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ENVIRONMENTAL PROTECTION PUBLIC EXPENDITURE AS A DETERMINANT OF GREEN TOTAL FACTOR PRODUCTIVITY: EVIDENCE FROM THE EUROPEAN UNION

Muhamed Ibrić[1], Emira Kozarević[2], Meldina Kokorović Jukan[3]

Abstract

We investigate the relationship between environmental protection public expenditure (EPE) and green total factor productivity (GTFP) across 27 EU countries from 2013 to 2022. Using the global Malmquist Luenberger index and Two-Step System GMM estimation, we test contemporaneous and lagged effects of EPE scale and structure on GTFP. The findings reveal that absolute EPE (EPEA) has a positive and significant effect on GTFP through pollution-emission reduction and clean-technology investment channels. However, expenditure intensity (EPEI) shows no significant effect. This points to a threshold issue: current spending (averaging 0.76% of GDP) likely falls below levels needed for measurable productivity gains. Neither one-period nor two-period lagged variables demonstrate significant relationships with GTFP, indicating that environmental spending impacts may require longer evaluation horizons than the observation period allows. Disaggregated analysis of individual EPE components reveals no significant effects for any single category, suggesting that integrated environmental strategies may be more effective than targeted categorical spending. Several limitations affect our findings. We cannot establish definitive causality. The observation period is relatively short. Our focus on public expenditure excludes private environmental investment. Our empirical findings suggest four policy priorities: prioritising absolute investment over intensity targets, integrating spending across categories, extending evaluation beyond 2-year horizons, and strengthening public-private coordination.

JEL classification: G31, G38, C33, H23, H30, O44, Q01, Q56
Keywords: Environmental Protection Public Expenditure, Green Total Factor Productivity, System GMM Estimation, EU Countries, Global Malmquist-Luenberger Index

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[1] University of Tuzla, Bosnia and Herzegovina, email: muhamed.ibric@untz.ba, ORCID: https://orcid.org/0009-0001-2094-1700.
[2] University of Tuzla, Bosnia and Herzegovina, email: emira.kozarevic@untz.ba, ORCID: https://orcid.org/0000-0002-5665-640X.
[3] University of Tuzla, Bosnia and Herzegovina, email: meldina.kokorovic@untz.ba, ORCID: https://orcid.org/0000-0002-4954-5437.

Introduction

Global greenhouse gas emissions reached historic highs between 2010-2019, with thermal activities generating unprecedented CO2 concentrations (IPCC, 2021; Wang et al., 2024). This climate crisis necessitates transitioning to low-carbon economies. The European Green Deal (2019) aims to achieve climate neutrality by 2050 through improving green total factor productivity (GTFP), economic output growth that incorporates energy consumption and emissions as undesirable outputs (Sun, 2022; Hodžić et al., 2023).

Improving GTFP has become critical for reconciling environmental limits with economic growth ambitions (Sun, 2022). This matters particularly when developing and developed countries need to coordinate their green strategies. GTFP improvements can accelerate the low-carbon transition while tackling resource depletion and environmental degradation. GTFP captures processes that optimize resource use and cut emissions without sacrificing GDP growth. GTFP represents the portion of economic growth that cannot be attributed to input growth alone. In essence, it extends the conventional concept of total factor productivity (TFP) by incorporating energy consumption and emissions of harmful substances (Hodžić et al., 2023). Classical economic theory long treated energy as secondary to production. Yet multi-factor studies by Menegaki (2014) and Borozan (2018) show energy input is indispensable for value creation. Green productivity, facilitated through GTFP, embodies the concept of sustainable development by fostering technological progress and ensuring future generations' right to a better quality of life (Ahmed, 2012).

Achieving a successful transition to a green economy requires substantial financial investments from both the public and private sectors (UN Environment, Economy Division, 2015). One of the important issues is how to finance the transition to a global low-carbon economy (Ibrić et al., 2024). Environmental issues have become a central topic in recent years in governmental policy agendas. "Environmental threats" are classified as global public goods in the public finance literature, as their impact transcends national borders (Caglar & Yavuz, 2023). Environmental protection public expenditure (EPE) has emerged by integrating green development principles into governmental fiscal policies. In a narrow sense, EPE consists of government spending on energy conservation and environmental protection to support environmental sustainability, stimulate technological innovation, and promote energy efficiency and emissions reduction (Fang et al., 2024). An increase in EPE indicates that governments are allocating more financial resources to environmental management, thereby emphasising national environmental governance commitments. Strengthening environmental management enhances public trust in government efficiency, fosters positive societal trends, and encourages collective environmental responsibility.

Environmental protection expenditure is, therefore, an essential indicator of society's response to ecological pressures. Environmental protection expenditure consists of capital and current expenditures on environmental protection activities. Activities include investing in equipment, labour, production methods, information systems, and products designed to collect, treat, prevent, or reduce pollution. Additionally, environmental protection expenditure can generate marketable by-products and financial savings or be subsidised through government programs. In such cases, environmental protection expenditure should be reported gross of any cost offsets (Eurostat, 2005). The level and structure of environmental protection expenditure depend on how these activities are organised within a country. The central government traditionally assumes responsibility for regulation, monitoring, and general administrative activities, as well as for the preservation of protected areas and biodiversity. Meanwhile, local governments have traditionally been responsible for waste collection, wastewater treatment, and sewage treatment, although recent privatisation trends have shifted some of these responsibilities to the private sector (European Communities, 2001).

Building on the objectives of the European Green Deal, the Eighth Environment Action Program (8th EAP) aims to accelerate the green transition. Increasing EPE in EU member states, particularly through increased spending on renewable energy, energy and resource efficiency, and circular economy initiatives, can be crucial to achieving this objective. EPE promotes sustainable development, reduces pollution and ecological degradation, and improves public health and ecosystem stability. There are two predominant perspectives regarding the relationship between EPE and economic development. The first argument is that EPE fosters positive economic outcomes by advancing technological progress, stimulating economic growth, and driving industrial upgrading. Advocates argue EPE boosts both economic and environmental performance while ensuring long-term stability. The second perspective suggests that the relationship between EPE and GTFP varies based on environmental conditions. Empirical research generally supports this proposition. Econometric studies employing panel data methods across various countries and regions have demonstrated that fiscal and financial instruments can significantly reduce pollution emissions and improve environmental quality (Caglar & Yavuz, 2023; Fang et al., 2024; Guo et al., 2022; He et al., 2021; Hodžić et al., 2023; Ibrić et al., 2025; Lee & Lee, 2022). The scale of government spending on the influence fiscal policy implementation. Some components of public expenditure exert a greater impact on green economic activity than others.

Using EU country-level data from 2013 to 2022, this study examines the impact of changes in the scale and structure of EPE on GTFP, drawing important conclusions and recommendations for policy development and implementation regarding the structuring of EPE to combat climate change.

Despite extensive research on environmental protection expenditure and green productivity in China and other Asian contexts, empirical evidence for EU countries remains limited. To address this research gap, this study poses the following research questions:

RQ_1: Does EPE significantly affect GTFP in EU countries?

This question examines whether the positive EPE-GTFP relationship documented in Chinese studies (Wang et al., 2024; Zhang & Tan, 2016; Zhao & Xu, 2022) holds in the EU institutional context. The analysis tests both absolute EPE (EPEA) and intensity EPE (EPEI) to determine which measure matters more for green productivity.

