2021).

Table 8 shows the individual findings. Accordingly, we evaluate the results of the two methods together. If a statistically significant result is detected in one of the two tests, there is a long-term relationship between the variables. Obtaining similar results from both tests means a strong relationship. Individual AMG and CCEMG results show positive and negative relationships in the long run. Accordingly, MF increases CO_2 emissions in Bulgaria, Czechia, Estonia, Greece, France, Croatia, Hungary, Malta, Portugal, and Finland. However, MF decreases CO_2 emissions in Germany, Spain, Luxembourg, Slovenia, and Sweden. These results show that developed countries (except for France and Finland) are more successful in MF. However, developing countries (except for Slovenia) fail to achieve a sustainable MF. While MF reduces emissions in 4 developed countries (Germany, Spain, Sweden, and Luxembourg), it increases emissions in 8 developing countries (Bulgaria, Czechia, Estonia, Greece, Croatia, Hungary, Malta, and Portugal).

The results reveal the need to establish long-term MF strategies, especially in developing countries. Comparing domestic material consumption with MF, Wiedmann et al. (2015) found that MF diverged less than economic growth and claimed that income growth does not increase resource efficiency. Even the absolute decoupling found by the domestic material consumption might not prove the resource efficiency as income rises. Therefore, in many countries that achieve decoupling between domestic material consumption and GDP, there is no decoupling in RMC because RMC considers the unaccounted

Table 4 CADF test results

Level (t-stats)				First difference		
	LNCO2	LNGDP	LNRMC	ΔLNCO2	ΔLNGDP	ΔLNRMC
Belgium	−0.67	−3.85****	−1.90	−3.98**	−2.49	−2.94
Bulgaria	−2.84	−1.99	−1.49	−3.30**	−1.64	−3.10
Czechia	−1.61	0.47	−2.37	−1.78	−1.02	−4.45**
Denmark	−2.05	−1.60	−1.72	−4.53**	−3.77***	−4.07**
Germany	−0.32	−2.86	−3.29***	−2.35	−1.93	−2.32
Estonia	−0.30	−1.61	−1.72	−1.46	−3.73***	−1.97
Ireland	−2.25	−1.87	−0.62	−2.16	−3.25***	−2.55
Greece	−3.13	−1.83	−3.25***	−4.25**	0.19	−2.24
Spain	−2.64	−1.07	−2.40	−3.25***	−3.40	−1.74
France	−3.13	−2.07	−2.58	−3.95***	−0.88	−2.74
Croatia	−1.09	−0.99	−5.49**	−3.15	−2.75	−3.32
Italy	−2.29	−0.04	−0.39	−2.32	−2.50	−2.12
Cyprus	−0.50	−0.50	−2.50	−1.68	−2.79	−2.17
Latvia	−1.61	−2.46	−3.73	−3.29***	−6.71*	−2.40
Lithuania	−1.41	−1.54	−2.60	−2.96	−5.87*	−3.56
Luxembourg	−1.57	−0.80	−1.02	0.04	−4.82**	−0.89
Hungary	−0.44	−1.91	−0.04	−1.28	−1.96	−1.95
Malta	−2.00	0.62	−3.71***	−1.95	−2.73	−3.82***
Netherlands	−5.55*	−0.12	−1.14	−5.53*	−3.04	−4.69**
Austria	−2.63	−1.68	−2.61	−5.46**	−1.44	−3.18
Poland	−1.18	−5.27**	−3.38***	−0.78	−0.41	−2.22
Portugal	−0.03	−0.01	−2.25	−2.92	−3.77	−3.64***
Romania	−5.32**	−2.79	−1.21	−5.16**	−3.42	−4.39**
Slovenia	−1.85	−0.33	−1.79	−3.47***	−1.37	−1.71
Slovakia	−1.65	−4.27**	−2.07	−6.74*	−3.54***	−1.29
Finland	−0.13	−0.97	−1.75	−4.31**	−1.90	−2.95
Sweden	−3.81	−8.64*	−0.53	−4.08**	−4.66**	−6.65*
Switzerland	−2.19	−0.76	−3.29***	−4.27**	−5.49**	−6.50*

Critical values: 1%: −5.53, 5%: −3.88, 10%: −3.22. *, **, *** denote 10%, 5% and 1% significance levels, respectively

