ANALYZING THE AGEING POPULATION AND HEALTHCARE EXPENDITURES FROM AN ENVIRONMENTAL SUSTAINABILITY PERSPECTIVE FOR THE EU COUNTRIES: A SPATIAL APPROACH[1]

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ABSTRACT | The aim of this study is to analyze the impact of population aging (AG), healthcare expenditures (HE), per capita GDP, and renewable energy budgets (REB) on environmental quality (EQ). To achieve this, data from 22 European Union (EU) countries covering the period from 2005 to 2020 were examined using spatial panel data analysis. The findings indicate the presence of spatial interactions among EU countries. Model specification tests supported the spatial panel lag model with fixed effects. The spatial effect coefficient was found to be 0.53 and statistically significant. While AG and REB positively influenced EQ, HE and per capita GDP exhibited negative effects. The results highlight the complex interactions among economic, social, and environmental factors. The study concludes with policy recommendations aimed at supporting EU countries in achieving their climate goals.

Keywords: *Health expenditures, ageing population, environmental sustainability, spatial panel*

JEL Codes: *H51, I15, Q16*

Scope: *Economics*
Type: *Research*

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[1] Compliance with the ethical rules of the relevant study has been declared.

YAŞLANAN NÜFUS VE SAĞLIK HARCAMALARININ ÇEVRESEL SÜRDÜRÜLEBİLİRLİK PERSPEKTİFİNDEN ANALİZİ: MEKÂNSAL BİR YAKLAŞIM

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ÖZ | Bu çalışmanın amacı, nüfus yaşlanması (AG), sağlık harcamaları (HE), kişi başına düşen GSYİH ve yenilenebilir enerji bütçelerinin (REB) çevre kalitesi (EQ) üzerindeki etkisini incelemektir. Bu amaç doğrultusunda, 22 Avrupa Birliği (AB) ülkesinde 2005-2020 yılları arasındaki veriler mekânsal panel veri analizi ile incelenmiştir. Bulgular, AB ülkeleri arasında mekânsal etkileşimler olduğunu göstermiştir. Model belirleme testleri, sabit etkiler içeren panel mekânsal gecikme modelini desteklemiştir. Mekânsal etki katsayısı 0.53 olup, istatistiksel olarak anlamlıdır. AG ve REB, EQ üzerinde olumlu bir etkiye sahipken, HE ve kişi başına düşen GSYİH negatif etkiler göstermiştir. Sonuçlar, ekonomik, sosyal ve çevresel faktörler arasındaki karmaşık etkileşimleri ortaya koymuştur. Çalışma, AB ülkelerinin iklim hedeflerine ulaşmalarını desteklemek için politika önerileriyle sona ermektedir.

Anahtar Kelimeler: *Sağlık harcamaları, Yaşlanan nüfus, çevresel sürdürülebilirlik, mekânsal panel*

JEL Kodları*: H51, I15, Q16*

Alan: *İktisat*
Türü: *Araştırma*

1. INTRODUCTION

Many human activities pose threats to ecosystems, impacting essential elements for life such as air, clean water, food, and other vital resources. The rate of natural resource consumption has exceeded the Earth's biological capacity, requiring 1.6 times the Earth's renewal capacity to sustain ecological services (Nathaniel, 2021). Basic human needs, including water, infrastructure, housing, energy, and food, place a significant burden on the ecosystem, leading to consequences such as resource depletion, increased emissions, and the disruption of ecological balance. These environmental pollutants make the Earth uninhabitable for living beings and serve as a major trigger for global climate change (Ahmed & Wang, 2019; Lin et al., 2018; Nathaniel, 2021). One of the most significant contributors to changing climate is carbon dioxide (CO_2) emissions, which account for approximately 70% of greenhouse gas emissions (Yang et al., 2022; Polat et al., 2024). Consequently, environmental degradation in the literature is often assessed through CO_2 levels, as CO_2 is a primary cause of air pollution and declining air quality (Aydın et al., 2024). The effects of CO_2 deeply impact various aspects of life, including public health, income levels, and Overall well-being (Kumar & Radulescu, 2024). The World Health Organization (WHO) reports that the energy and housing sectors account for 18% of global CO_2 emissions, creating significant risks for both environmental sustainability (ENS) and human health. The report suggests adopting renewable energy (RE) production and clean energy sources as a means to mitigate this threat. Between 2010 and 2020, the adoption of renewable energy sources is estimated to have reduced CO2 emissions by 0.4 to 0.9 billion tons (WHO, 2015; Karaaslan & Çamkaya, 2022).