RQ_2: Do the effects of EPE on GTFP occur immediately or with a time lag?

Environmental investments may not generate immediate productivity improvements, as policy implementation and investment effects can take time to materialise. This question explores the temporal dynamics of EPE effects by comparing contemporaneous (same-year) impacts with one-year and two-year lagged effects.

RQ_3: Do different components of EPE have differential impacts on GTFP?

Environmental protection encompasses diverse activities, including waste management, wastewater treatment, pollution abatement, biodiversity protection, and environmental research and development (R&D). This question examines whether these components contribute equally to GTFP or whether certain expenditure categories are more effective than others.

These research questions guide the empirical analysis and will be explicitly addressed in the results and conclusion sections.

Literature review

GTFP has become an essential indicator for balancing energy consumption, economic development, and environmental protection (Han et al., 2023). Traditional total factor productivity (TFP) measures focus exclusively on how efficiently inputs convert to desirable outputs, overlooking environmental costs. GTFP addresses this limitation by incorporating energy consumption and pollution emissions as undesired outputs, making it a comprehensive measure of green economic efficiency that captures both economic performance and environmental sustainability (Sun, 2022). GTFP treats pollution as an undesirable output. This helps researchers and policymakers find development paths that achieve real green growth instead of just shifting costs between economy and environment. Currently, key areas of GTFP research include the index system, evaluation procedures, and influencing factors (Han et al., 2023).

Using grounded theory, Zhang et al. (2021) identified three research streams shaping GTFP, what they call the Technical-Economic-Government (TEG) framework. The technical stream covers technology and efficiency gains. Economic factors include industrial structure, production inputs, and market forces. Government influences come through regulation, fiscal policy, and institutions. In their model, technology drives change, the economy guarantees resources, and government regulates, all three interconnected. Within the economic stream, studies have demonstrated the notable influence of foreign direct investment (Chen et al., 2024; Guo et al., 2024), economic openness (Zhang et al., 2021), and urbanisation (Wang & Li, 2025; Wang et al., 2022; Yang et al., 2024) on GTFP. Bridging the technical and economic streams, the digital economy has emerged as a significant factor: Gao et al. (2022) demonstrated that digitisation improves green total factor energy efficiency, consistent with findings on ICT's role in reducing energy consumption (Bastida et al., 2019) and the digital economy's contribution to energy efficiency (Wang & Shao, 2023). Additionally, Xuechen and Qianwei (2024) found that the impact of industrial transfer on GTFP varies significantly across industries and regions. Bridging the government and technical streams, green and sustainable finance has emerged as especially important (Guo et al., 2022; Hodžić et al., 2023; Khan et al., 2022; Lee & Lee, 2022). Zhan and Zhang (2024) identify multiple transmission mechanisms through which green finance affects GTFP and highlight that this relationship may exhibit a U-shaped pattern, suggesting that green finance must exceed a critical threshold before positive effects become significant. This nonlinearity also matters for EPE spending may require critical thresholds before productivity gains appear.

EPE fits primarily in the government stream as a fiscal tool, though it also affects technology and economic structure indirectly. EPE's cross-cutting role makes it crucial for understanding GTFP. EPE represents one of two primary fiscal instruments through which governments can influence environmental outcomes. Environmental degradation constitutes an externality, and the objective of environmental policy, including EPE, is to correct market failure by incorporating external costs into resource allocation decisions (Hemming & Miranda, 1991). While environmental taxes internalise negative externalities through pricing mechanisms (Delgado et al., 2022; Grdinić et al., 2017; Gyurián & Gyurián-Nagy, 2022; Kozarević & Ibrić, 2023; Majić et al., 2020), EPE represents direct government investment in environmental protection activities (Caglar & Yavuz, 2023; Pearce & Palmer, 2005; Zhao & Xu, 2022). Both instruments are part of a broader environmental finance framework that connects public and private channels to sustainable development.

EPE shows varied patterns across regions and development stages. Hemming and Miranda (1991) note that expenditures are expected to decline as economies reorient toward environmentally friendly industries, consistent with the environmental Kuznets curve hypothesis. In the EU, Broniewicz (2011) and Rokicki et al. (2019) identified substantial cross-country variation, with the latter finding a strong positive correlation between GDP and environmental spending levels. Ercolano and Romano (2018) demonstrated that these differences do not diminish over time, thereby rejecting the convergence hypothesis. Barrell et al. (2021) used data envelopment analysis across 30 European countries. Their finding is sobering - higher spending doesn't guarantee better outcomes. Efficiency actually deteriorated as spending rose. Structure matters more than total amounts. The scale of required investment has been extensively documented. Baccianti (2022) analysed public spending needs for climate targets, noting that achieving net-zero by 2050 requires notable increases in public investment. The European Commission (2021) estimates a green investment gap of €520 billion per year (Schratzenstaller, 2023), underscoring the fiscal significance of EPE and the need for empirical analysis of its effectiveness.

He et al. (2021) demonstrated that EPE enhances GTFP through two primary channels: reducing pollution emissions and investing in clean technologies. Beyond direct environmental effects, Onaran and Oyvat (2022) found that annual increases in green public spending by 1 percentage point of GDP generate cumulative GDP increases ranging from 1.9% to 22% across eight countries, suggesting that EPE generates both environmental and economic returns. Importantly, they highlight that not only the amount but also the composition of spending plays a role, aligning with Barrell et al. (2021) emphasis on expenditure efficiency. Empirical evidence on the EPE-GTFP relationship has accumulated primarily from Chinese studies. Zhang and Tan (2016), Zhao and Xu (2022), and Wang et al. (2024) similarly found positive relationships between fiscal expenditures and green productivity, while highlighting heterogeneous governance effects across regions. Beyond the Chinese context, Pearce and Palmer (2005) contributed to the understanding of public-private expenditure coordination in OECD countries, while Corrocher and Cappa (2020) found that public expenditure positively affects GTFP in Belt and Road Initiative countries, particularly those with higher institutional quality. Panel data techniques have become the predominant methodological approach, employing fixed effects, IV-2SLS, system GMM, and spatial econometric methods to address endogeneity and dynamic panel bias (Liu et al., 2024; Xu & Zhao, 2023). In the EU, empirical evidence on EPE and environmental outcomes remains limited. Dornean et al. (2023) found a positive relationship between government environmental expenditure and the Environmental Performance Index across 27 EU member states, though the correlation weakened towards the end of the analysed period. Caglar and Yavuz (2023) found that current public spending levels are insufficient to achieve sustainability goals. Jarczok-Guzy et al. (2024) examined EPE efficiency across EU member states and found a positive association between environmental spending and the Sustainable Development Goals. Yet research on how specific EPE categories affect GTFP is scarce. Benatti et al. (2023) tested the Porter hypothesis in the euro area and found that policy tightening negatively affects the productivity of high-polluters, whereas larger firms with greater innovativeness experience positive productivity growth following regulatory tightening. Their findings suggest that the relationship between environmental fiscal instruments and productivity may be contingent on firm characteristics, policy design, and time horizons, which may explain why aggregate-level analyses over shorter periods yield modest effects. Recent studies have also begun addressing transition economies. Ibrić et al. (2025) examined the effectiveness of green fiscal instruments in the context of EU integration, underscoring the relevance of fiscal policy instruments for candidate countries. However, direct empirical analysis of the EPE-GTFP relationship in this broader European context remains an area requiring further investigation.