Table 5 CIPS test results

At level		At first difference	
Variables	t-stat	Variables	t-stat
LNCO2	−1.94	ΔLNCO2	−3.22*
LNGDP	−1.81	ΔLNGDP	−2.89*
LNMF	−2.17	ΔLNRMC	−3.06*

*, **, and *** indicate 10%, 5%, and 1% levels of significance. Figures in parentheses show probability value. Critical values: 1%: 2.54, 5%: 2.27, 10%: 2.12

Table 6 Westerlund (2007) cointegration test

Statistic	Value	Prob
Gτ	−25.12	0.00*
Gα	−59.24	0.00*
Pτ	−140.87	0.00*
Pα	−54.39	0.00*
Variance ratio	**141.82**	**0.00***

*, **, and *** indicate 10%, 5%, and 1% levels of significance. Figures in parentheses show probability value

effects of domestic material consumption (Giljum et al. 2015). It is clear from this situation that more material extraction was outsourced. In addition, while empirical findings confirm Steinberger et al. (2013)'s thesis that developed countries are more advantageous in decarbonization, they do not support Wang (2013)'s view that there is not much difference between developed and developing countries in terms of MF. Because in the analysis, it is seen that developed countries are more successful.

For the EURO-26 panel overall, the finding that MF increases CO_2 emissions is supported by some studies (Ansari et al. 2020, Sahoo et al. 2021). These results show that it is too early to claim a decoupling success between emissions and MF in the European Region. In addition, empirical results

Table 7 Long-run coefficient estimation

Variable	Coefficient	Std. Err	Prob
CCEMG estimator			
LNGDP	3.64	3.37	0.28
LNMF	5.09**	2.25	0.02
AMG estimator			
LNGDP	0.61	1.76	0.73
LNMF	3.72*	1.50	0.01

*, **, and *** indicate 10%, 5%, and 1% levels of significance

Table 8 AMG and CCEMG test results by country

		AMG		CCEMG	
Country	Variable	Coefficient	Prob	Coefficient	Prob
Belgium	LNGDP	−0.06	0.80	−0.23	0.47
	LNRMC	−0.19	0.60	−0.34	0.43
Bulgaria	LNGDP	0.01	0.98	−0.46	0.13
	LNRMC	−0.14	0.78	0.91	0.07*
Czechia	LNGDP	0.04	0.80	0.06	0.73
	LNRMC	30.32	0.03**	46.83	0.00***
Denmark	LNGDP	−0.14	0.56	−0.15	0.55
	LNRMC	−0.44	0.56	−0.39	0.66
Germany	LNGDP	14.21	0.49	27.48	0.31
	LNRMC	−0.51	0.05**	−0.70	0.02**
Estonia	LNGDP	−0.15	0.32	−0.23	0.18
	LNRMC	20.78	0.09*	32.83	0.02**
Ireland	LNGDP	−6.57	0.39	−10.42	0.13
	LNRMC	5.39	0.45	8.14	0.13
Greece	LNGDP	−0.11	0.70	−0.38	0.01***
	LNRMC	0.37	0.95	7.38	0.04*
Spain	LNGDP	0.18	0.70	0.18	0.43
	LNRMC	−1.45	0.01***	−1.42	0.02**
France	LNGDP	−1.25	0.00***	−1.06	0.00***
	LNRMC	0.45	0.01***	0.49	0.01***
Croatia	LNGDP	−0.30	0.11	−0.35	0.10*
	LNRMC	21.82	0.07*	21.84	0.07**
Italy	LNGDP	−0.03	0.44	−0.004	0.56
	LNRMC	0.01	0.69	0.002	0.87
Cyprus	LNGDP	−0.10	0.66	−0.01	0.98
	LNRMC	0.02	0.72	0.07	0.41
Latvia	LNGDP	−0.12	0.54	−0.15	0.60
	LNRMC	0.02	0.78	0.03	0.76
Lithuania	LNGDP	0.18	0.14	0.19	0.25
	LNRMC	0.03	0.95	0.12	0.86
Luxembourg	LNGDP	−0.72	0.00***	−0.58	0.00***
	LNRMC	0.00	0.33	−0.001	0.18
Hungary	LNGDP	−0.17	0.25	−0.15	0.35
	LNRMC	15.42	0.04**	0.10	0.93
Malta	LNGDP	−0.29	0.47	−0.28	0.50
	LNRMC	0.14	0.05**	0.23	0.03**
Netherlands	LNGDP	0.01	0.97	0.10	0.73
	LNRMC	−0.22	0.67	−0.09	0.91
Austria	LNGDP	−0.14	0.65	−0.21	0.64
	LNRMC	−0.28	0.67	−0.18	0.81
Poland	LNGDP	−0.03	0.69	−0.03	0.76
	LNRMC	−0.00	0.24	−0.004	0.11
Portugal	LNGDP	−0.01	0.01***	−0.01	0.00***
	LNRMC	0.39	0.00***	0.38	0.00***
Romania	LNGDP	0.01	0.06*	0.01	0.02**
	LNRMC	0.001	0.92	0.01	0.20
Slovenia	LNGDP	43.58	0.18	89.84	0.00***
	LNRMC	0.20	0.73	0.23	0.79