Many developed and developing countries jeopardize air quality and a healthy environment subsequently rapid economic growth (EG). At the root of this issue lies the assumption of infinite growth embedded in current economic systems, which is simply unattainable on a finite planet (Wang & Azam, 2024). Particularly in recent years, numerous scholars havefocused on ENS. In this context, extensivescientific research has been conducted on topics such as the causes of environmental pollution, environmental quality (EQ), climate change, and global warming (Bilgili et al., 2016). In fact, institutional interest in environmental issues dates back to the early 1970s. For instance, the report *The Limits to Growth* published by the Club of Rome highlighted a potential relationship between EQ and EG. According to this report, EG is not sustainable in terms of natural resources and the environment (Meadows et al., 1972).

The foundations of sustainable development havebeen severely undermined by current environmental issues. To tackle this global challenge, the

United Nations (UN) established the Sustainable Development Goals (SDGs), which comprise 17 objectives that countries are expected to achieand by 2030. The SDGs aim to reshape existing EG models to restore global balance. Among these goals, SDG 13 holds critical importance due to its direct relevance to climate action (UN, 2024). With population growth and the acceleration of industrialization, the demand for commercial energy has increased significantly. Since fossil fuels remain the most common source of commercial energy, this growing demand exacerbates the adverse effects on environmental air pollution, health, and climate change, directly linking it to SDG 3 (health and well-being) (Yang et al., 2022; Sabău-Popa et al., 2024). Thus fulfilling the requirements of SDG 13 also necessitates implementing SDG 7, which targets clean, renewable, and accessible energy solutions, as well as SDG 3. Therefore, addressing current climate challenges requires the development and deployment of clean energy technologies (Xue et al., 2022).

Health is one of the fundamental elements of economic development, as a healthy society leads to higher productivity and increased per capita income. Health expenditures (HE) are considered an investment in human capital, enhancing labor force efficiency, raising income levels, and contributing to overall societal well-being (Yadav et al., 2023). According to the UN, leading a healthy life is a fundamental human right. Moreover, health is one of the most significant indicators of sustainable development. Of the 17 SDGs set by the UN in 2015, SDG 3, "Good Health and Well-being," is particularly crucial in this context (UN, 2024). In this context, while reducing CO_2 emissions may not have an immediate impact on HE, it creates a favorable foundation for the long-term prevention of diseases caused by environmental pollution and extreme weather conditions (Yang et al., 2022). For instance, CO_2 emissions penetrate the lungs and bloodstream, leading to cardiovascular, cerebrovascular, and respiratory diseases. Moreover, it has been proven that these pollutants harm other organs and contribute to various diseases (Aydın & Bozatlı, 2023). Environmental pollution caused by anthropogenic emissions, such as CO_2, and the resulting diseases are significant factors that driand up healthcare costs (Ahmad et al., 2021). The accurate assessment of the health impacts of environmental degradation and the associated costs has become increasingly important. While improvements in public health enhance life expectancy and well-being, addressing both health and environmental issues with limited resources remains a significant challenge (Apergis et al., 2020). Industrial transformations aimed at reducing emissions can promote not only environmental justice but also improvements in public health, reductions in health inequities, and increased resilience for individuals, communities, and society at large (Muntean et al., 2018; Yang et al., 2022; Çobanoğulları, 2024). Rising HE reflect the growing public awareness of health and the impacts of industrial environmental pollution (Watts et al., 2015).