This paper explores the impact of EPE on GTFP in EU countries for the period 2013–2022. By focusing on both absolute EPE (EPEA) and its intensity relative to GDP (EPEI), and by analysing relationships between expenditure categories and GTFP, this study aims to fill these gaps. Special attention is given to the different categories of EPE.

Methodology

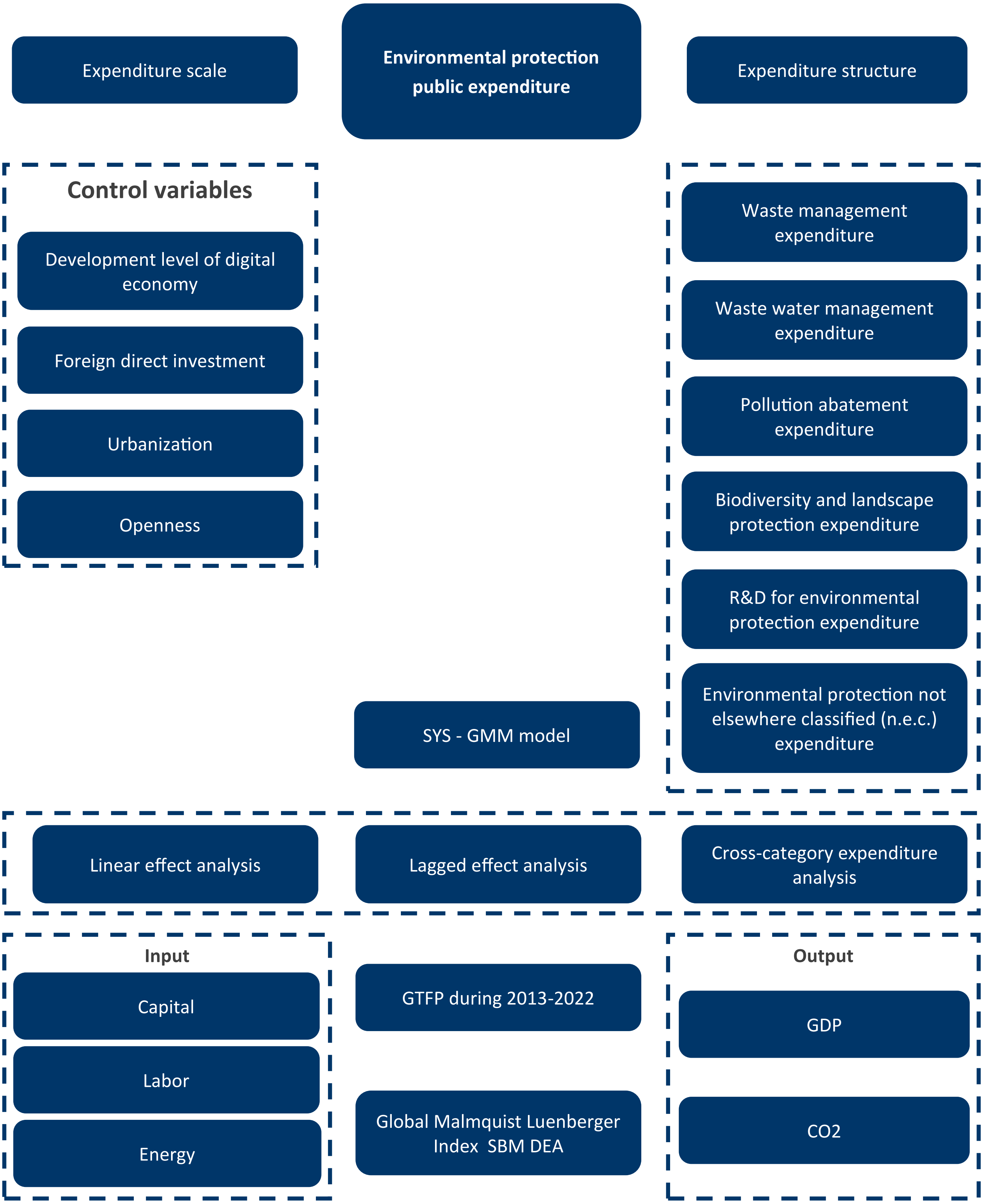
Research framework

Figure 1 outlines the research framework used in this study, developed in line with the methodological approach presented by Fang et al. (2024). EPE affects GTFP as a financial input that can drive advancements in environmentally sustainable practices. By funding pollution control, waste management, renewable energy, and similar initiatives, EPE directly affects how efficiently economies produce with minimal environmental harm. In other words, EPE helps reduce emissions

emissions and resource depletion and fosters innovation in cleaner production technologies, potentially boosting GTFP over time.

We evaluate GTFP's relationship with EPE along two dimensions. First, expenditure scale: we measure this both as absolute spending (EPEA, in million euros) and as intensity relative to GDP (EPEI, expressed as a percentage). Second, expenditure structure: we disaggregate spending into categories including waste management, wastewater treatment, pollution abatement, biodiversity protection, environmental R&D, and other protection activities.

Figure 1: Research framework



Source: Authors' creation, adapted from the methodological framework of Fang et al. (2024).

The authors use the global non-desirable super-SBM model to develop the final model GML index to measure GTFP. The global model adopted in this paper constructs a unified production frontier for all decision-making units (DMUs), which ensures that the efficiency values of different DMUs in different years are comparable. The GML index is used to measure changes in efficiency values. The construction of the GML index is as follows (Nie et al., 2024):

$$GML = \frac{\rho(x_{ai}^{t+1}, y_{ak}^{t+1}, z_{al}^{t+1})}{\rho(x_{ai}^{t}, y_{ak}^{t}, z_{al}^{t})} \left(\frac{\rho G(x_{ai}^{t+1}, y_{ak}^{t+1}, z_{al}^{t+1})}{\rho(x_{ai}^{t+1}, y_{ak}^{t+1}, z_{al}^{t+1})} \frac{\rho(x_{ai}^{t}, y_{ak}^{t}, z_{al}^{t})}{\rho G(x_{ai}^{t}, y_{ak}^{t}, z_{al}^{t})}\right) = EC \times TC \quad (1)$$

where:

$$\rho(x_{ai}^{t+1}, y_{ak}^{t+1}, z_{al}^{t+1})$$

represents the efficiency of the DMU at time t + 1, measured against the global production frontier, and

$$\rho(x_{ai}^{t}, y_{ak}^{t}, z_{al}^{t})$$

represents the efficiency score at time t measured against the same global frontier GML can be decomposed into TC (technological progress) and EC (changes in technological efficiency) indexes. When GML is greater than 1, it indicates that efficiency has improved from time t to t + 1. However, when GML is less than 1, it indicates a decline in efficiency.

The measurement of GTFP, using the elaborated models, will be conducted with the support of the Stata/MP 17 software package. According to Wang et al. (2021), this process involves utilising the "gtfpch" command to conduct dynamic GTFP analysis, based on the GML index.