confirm the thesis that there is a carbon leakage and outsourcing problem in the European Union (Karakaya et al. 2021), especially in developing European countries.

Discussion and policy implications

According to the Sustainable Development Goals Report published by the United Nations (2021b), global MF increased by about 10% over 2000–2017. Consumption-based mitigation policies are essential tools to reduce environmental degradation. Reducing CO_2 emissions alone is insufficient to improve ecological quality in the world. In this context, MF is an appropriate tool as an essential policy proposal for improving environmental quality (Wiedmann et al. 2015). However, achieving a decoupling between economic growth and MF will become more difficult and complex if countries do not formulate specific MF strategies immediately. Many instruments tackle climate change, but this study is aimed at providing empirical evidence for integrating material productivity into climate policies. This study examines the relationship between MF and economic growth and CO_2 emissions over 2008–2019 for EURO-26.

The European Region has achieved significant success in reducing emissions in the fight against climate change. Domestic material consumption and MF strategies will provide different advantages in tackling climate change in the long run. Today, especially in Europe, there is success in decoupling between economic growth and domestic material consumption. However, achieving a decoupling between MF and economic growth is a real success in environmental sustainability. In this context, this study suggests that European countries that are successful in domestic material consumption should also consider MF strategies. The results show that there is a long-term relationship between MF and CO_2 emissions across EURO-26. As MF increases, the region's CO_2 emissions that cause climate change also increase. On the other hand, individual country results generally differ based on countries' development levels. Many studies have used various environmental indicators such as CO_2 emissions and ecological footprint, to measure environmental

Table 8 (continued)

		AMG		CCEMG	
Country	Variable	Coefficient	Prob	Coefficient	Prob
Slovakia	LNGDP	0.001	0.14	0.003	0.18
	LNRMC	−0.01	0.08*	−0.01	0.08*
Finland	LNGDP	−0.04	0.75	−0.12	0.51
	LNRMC	22.55	0.01[a]	25.80	0.01[a]
Sweden	LNGDP	−0.85	0.00[a]	−0.67	0.01[a]
	LNRMC	−0.001	0.90	0.00	0.95
Switzerland	LNGDP	−0.23	0.53	−0.41	0.27
	LNRMC	−0.39	0.67	−0.76	0.38

*, **, and *** indicate 10%, 5%, and 1% levels of significance

quality. This study considers the MF variable as suggested in previous papers (Giljum et al. 2015; Karakaya et al. 2021; Sahoo et al. 2021). The empirical findings are consistent with the findings of (Karakaya et al. 2021; Ansari et al. 2020, Sahoo et al. 2021).

The increase in efficiency in the material footprint will primarily be an effective tool in achieving the SDGs. Decoupling between material footprint, economic growth and CO_2 emissions will effectively help to achieve six sustainable development goals (Goal 7,[1] Goal 8,[2] Goal 9,[3] Goal 11,[4] Goal 12,[5] and Goal 13[6]). This achievement will (i) facilitate the supply of sustainable and modern energy for all, (ii) ensure a sustainable economic growth structure, (iii) ensure sustainable industrialization and encourage innovation, (iv) create safer, resilient, and sustainable cities, (v) provide sustainable consumption and production patterns, and (vi) contribute to the fight against climate change. In addition, technological developments in the field of renewable energy may also contribute to the reduction of emissions and cause a decrease in MF. Increasing renewable energy consumption will reduce the ecological footprint, strengthen the fight against climate change, and help to achieve sustainable development goals.