In addition, the acceleration of global aging and the growth of the elderly population will lead to significant changes in the scale and structure of societal consumption. Literature reviews address the impact of aging populations (AG) on HE and the determinants of these expenditures. While Feldstein (1988) and Hitiris and Posnett (1992) examined the accounting of national income and HE, Zweifel et al. (1999) demonstrated a positive relationship between age and HE. In aging societies, the participation of fewer individuals in the labor market, coupled with the rapid increase in welfare expenditures, slows global productivity growth (Li et al., 2024). It has been demonstrated by researchers such as Meng et al. (2018) and Zheng et al. (2022) that shifts in production and consumption processes have long-term implications for CO_2 emissions. Consequently, assessing the influence of aging on CO_2 emissions requires an examination of the indirect effects embedded within both production and consumption processes (Li et al., 2024). The increased demand for healthcare services drivenby an AG might give rise to higher HE, which, subsequently, could contribute to a rise in CO_2 emissions (Çobanoğulları, 2024). For instance, as elderly individuals spend more time at home, household energy consumption tends to increase (Shi et al., 2023). Furthermore, higher hospitalization rates among the elderly result in increased CO_2 emissions in the healthcare sector (Yang et al., 2022). These factors highlight a strong link between aging and CO_2 emissions. The impact of aging on CO_2 emissions has become a significant focus of academic research (Yu et al., 2022; Li et al., 2024). Recent literature offers varying Perspectives on the environmental implications of AG. York (2007) and Liddle (2011) identified a relationship between the age structure of the population and CO_2 emissions. Some studies suggest that the energy usage habits of elderly societies contribute to increased CO_2 emissions (Menz & Welsch, 2012; Yang et al., 2015; Zhang & Tan, 2016; Aslam & Ahmad, 2018; Yu et al., 2018; Wu, 2019; Pan et al., 2021; Yang et al., 2022; Jiang et al., 2023). However, other research argues that aging may promote industrial transformation, thereby reducing CO_2 emissions (Yang & Wang, 2020; Yang et al., 2021; Zheng et al., 2022; Wang et al., 2023; Chu, 2024). In this context, the relationship between aging and CO_2 emissions appears to be highly complex, with findings varying depending on the period and region analyzed. Consequently, analyzing the interconnections among environmental issues, EG, and HE has become increasingly crucial.

In light of the aforementioned information, this study focuses on European Union (EU) countries due to the increasing prominence of environmental and economic concerns in recent years.

Developing countries within the EU face interconnected challenges such as air pollution, rising HE, AG, and rapid EG. AG in the EU also emerge as a significant issue. Low fertility rates and increasing life expectancy in the EU countries have led to population aging. The transition to a low fertility regime worldwide after 1993 has accelerated the aging process (Ertürk & Koç, 2023). Declining fertility rates and increasing life expectancy haveled to a rapid rise in the proportion of people aged 65 and older in the EU countries. While this proportion was around 16% in 2010, it is projected to reach 30% by 2050 (EU, 2023). However, the pace of aging varies across the EU countries. In Northern European countries, the process is progressing more slowly, whereas in Southern European countries, it is occurring at a faster rate. AG not only places considerable pressure on healthcare systems but also alters consumption behaviors and production structures, leading to a demand model associated with higher emissions. In the EU countries, the AG has increased the demand for healthcare services, causing the share of HE in GDP to rise rapidly. In some countries, this share exceeds 10%, while in others, it remains below 5% (MS, 2023). At the same time, increased investments in RE sources haveemerged as a critical tool for reducing CO_2 emissions in line with ENS goals. Finally, collaborative efforts to implement interrelated SDGs, could strengthen policy coordination within the EU. This study aims to examine the interactions among these factors in the EU context, assessing the effect of air pollution on HE and GDP growth.

In light of this information, this study contributes to the literature on EU countries in the following ways: First, it uses spatial econometric data analysis to examine 22 EU member states experiencing AG during the period 2005-2020 using variables such as EQ, AG, HE, GDP per capita and renewable energy budgets (REB).

EU countries were selected for the analysis due to their shared environmental, economic, social, and health policies, as well as their strong spatial interdependence. The period 2005–2020 was chosen primarily to ensure data continuity within this country group and to provide a detailed assessment of the environmental policy changes initiated by the Kyoto Protocol. Additionally, during this period, the impact of population aging and health expenditures on the environment became more evident, the share of renewable energy investments in R&D expenditures increased significantly, and sustainability policies gained priority. Furthermore, to maintain the consistency of the results, the study was limited to pre-pandemic data, as 2020 marked a year in which the COVID-19 pandemic led to a significant reallocation of national budgets toward health expenditures. Considering these factors, this period and country group were deemed appropriate for the study.