Variables and data sources

This section presents the variables employed in the empirical analysis. The study utilises a balanced panel dataset comprising 27 European Union member states over the period 2013 - 2022. All data are sourced from Eurostat unless otherwise specified. The main explanatory variable, EPEA, represents total EPE expenditure and is calculated as the sum of six component categories: waste management (WME), wastewater management (WWME), pollution abatement (PAE), biodiversity and landscape protection (BLP), research and development for environmental protection (RDEP), and environmental protection not elsewhere classified (EPN). Detailed definitions and measurement methods for all variables are provided in Appendix 1.

Econometric models

A dynamic panel data modelling approach is applied using the Two-Step System Generalised Method of Moments (SYS-GMM) estimator. This methodology addresses econometric issues such as endogeneity, unobserved heterogeneity, and autocorrelation. We chose System GMM for three reasons tied to our data structure and research design. First, GTFP exhibits temporal persistence, as current productivity levels are influenced by past performance through accumulated technological capabilities and institutional learning effects. This persistence necessitates the inclusion of lagged dependent variables, which creates correlation between regressors and error terms in standard fixed effects models, leading to Nickell bias (Nickell, 1981). Second, the relationship between environmental protection expenditure (EPE) and GTFP is potentially subject to simultaneity bias, as governments may adjust environmental spending in response to observed productivity trends, and unobserved country-specific factors may jointly influence both variables. System GMM addresses this endogeneity by using lagged levels and differences as instruments. Third, the panel structure, with a moderate number of countries (N = 27) observed over a relatively short period (T = 10), favours System GMM over Difference GMM, as the former exploits additional moment conditions from level equations, improving efficiency when the autoregressive parameter is close to unity (Blundell & Bond, 1998). The validity of instruments is assessed through the Hansen test for over-identifying restrictions, while the Arellano-Bond tests for AR(1) and AR(2) verify the absence of second-order serial correlation in the differenced residuals. The use of SYS-GMM is consistent with prior research on the relationship between public spending and GTFP (Lin & Zhu, 2019; Wu et al., 2017; Zhang & Tan, 2016; Zhang et al., 2021; Zhao & Xu, 2022).

We select control variables based on Zhang et al.'s (2021) TEG framework, ensuring our literature review aligns with our empirical model. Within the technical stream, the digital economy development index (DIGECO) captures technological advancement and digitalisation intensity, which have been shown to improve GTFP through enhanced resource allocation and reduced information asymmetries (Gao et al., 2022; Wu et al., 2021). Foreign direct investment (FDI) bridges the technical and economic streams by serving as a conduit for international technology transfer, cleaner production methods, and management practices that can enhance environmental performance (Guo et al., 2024). Within the economic stream, urbanisation (URBAN), measured as the proportion of urban population to total population, captures the structural transformation of economies from rural-agricultural to urban-industrial configurations. This variable is included based on empirical evidence demonstrating its influence on GTFP through multiple channels (Wang & Li, 2025; Wang et al., 2022; Yang et al., 2024). On one hand, urbanisation can enhance GTFP through agglomeration economies, knowledge spillovers, and more efficient resource utilisation associated with concentrated economic activity. On the other hand, rapid urbanisation may negatively affect GTFP through increased energy consumption, transportation emissions, construction-related pollution, and infrastructure strain that outpace environmental management capacity. Net effects depend on urbanization stage, planning quality, and how well cities manage environmental issues. Trade openness (OPENN) reflects integration into global markets, which can affect GTFP through competitive pressures, access to green technologies, and exposure to international environmental standards (Zhang et al., 2021). The primary explanatory variables, EPEA and EPEI, represent the government stream through direct fiscal intervention for environmental protection, while also exerting indirect effects on the technical stream through funding for green R&D and clean technology development. This alignment between the theoretical framework and empirical variables ensures that the model captures the multidimensional nature of GTFP determinants identified in the literature.

To examine the impact of the EPE scale on GTFP, the following models are developed. Fundamental models (2-3):

$$GTFP_{i,t} = a + b_0 GTFP_{i,t-1} + b_1 EPEA_{i,t} + b_j Control_{i,t} + e_{i,t} \quad (2)$$

$$GTFP_{i,t} = a + b_0 GTFP_{i,t-1} + b_1 EPEI_{i,t} + b_j Control_{i,t} + e_{i,t} \quad (3)$$

where i and t are the individual and the year, respectively, α is a constant term, β is a parameter to be estimated, ε it is a random error term, GTFP is the green total factor productivity, GTFP i,t − 1 is the lag period of the explained variable, EPEA is the absolute environmental protection expenditure, EPEI is the environmental protection expenditure intensity and control denotes the control variables.

Control variables are the development level of the digital economy, foreign direct investment, urbanisation, and openness. Control variables are selected based on the theoretical framework of Zhang et al. (2021) and related studies, which identified economic and technological factors as key determinants of GTFP, alongside government policy instruments. Models with the lagged independent variable (4-7):

The impact of the EPE on GTFP may not be instantaneous and could require time to materialise (e.g., due to delays in policy implementation or investment effects). To that end, the following models with lagged independent variables (for one and two periods) are developed.

Models with the independent variable lagged for one period (4-5):

$$GTFP_{i,t} = a + b_0 GTFP_{i,t-1} + b_1 EPEA_{i,t-1} + b_j Control_{i,t} + e_{i,t} \quad (4)$$

$$GTFP_{i,t} = a + b_0 GTFP_{i,t-1} + b_1 EPEI_{i,t-1} + b_j Control_{i,t} + e_{i,t} \quad (5)$$

Models with the independent variable lagged for two periods (6-7):

$$GTFP_{i,t} = a + b_0 GTFP_{i,t-1} + b_1 EPEA_{i,t-2} + b_j Control_{i,t} + e_{i,t} \quad (6)$$

$$GTFP_{i,t} = a + b_0 GTFP_{i,t-1} + b_1 EPEI_{i,t-2} + b_j Control_{i,t} + e_{i,t} \quad (7)$$

Model for EPE structure. Not all components of EPE have an equal effect on GTFP. To explore the influence of various components of EPE related to environmental protection, the following model is developed (8):

$$\begin{aligned} GTFP_{i,t} &= a + b_0 GTFP_{i,t-1} + b_1 WME_{i,t} + b_2 WWME_{i,t} + b_3 PAE_{i,t} \\ &+ b_4 BLP_{i,t} + b_5 RDEP_{i,t} + b_6 EPN_{i,t} + b_7 Control_{i,t} + e_{i,t} \end{aligned} \quad (8)$$

where i and t are the individual and the year, respectively, WMEi,t is the absolute waste management expenditure, WWMEi,t is the absolute wastewater management expenditure, PAEi,t is the absolute pollution abatement expenditure, BLPi,t is the absolute biodiversity and landscape protection expenditure, RDEPi,t is the absolute research and development for environmental protection expenditure, and EPNi,t is the absolute environmental protection not elsewhere classified (n.e.c.) expenditure.

Two validity tests will be applied to ensure the reliability of the results. The Hansen-Sargan test will check the validity of the instruments by ensuring they are uncorrelated with the error term.

The AR(2) test will assess the absence of second-order autocorrelation in the residuals, which is essential for the validity of the GMM estimation.