Net zero targets are far from achieving the greenhouse gas emission transition required to keep the earth's temperature at 1.5 °C and below set in the Paris Agreement (Hans et al. 2022). Many studies suggest that this emission reduction comes from reforestation (Griscom et al. 2017) and technology and innovation (Nemet et al. 2018). This study's most important policy recommendation is to focus on MF as a strategic tool to close the emission gap among SDGs, net zero targets, and GHG emissions. Emissions from products manufactured with intensive materials equal more than 40% of EU manufacturing emissions (Scott et al. 2018). In this context, policies that focus on product supply chains can offer significant opportunities to reduce emissions. In addition, reducing cost burdens in energy-intensive material sectors, such as cement, will also help meet climate targets (Rootzén and Johnsson 2017). If developing countries in EURO-26 achieve decoupling between MF and CO_2 emissions, that will increase the success of the EU's energy, environment, and climate policies and inspire other developing countries.

Another critical policy recommendation is that the European Green Deal (EGD) can be an opportunity in the context of reducing MF. Dirty productions outsourced to other countries may become cleaner through the charges applied with the carbon border adjustment mechanism within the scope of EGD (Karakaya et al. 2021). However, the increase in the production costs of a carbon border country should be at a compensable level. Otherwise, the commercial losses might cause additional environmental degradation. In this context, if outsourcing becomes cleaner, the EU should provide other incentives and privileges to the partners. Thus, a win–win mechanism will emerge for both parties and the environment.

Finally, specific policies for some sectors may reduce MF. There is significant potential to reduce emissions in manufacturing materials used in buildings and vehicles (Hertwich et al. 2019). For example, the carbon tax for green building projects will save energy and reduce the building sector's carbon footprint (Tsai et al. 2017). In addition, the carbon tax can promote low-carbon material substitution (Hertwich et al. 2020) and can be recycled by reducing the overall tax burden for fiscal policy (Hájek et al. 2019).

There is a limitation in this study. Using independent variables such as urbanization, financial growth, and energy consumption for empirical analysis could strengthen the MF model. At the same time, different ideas could arise in terms of policy propositions. However, too many results could have been a distraction, as the empirical results were evaluated for each country on a case-by-case basis. Therefore, we only used GDP data as the control variable. In this way, we interpreted the empirical results more clearly and focused on MF.

This study has an important future research proposal. As it is known, it is impossible to discuss environmental policies without the economy. The money supply released by governments during the COVID-19 period caused inflation

[1] SDG 7: ensure access to affordable, reliable, sustainable, and modern energy for all.

[2] SDG 8: promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.

[3] SDG 9: build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.

[4] SDG 11: make cities and human settlements inclusive, safe, resilient, and sustainable.

[5] SDG 12: ensure sustainable consumption and production patterns.

[6] SDG 13: take urgent action to combat climate change and its impacts.

to increase. When the Russia-Ukraine War started, the rise in energy prices in the global markets further increased the inflation pressure. Today, inflation rates in Europe, the USA, and many countries are breaking records compared to previous years. Concerns about the global economy also lead to recession fears in the future. In conclusion, if an economic contraction emerges, how will European countries update their policies in the context of EGD? How will the European Union combat rising prices while attempting to lower MF through EGD? Research on these questions will significantly contribute to the literature, especially in restructuring EGD.

Another policy recommendation is to examine MF by Fourier methods that consider structural breaks. Fourier-based approaches consider structural breaks and give robust results in small samples.

Author contribution Emrah Sofuoğlu conducted the investigation and gathered the data. Dervis Kirikkaleli wrote the introduction and the literature review, while Emrah Sofuoğlu prepared the methodology and the empirical findings as indicated in this paper. In addition, Emrah Sofuoğlu assisted in the explanation of the results. Finally, as the corresponding author, I confirm that the final version of this paper was reviewed and endorsed by all authors.

Data availability The data that support the results of this research are accessible from the World Bank.

Declarations

Ethics approval We declare that this paper is original, has not been published before, and is not currently being considered for publication by another journal. Therefore, this research does not require ethical authorization or informed consent.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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