This study employs the spatial panel data analysis model for several reasons. Factors such as health expenditures, an aging population, and environmental sustainability extend beyond national borders and directly influence neighboring countries. Traditional panel data methods fail to account for these spatial dependencies, whereas spatial econometric techniques enable a more precise analysis of interactions between countries. Neglecting spatial dependencies could result in an incomplete evaluation of how health expenditures impact carbon emissions or how an aging population affects environmental sustainability. In this regard, analyzing the spatial interactions among the EU countries constitutes a key contribution of this study.

A review of the literature reveals an absence of spatial econometric studies that encompass almost the entirety of the EU and focus specifically on the topic under investigation. In this regard, the study is expected to fill a significant knowledge gap in the literature.

Secondly, the analysis of REB instead of RE consumption is based on the premise that R&D budgets underpin the use of renewable energy. Higher allocations for REB increase a country's potential to develop its RE market. In this context, public funding plays a vital role in the expansion of RE sources. Thirdly, the study focuses on EU countries, which share common challenges such as AG and high HE. Among developed economies, EU countries stand out for their efforts to develop sustainable energy and healthcare policies. Lastly, by examining the relationship between HE and REB, this study extends beyond the existing debates in the EU context to offer policy recommendations for the more efficient use of financial resources in EU countries. These approaches will contribute to the EU’s ability to more effectively align its energy and healthcare policies with its sustainable development goals.

The rest of this study is structured as follows: (1) the "Literature Review" section covers the most relevant and useful studies on the topic, (2) the "Methodology" section provides a detailed explanation of the dataset and methods used in the study, (3) the "Empirical Findings" section presents the estimation results of the research, and (4) the "Discussion and Conclusion" section offers interpretations and evaluations of the findings.

2. LITERATURE REVIEW

The demographic structure of a population is an vital factor that can influence a country's economic structure and energy consumption. According to Germany's climate law, which came into effect in 2019, the country plans to reach zero greenhouse gas emissions by 2050. Italy and France show strong political performance in RE based on the size of their supply share in this sector (CT, 2022).

This paper aims to contribute to the literature examining the relationships among GDP, CO_2, REB, AG and HE. Accordingly, the literature has a number of noteworthy research examining the impacts of diverse factors on EQ in different countries and regions.

Jerrett et al. (2003) conducted the first study to explore the relationship between environmental factors and HE. Using cross-sectional data from 49 districts in Ontario, Canada, during 1991–1992, the study examined the association between air pollution and HE through a two-stage regression approach. The results showed that although districts that made greater investments in enhancing EQ allocated fewer resources to health services, districts with high pollution levels allocated more money to HE. Using a panel data set from eight OECD nations between 1980 and 1999, Narayan and Narayan (2008) investigated how health expenditure was impacted by income per capita, carbon monoxide, sulfur dioxide, and nitrogen dioxide emissions. According to their findings, health expenditure was positively impacted by carbon monoxide, sulfur dioxide emissions, and income per capita in a statistically significant way. The aging of the population has a suppressive influence on the increase of HE, as Zweifel et al. (1999) highlighted. Using a conceptual model, Pammolli et al. (2012) assessed how aging indirectly affects HE by taking into account sociocultural variables including medical technology. De Meijer et al. (2013) looked at how aging affected health spending in light of how different variables interacted.

Energy consumption, share, and technology have been the main areas of attention when it comes to RE (Qi et al., 2014; Uz Zaman et al., 2021; Chen et al., 2022; Charfeddine & Kahia, 2021; Altıntaş & Kassouri, 2020). There haven't been many research on REB, though. Important contributions include Yang et al. (2022), which investigated the relationship between AG, HE, and CO_2 emissions in G7 countries; Ahmad et al. (2022), which investigated the relationship between financial risk, REB, and ecological footprint; and Ahmed et al. (2021), which investigated the effects of economic uncertainty and REB on ENS. In terms of environmental concerns, the research also highlights how crucial the relationship between economic development and emissions is. Upon reviewing the current literature, it can be observed that two primary approaches panel data analysis and time series analysis dominate the research. A review of the panel data-based literature is outlined below:

Table 1: Literature Review (studies based on panel data)