Results and discussion

Descriptive statistics

The following table provides descriptive statistics for observed variables. GTFP shows a mean value of 1.019798 with a relatively stable standard deviation of 0.043, ranging from 0.899 to 1.408. EPEA averages 3952.462 but exhibits significant variability with a standard deviation of 6266.737, spanning from 44 to 28612. EPEI has a mean of 0.763 and a standard deviation of 0.328, ranging from 0.200 to 1.700. WME averages 1744.371, with considerable variability indicated by a standard deviation of 3174.094, and ranges from 14.300 to 14061. WWME has a mean of 732.709 and a standard deviation of 1257.332, with values ranging from 0 to 5493. PAE averages 649.301, with a standard deviation of 1150.441, spanning from 1.900 to 7528. BLP shows a mean of 386.513 and a standard deviation of 620.224, ranging from 0 to 2568. RDEP averages 187.179, with a standard deviation of 384.250, ranging from 0 to 1765.

The development level of the digital economy has a mean of 84.153 and a standard deviation of 9.871, ranging from 54.820 to 99.230. Foreign direct investment averages 376.307, with significant variability indicated by a standard deviation of 1083.994, spanning from 0 to 6729.521. Urbanisation exhibits the highest mean value of 7156.158 and the highest standard deviation of 9922.731, ranging from 158.800 to 41355.100. Lastly, openness has a mean value of 60.436 and a standard deviation of 32.994, with values ranging from 18.463 to 149.523.

Table 1: Descriptive statistics

Variable	Obs.	Mean	Std. dev.	Min.	Max.
GTFP	270	1.020	0.043	0.899	1.408
EPEA	270	3952.462	6266.737	44.000	28612.000
EPEI	270	0.763	0.328	0.200	1.700
WME	270	1744.371	3174.094	14.300	14061.000
WWME	270	732.709	1257.332	0.000	5493.000
PAE	260	649.301	1150.441	1.900	7528.000
BLP	268	386.513	620.224	0.000	2568.000
RDEP	260	187.179	384.250	0.000	1765.000
DIGECO	270	84.153	9.871	54.820	99.230
FDI	261	376.307	1083.994	0.000	6729.521
URBAN	270	7156.158	9922.731	158.800	41355.100
OPENN	270	60.436	32.994	18.463	149.523

Source: Authors' calculations using StataMP 17 software.

GTFP statistics in EU countries

Table 2 presents the GTFP values for each EU member state, calculated using the Global Malmquist-Luenberger (GML) index. This table serves multiple analytical purposes. First, it provides the dependent variable values used in the subsequent regression analysis, establishing transparency regarding the productivity measures being explained. Second, it complements the descriptive statistics in Table 1 by revealing cross-country heterogeneity in GTFP that motivates the panel-data approach. Third, examining individual country values enables identification of productivity leaders and laggards, contextualising the aggregate findings. Countries with GTFP values exceeding 1.0 experienced productivity improvements during the observation period, while values below 1.0 indicate productivity decline. The substantial variation across countries, ranging from 0.899 to 1.408, underscores the importance of understanding determinants of these cross-country differences, which constitutes the primary research objective.

Table 2: Analysis of GTFP presented using the GML index (EU, 2013-2022)

Country/ Year	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Avg.	Rank
Austria	1.025	1.007	1.020	0.992	1.033	0.988	1.023	1.009	1.034	1.013	20
Belgium	1.016	0.998	1.011	1.01q	1.005	1.011	1.011	1.028	1.057	1.015	18
Bulgaria	1.001	1.008	1.017	1.012	1.024	1.025	1.021	1.184	1.408	1.070	1
Croatia	1.006	1.009	1.011	1.005	1.029	1.013	0.982	1.041	1.059	1.016	16
Cyprus	0.983	1.010	0.999	1.005	1.013	1.023	0.997	1.036	1.034	1.009	26
Czechia	0.999	1.012	1.005	1.020	1.015	1.028	1.003	1.021	1.059	1.016	14
Denmark	1.019	1.003	1.005	1.019	1.002	1.009	1.017	1.038	1.068	1.018	10
Estonia	1.014	1.021	1.001	1.012	1.023	1.066	1.028	1.019	1.035	1.022	5
Finland	1.022	1.023	0.990	1.026	1.000	1.024	1.048	1.017	1.019	1.017	12
France	1.032	1.008	1.005	0.999	1.020	1.021	1.022	1.006	1.032	1.014	19
Germany	1.027	1.013	1.016	1.019	1.015	1.027	1.020	1.002	1.027	1.017	13
Greece	1.004	1.007	1.005	0.995	1.006	1.017	1.007	1.021	1.048	1.011	25
Hungary	1.007	1.009	1.011	1.020	1.017	1.026	0.972	1.035	1.028	1.013	22
Ireland	1.044	1.197	0.913	1.044	0.998	0.903	1.114	1.046	1.000	1.026	4
Italy	1.023	0.999	1.011	1.007	1.014	1.014	1.009	1.009	1.025	1.011	24
Latvia	1.013	1.006	1.014	1.019	1.014	1.012	1.026	1.031	1.052	1.019	9
Lithuania	0.997	0.975	0.971	1.042	1.036	0.999	0.960	1.050	1.082	1.011	23
Luxembourg	1.073	1.123	0.986	0.919	1.006	1.096	0.899	1.112	1.000	1.021	7

Country/ Year	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Avg.	Rank
Malta	1.047	0.958	0.998	1.040	1.005	1.000	0.953	1.049	1.000	1.005	27
Netherlands	1.008	1.001	1.011	1.018	1.023	1.027	1.021	1.033	1.065	1.021	8
Poland	1.013	1.033	0.968	1.142	1.075	1.034	0.924	1.146	1.265	1.059	2
Portugal	1.006	0.992	1.024	0.996	1.035	1.036	1.012	1.034	1.041	1.017	11
Romania	1.009	1.018	1.017	1.035	1.039	1.040	0.993	1.027	1.079	1.026	3
Slovakia	1.016	1.007	0.999	1.007	1.019	1.026	1.012	1.007	1.058	1.015	17
Slovenia	1.034	1.009	1.007	1.023	1.020	1.024	0.987	1.053	1.062	1.022	6
Spain	1.001	0.998	1.024	0.999	1.020	1.031	1.015	1.011	1.030	1.013	21
Sweden	1.007	1.013	0.999	1.023	0.989	1.017	1.067	1.027	1.019	1.016	15

Source: Authors' calculations using StataMP 17 software.

Results of econometric analysis and discussion – dynamic panel estimation

The following sections present the results of econometric models using the Two-Step System of GMM. The findings are discussed in relation to the three research questions posed in the introduction.

The impacts of EPE scale on GTFP

Table 3 represents a summary of the estimation results examining the impact of EPE scale on GTFP. Models 1, 3, and 5 correspond to EPEA, while models 2, 4, and 6 correspond to EPEI. Diagnostic tests confirm model validity for Models 1-4: Hansen test p-values (Model 1: p = 0.172; Model 2: p = 0.098; Model 3: p = 0.054; Model 4: p = 0.101) exceed 0.05, indicating valid instruments. AR (2) tests detect no second-order autocorrelation (all p > 0.35). Models 5-6 show marginal Hansen p-values (p = 0.018, p = 0.001), suggesting potential instrument weakness with 2-year lags. These results should be interpreted cautiously.

Model 1's positive and significant EPEA coefficient directly answers RQ1: EPE affects GTFP in EU countries when measured in absolute terms. This effect magnitude is smaller than Chinese studies (Zhang & Tan, 2016; Zhao & Xu, 2022), likely reflecting diminishing returns in developed EU economies with higher environmental baselines. This confirms government fiscal tools can boost green productivity, the core claim of Zhang et al. (2021), the TEG government stream. He et al. (2021) identified a dual-channel mechanism that helps explain this result: EPE enhances GTFP both by reducing pollution emissions (lowering undesirable outputs in GTFP calculations) and by investing in clean technology (improving technical efficiency). The empirical literature increasingly documents positive EPE-productivity relationships. Our findings fit this broader pattern. Zhang and Tan (2016) found fiscal expenditures positively correlated with GTFP across 285 Chinese prefecture-level cities, while Zhao and Xu (2022) and Fang et al. (2024) reported comparable positive relationships in Chinese urban contexts. Corrocher and Cappa (2020), using panel data from 46 Belt and Road Initiative countries, similarly found that public expenditure positively affects GTFP, particularly in countries with higher institutional quality. We extend these findings to the EU. The positive EPE-GTFP link isn't just a Chinese phenomenon, it holds in developed economies too. Multiple mechanisms explain this pattern. First, absolute EPE levels provide the necessary investment scale to achieve meaningful environmental improvements and technology adoption, which Zhan and Zhang (2024) term the "threshold effect" in green finance. Second, higher absolute spending enables governments to pursue multiple environmental objectives simultaneously, potentially generating synergistic productivity effects, similar to Onaran and Oyvat's (2022) finding that green public spending yields multiplier effects ranging from 1.9% to 22% in cumulative GDP increases across countries. Third, substantial EPE signals credible government commitment to environmental protection, potentially crowding in private investment, a mechanism highlighted by Pearce and Palmer (2005) in their analysis of public-private expenditure coordination in OECD countries.

However, the results in Model 2 indicate that the answer to RQ1 is measurement-dependent: EPEI shows no statistically significant effect on GTFP, suggesting that while absolute investment scale matters, expenditure intensity relative to GDP does not generate measurable productivity effects at current levels. Given that environmental spending averages only 0.76% of GDP across EU countries, three factors may explain this null result. First, the insignificance of EPEI probably reflects threshold effects documented in the green finance literature. Zhan and Zhang (2024) observed that the relationship between green finance and GTFP exhibits nonlinear characteristics, with positive effects becoming significant only after a critical investment threshold is reached. With EPEI averaging only 0.76% of GDP, current spending intensity in many EU countries may be below the threshold required to generate measurable productivity effects. This interpretation aligns with Caglar and Yavuz's (2023) finding that current levels of public environmental spending in the EU may be insufficient to achieve sustainability goals. Second, the significance of absolute rather than relative expenditure suggests that investment scale matters independently of economic size. This finding has important theoretical implications within the TEG framework - the mechanisms through which EPE affects GTFP, technology adoption, infrastructure development, and institutional capacity building may require minimum absolute investment levels regardless of a country's GDP. Large economies may achieve productivity gains through EPE even when intensity remains modest, while smaller economies with higher intensity may lack the absolute investment scale to generate comparable effects. Third, despite its modest relative magnitude, EPE may generate disproportionate effects through several amplification mechanisms. EPE represents highly targeted expenditure specifically designed to address environmental externalities, unlike general government spending that serves multiple objectives. Onaran and Oyvat (2022) demonstrated that green public spending generates substantial multiplier effects, suggesting that the direct magnitude of EPE may understate its total economic impact. Additionally, EPE operates through quality-enhancing channels, improving environmental management capacity, supporting green R&D, and building institutional frameworks that may have effects that exceed what the expenditure magnitude alone would suggest.

Practical interpretation using specific country examples illustrates this divergence: Germany, with EPEA = €28,612M (0.80% of GDP), achieves measurable GTFP gains through absolute scale despite modest intensity. Conversely, smaller economies like Malta (EPEA = €44M, 1.2% of GDP) exhibit higher intensity but lack sufficient absolute investment to generate comparable productivity effects. This suggests that achieving critical investment thresholds may require EU-level coordination for smaller member states, potentially through enhanced Cohesion Policy co-financing mechanisms.

Notably, URBAN shows a statistically significant negative coefficient in Model 1. This finding suggests that higher levels of urbanisation are associated with lower GTFP in the short term. This result aligns with the theoretical expectation that rapid urbanisation can generate environmental pressures through increased resource consumption, pollution concentration, and infrastructure strain that may temporarily offset productivity gains. However, this effect is not robust across other model specifications, indicating that the urbanisation-GTFP relationship may be sensitive to model structure and the inclusion of lagged variables. The transient nature of this significance suggests that urbanisation effects on green productivity may operate through complex, time-varying mechanisms that warrant further investigation.

RQ2 asks: do EPE effects appear immediately or with delay? Models 3-6 answer clearly, neither EPEA nor EPEI shows significant lagged effects within two years. The contemporaneous effect in Model 1 appears dominant, while longer-term dynamics remain hidden within our observation period. What explains this temporal pattern? Several theoretical perspectives help answer this. First, the ten-year observation period may be insufficient to capture longer-term dynamics of environmental investment. Benatti et al. (2023), examining the Porter hypothesis in the euro area using panel local projections, employed five-year projection horizons and found heterogeneous effects across firm characteristics and policy types. Environmental investments in infrastructure, R&D, and institutional capacity may require horizons beyond two years to generate measurable productivity effects, particularly in developed economies where marginal environmental improvements are more costly to achieve. Second, the null lagged effects may reflect the continuous nature of environmental spending rather than discrete policy interventions. Unlike the specific fiscal policies examined by Wang et al. (2024) using difference-in-differences methods, general EPE represents an ongoing government commitment that may generate contemporaneous rather than lagged effects through continuous maintenance of environmental quality and incremental improvements.

Table 3: Estimation results on the impact of EPE scale on GTFP

VARIABLES	Absolute			Intensity		
	Model 1 (Baseline)	Model 3 (One-Period Lag)	Model 5 (Two-period Lag)	Model 2 (Baseline)	Model 4 (One-Period Lag)	Model 6 (Two-period Lag)
	GTFP	GTFP	GTFP	GTFP	GTFP	GTFP
L.GTFP	-0.13617 (0.53800)	-0.11662 (0.62900)	0.14291 (0.50200)	-0.14264 (0.53500)	-0.09605 (0.69600)	0.31381 (0.37000)
EPEA	2.95e-06** (0.00600)					
L.EPEA		7.23e-07 (0.91200)				

VARIABLES	Absolute			Intensity		
	Model 1 (Baseline)	Model 3 (One-Period Lag)	Model 5 (Two-period Lag)	Model 2 (Baseline)	Model 4 (One-Period Lag)	Model 6 (Two-period Lag)
	GTFP	GTFP	GTFP	GTFP	GTFP	GTFP
L2.EPEA			-6.39e-06 (0.74100)			
EPEI				-0.03918 (0.18400)		
L.EPEI					0.00105 (0.99100)	
L2.EPEI						0.01545 (0.66800)
DIGECO	0.00037 (0.16800)	0.00048 (0.43000)	0.00313 (0.57100)	0.00023 (0.64600)	0.00084 (0.41500)	0.00045 (0.38700)
FDI	9.81e-08 (0.88100)	9.14e-08 (0.95400)	-1.30e-06 (0.72800)	2.18e-06 (0.31200)	1.42e-08 (0.99800)	-2.91e-06 (0.13000)
URBAN	-1.67e-06 (0.00900)**	1.59e-09 (1.00000)	4.63e-06 (0.73200)	4.79e-07 (0.29300)	7.17e-08 (0.92500)	-1.37e-07 (0.74100)
OPENN	0.00007 (0.25900)	0.00009 (0.45500)	0.00023 (0.37200)	0.00019 (0.15800)	0.00011 (0.55600)	0.00006 (0.74200)
Constant	1.11980*** (0.00000)	1.08790*** (0.00000)	0.74738*** (0.05600)	1.15705*** (0.00000)	1.03570*** (0.00200)	0.65070* (0.06900)
Observations	234	234	207	234	234	207
Number of IDs	27	27	27	27	27	27
Hansen	0.17200	0.05400	0.01800	0.09800	0.10100	0.00100
AR(2)	0.40300	0.48900	0.86200	0.37800	0.53900	0.84500

Note: Significance levels of 1%, 5% and 10% are denoted by ***, ** and *, respectively. P-values are given in parentheses

Source: Authors' calculations using StataMP 17 software.

The insignificance of control variables (DIGECO, FDI, OPENN) across most specifications deserves discussion within the TEG framework that guided variable selection. Within the technical stream, DIGECO was expected to influence GTFP through enhanced resource allocation and reduced information asymmetries, as documented by Gao et al. (2022) and Wu et al. (2021) in Chinese contexts. Why no effect? EU member states are relatively homogeneous in digital infrastructure compared to samples in prior research. Limited variation makes effects harder to detect. Similarly, FDI, which bridges the technical and economic streams through international technology transfer (Guo et al., 2024; Chen et al., 2024), shows no notable effect. This probably reflects that EU countries, as developed economies with established technological capabilities, derive less marginal benefit from FDI-facilitated technology transfer compared to emerging economies, where this effect has been more consistently documented. Trade openness (OPENN), which represents economic integration and exposure to international environmental standards within the economic stream (Zhang et al., 2021), also shows no notable effect. The high baseline level of economic integration among EU member states through the single market may limit the variable's additional explanatory power for GTFP differences. These null findings for control variables contrast with studies conducted in more heterogeneous country samples, suggesting that relationships documented in emerging-economy contexts may not generalise directly to developed-economy settings characterised by greater institutional and technological homogeneity.

The impact of EPE structure on GTFP

Table 4 presents results for individual EPE components, addressing RQ3: do different spending categories have different impacts on GTFP? The disaggregation of EPE into six component categories, waste management, wastewater management, pollution abatement, biodiversity and landscape protection, R&D for environmental protection, and environmental protection n.e.c., reveals no statistically significant effects for any individual component. This finding provides a clear answer to RQ3: the evidence does not support differential impacts of individual EPE components on GTFP, suggesting instead that the significant aggregate effect identified in response to RQ1 arises from the combined and coordinated deployment of environmental spending across categories rather than from any single dominant expenditure type.

Table 4: Estimation results on the impact of individual EPE components on GTFP

VARIABLES	GTFP
L.GTFP	0.0749216 (0.727)
WME	4.08e-06 (0.286)
WWME	-0.0000291 (0.220)
PAE	5.71e-06 (0.756)
BLP	-0.0000271 (0.718)
RDEP	0.0001154 (0.296)
EPN	0.0000501 (0.263)
DIGECO	0.0007785 (0.196)
FDI	-7.66e-07 (0.824)
URBAN	-3.08e-06 (0.155)
OPENN	0.0001501 (0.381)
Constant	0.8743*** (0.000)
Observations	225
Number of IDs	26
Hansen	0.294
AR(2)	0.984

Note: Significance levels of 1%, 5% and 10% are denoted by ***, ** and *, respectively. P-values are given in parentheses

Source: Authors' calculations using StataMP 17 software.

This finding contrasts with the significant positive effect of aggregate EPEA in Model 1, suggesting important methodological and substantive implications that can be interpreted within the TEG framework. From a methodological perspective, the disaggregation of EPE introduces multicollinearity concerns, as component categories are determined jointly through government budget allocation processes and may respond to common economic and political factors. Correlations among components may reduce statistical power to identify individual effects, even when the aggregate relationship is significant. Substantively, the null component-level results suggest that integrated environmental strategies may be more effective than targeted categorical spending. This interpretation aligns with the systems perspective embedded in the TEG framework (Zhang et al., 2021), which emphasises the interconnection among technical, economic, and government factors in shaping GTFP. Environmental productivity improvements may require coordinated investments across multiple domains, waste management, pollution control, R&D, and biodiversity protection, rather than isolated spending in any single category. This finding resonates with Onaran and Oyvat's (2022) observation that differences in green spending multiplier effects across countries indicate that not only the amount but also the composition and targeted nature of spending play important roles. The finding further aligns with Barrell et al. (2021), who, in a DEA analysis of EPE efficiency across 30 European countries, found that higher environmental protection expenditures do not necessarily yield better environmental outcomes and identified declining efficiency as spending increased. Ultimately, the composition and coordination of spending may matter more than individual category amounts, suggesting that governments should focus on strategic allocation across categories rather than maximising any single component.

RDEP's particularly weak performance deserves attention, given its theoretical importance within the technical stream of the TEG framework. Green R&D spending is expected to generate productivity improvements through technological innovation, as suggested by He et al. (2021) in their clean technology investment channel. Why no RDEP effect? Three factors matter. First, RDEP levels are modest (mean €187 million, many zeros). Second, R&D needs long gestation periods, likely beyond our ten-year window. Third, private green R&D, which we don't capture, may drive productivity more directly than public spending. Benatti et al. (2023) found that technology support policies can enhance productivity among firms with sufficient resources, suggesting that the effectiveness of public R&D spending may be contingent on the presence of complementary private-sector capabilities.

Conclusions and policy recommendations

This paper examines how EPE affects GTFP in 27 EU countries from 2013 to 2022. We use GML super-efficiency SBM DEA combined with System GMM econometric analysis. Building on Zhang et al. (2021) TEG framework, we analyze both the scale and structure of environmental spending. This dual focus reveals important nuances in how fiscal environmental policy influences green productivity.

The empirical analysis yields several important findings. For RQ1, EPEA has a positive and significant effect on GTFP (Model 1), confirming that government fiscal commitment to environmental protection can enhance green productivity in EU countries and extending the positive EPE-GTFP relationships documented in prior studies to the EU context. EPEI, however, shows no significant effect (Model 2), suggesting that the absolute scale of environmental investment matters more than its relative magnitude. This may reflect threshold effects, whereby current spending intensity, averaging only 0.76% of GDP, remains below the critical levels required to generate measurable productivity impacts. RQ2 reveals that EPE effects are contemporaneous rather than lagged. Neither one-period nor two-period lagged variables for EPEA and EPEI show significant relationships with GTFP (Models 3-6), indicating that contemporaneous channels dominate within the two-year lag structure examined, whereas longer-term dynamics may require extended evaluation horizons to be detected. RQ3 shows no individual EPE component shows significant effects (Model 7), contrasting with the significant aggregate EPEA result. This suggests that integrated environmental strategies that coordinate multiple categories may be more effective than targeted categorical spending, although disaggregation may also introduce multicollinearity, reducing statistical power to identify individual effects.

This is the first systematic empirical study of the EPE-GTFP relationship in the EU, prior research focused heavily on China. The contrasting results between absolute and intensity-based measures of EPE introduce new theoretical insights regarding threshold dynamics in environmental fiscal policy, suggesting that the scale of investment may be a more relevant determinant of green productivity than its proportional share of economic output. By applying the TEG framework and System GMM methodology to a panel of developed economies, the study also establishes an analytical and methodological foundation for investigating EPE-GTFP relationships in institutional settings characterised by higher baseline environmental standards, greater regulatory maturity, and more homogeneous governance structures.

At the same time, the study faces certain limitations. While System GMM addresses endogeneity concerns, it cannot establish a causal relationship between environmental expenditure and productivity, as governments may adjust spending in response to productivity trends. The 2013-2022 observation period may also be insufficient to capture longer-term dynamics, given that environmental spending on infrastructure, R&D, and institutional capacity building may require evaluation horizons exceeding ten years. Although theoretically grounded, the GTFP measure relies on specific data inputs and assumptions, and alternative productivity specifications could enhance its robustness. The analysis also treats EU member states as a relatively homogeneous group; future research could explore heterogeneous effects across country clusters or examine how institutional quality moderates the effectiveness of EPE, as suggested by Corrocher and Cappa (2020). Finally, the focus on public expenditure omits private environmental investment, which may complement or substitute for government spending. An integrated analysis of public and private environmental finance, as advocated by Pearce and Palmer (2005), could provide a more comprehensive understanding of the total environmental investment effects on productivity.

Our findings suggest several policy priorities. The significant effect of absolute EPE rather than intensity suggests governments should prioritize achieving minimum absolute investment thresholds. Analysis reveals substantial variation: Germany (€28.6 billion) vs. Malta (€44 million), with smaller economies requiring EU-level coordination to reach critical mass. The null findings for individual EPE components indicate integrated strategies balancing waste management, pollution abatement, and R&D may outperform categorical spending. Current EU allocation (44% waste, 5% R&D) suggests rebalancing toward 15-20% R&D investment. Lagged effects don't appear within two years. Policymakers need evaluation windows exceeding five years, matching infrastructure timelines like wastewater plants (5-7 years). The potential threshold effects (current mean EPEI = 0.76% vs. green finance threshold ≈1.2%), combined with the European Commission's €520 billion annual investment gap, underscore the required investment scale. Finally, EPE programs should leverage public-private partnerships, with public spending designed to crowd in private capital at ratios of 2:1 to 3:1, as documented by Onaran & Oyvat (2022).

Future research should extend this analysis by observing for longer periods, thereby enabling examination of longer lag structures and potential nonlinear dynamics. Heterogeneity analysis across EU country clusters could identify whether EPE effects vary with institutional quality, economic development level, or environmental baseline conditions. Integration of private environmental spending data, examination of transmission mechanisms such as innovation and industrial restructuring, and extension of the analysis to EU candidate countries and neighbouring transition economies would all provide valuable additional insights into the EPE-GTFP relationship.

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Appendix

Appendix 1: Selection of variables - definition and explanation

Variable	Variable type	Dimension/ Indicator	Symbol	Measurement method	References
Green Total Factor Productivity (GTFP)	Dependent variable	Labor	L	Number of people employed (thousands of persons)	Shi et al. (2022) He et al. (2021)
		Capital stock	K	Capital stock is calculated using the Perpetual Inventory Method (PIM), based on gross fixed capital formation (GFCF), the depreciation rate, and the initial output growth rate. GFCF represents investments made by resident producers in fixed assets after deducting disposals, including improvements of non-produced assets (2012–2022, current prices, million euros, Eurostat). The initial real GDP growth rate (g) is calculated as the three-year annual average real GDP growth rate (2012-2014, Eurostat). Because capital stocks are fundamentally unobservable, their estimation relies on a theoretical model that introduces measurement uncertainty. In this study, capital stock is estimated using the PIM, which represents the solution to the Goldsmith difference equation (Radičić et al., 2023; Burda & Severgnini, 2009): $K_{t+1} = (1-\delta_t)K_t + I_t$ where I denotes investment and δ the depreciation rate. The depreciation rate may vary over time or across asset types, but following Radičić et al. (2023) and Burda & Severgnini (2009), a constant rate of 0.06 is adopted, which lies within the commonly used 0.04-0.10 range in the literature. The initial capital stock is calculated following the Burea of Economic Analysis (BEA) procedure (Burda & Severgnini, 2009; Radičić et al., 2023), using the steady-state approximation: $K_0 = I_0 \frac{(1+\delta)}{(g+\delta)}$' where g denotes the average output growth rate during the three years preceding the analysis. The initial capital stock is estimated for the base year 2013. Annual Eurostat data on capital utilisation are incorporated to avoid biased estimates of GTFP.	Radičić et al. (2023)

Variable	Variable type	Dimension/ Indicator	Symbol	Measurement method	References
Green Total Factor Productivity (GTFP)	Dependent variable	Capital stock	K	The current capital stock is then derived using the linear depreciation method, representing a weighted aggregation of the initial capital and subsequent investment flows, where the weights reflect declining values after depreciation (Burda & Severgnini, 2009; Radičić et al., 2023): $K_t = K_0(1-t\delta)+\sum_{i=0}^{t-1}(1-t\delta)I_{t-1}$,	Radičić et al. (2023)
		Energy consumption	C	Final energy consumption (millions kg of oil equivalent)	Shi et al. (2022) He et al. (2021)
		Gross domestic product	Y	Gross domestic product at market prices (million euros)	Shi et al. (2022)
		Carbon dioxide emissions	CO2	CO2 emissions (thousand tonnes)	Wu et al. (2021)
Environmental protection public expenditure	Explanatory variable	Environmental public protection expenditure absolute	EPEA	Government spending on environmental protection for total economy (million euros)	Eurostat
		Environmental public protection expenditure intensity	EPEI	Proportion of environmental public protection expenditure to GDP	Eurostat
		Waste management expenditure	WME	Government spending on waste management (million euros)	Eurostat
		Wastewater management expenditure	WWME	Government spending on wastewater management (million euros)	Eurostat
		Pollution abatement expenditure	PAE	Government spending on pollution abatement activities (million euros)	Eurostat
		Biodiversity and landscape protection expenditure	BLP	Government spending on the protection of biodiversity and landscape (million euros)	Eurostat
		Research and development for environmental protection expenditure	RDEP	Government spending on research and development in the field of environmental protection (million euros)	Eurostat
		Environmental protection not elsewhere classified (n.e.c.) expenditure	EPN	Government spending on environmental protection activities not elsewhere classified (million euros)	Eurostat
Control variables		Development level of digital economy	DIGECO	The percentage of individuals who used the Internet in the last 12 months	Eurostat

Variable	Variable type	Dimension/ Indicator	Symbol	Measurement method	References
Control variables		Foreign direct investment	FDI	Foreign direct investment in the reporting economy (FDI/GDP×100)	Eurostat
		Urbanisation	URBAN	This indicator captures the degree of spatial concentration of economic activity and population. Number of households by degree of urbanisation (thousand households)	Eurostat
		Openness	OPENN	Proportion of total imports and exports in GDP	Eurostat

Source: Authors' creation.