Author(s)	Region/ Period	Methods	Results
Narayan & Narayan (2008)	8 OECD country groups	Panel co-integration	Rising EG harms environmental quality.
Qureshi (2015)	5 Asian country groups 2000-2013	FMOLS-DOLS and CCR	As EG increases, HE increase.
Siti Khalijah (2015)	Malaysia 1970-2013	Panel co-integration	The deterioration of EQ increases HE.
Yahaya et al. (2016)	125 Developing country group 1995-2012	Panel co-integration	EQ negatively affects HE.
Chaabouni et al. (2016)	51 country groups 1995-2013	Panel dynamic synchronous equations	The increase in EG reduces the EQ.
Cetin (2018)	BRICS-T country group 2000-2015	Panel ARDL	EG and EQ have a positive impact on HE.
Zaidi & Saidi (2018)	Sub-Saharan Africa country group 1990-2015	Panel ARDL	EG positively affects HE, whereas EQ negatively influences HE.
Apergis et al. (2020)	178 country groups 1995-2017	Panel GMM	EG positively influences HE. Likewise, the deterioration of EQ leads to an increase in HE.
Yang & Wang (2020)	China 10 provinces 2000-2016	Panel threshold	As the aging level of the population increases, EQ improves.
Nawab et al. (2021)	6 ASEAN country groups 2000-2018	GMM and Granger causality	Health sector investments and RE use contribute to reducing environmental degradation.

Table 1: Literature Review (studies based on panel data, continued)

Author(s)	Region/ Period	Methods	Results
Bilgili et al. (2021)	36 Asian country groups 1991-2017	GMM, FMOLS and quantile regression	HE increase the EQ.
Ahmad et al. (2022)	OECD country groups 1984-2018	Panel data analaysis	RE technology contributes to the ENS of budgets.
Yang et al. (2022)	G7 group of countries 1985-2019	Panel causality and CS-ARDL	HE and EG adversely affect EQ.
Li et al. (2022)	BRICS countries 2000-2019	Fourier ARDL	EG in Brazil and India is reducing EQ. In South Africa, HE increase as growth increases.
Karimi et al. (2023)	G-7 countries 2000-2019	MMQR, FMOLS, DOLS	The decrease in EQ negatively affects life expectancy.
Al (2023)	OPEC countries 2000-2020	Multiple regression analaysis	The deterioration of EQ increases HE.
Dorbonova & Sugozu (2024)	Asian countries 2000-2020	Dumitrescu-Hurlin panel causality	Higher HE results in increased consumption of renewable energy.
Chu (2024)	30 OECD country groups 1995-2015	Quantil panel analaysis	AG's effect on the ecological footprint is non-linear, following an inverted U-shape.
Kumar & Radulescu (2024)	45 Sub-Saharan African country groups 1991-2020	Dumitrescu–Hurlin panel causality analysis and Fisher Johnson cointegration test	EQ has a strong positive relationship with EG and life expectancy.
Li et al. (2024)	China (30 provinces) 2000-2020	Dynamic panel threshold	The increase in aging on both the producer and the consumer side deteriorates the EQ.
Sui et al. (2024)	212 country group 2000-2021	Panel GMM	RE development is significantly and positively influenced by AG.

Table 2: Literature Review (studies based on time series)

Author(s)	Region/ Period	Methods	Results
Apergis et al. (2018)	ABD 1996-2009	Quantity regression	EQ has a positive effect on HE.
Metu et al. (2018)	Nigeria 1990-2015	ARDL	There is a negative relationship between EQ and HE.
Gunduz (2020)	ABD 1970-2016	Granger and Yoon secret co-integration	The deterioration of EQ increases HE.
Ullah et al. (2020)	Pakistan 1998-2017	2SLS, 3SLS, and Granger causality	The use of RE improves EQ, which in turn reduces HE.
Karaaslan & Çamkaya (2022)	Türkiye 1980-2016	ARDL and Toda-Yamamoto causality	EQ increases as HE and RE consumption rise.
Aydin & Bozatli (2023)	Türkiye 1979-2019	Fourier based co-integration	The relationship between EQ and HE is negative.
Triki et al. (2023)	Saudi Arabia 1980-2020	ARDL and NARDL	It increases the EQ of HE and renewable energy.
Çobanogulları (2024)	Türkiye 1975-2020	ARDL	The increase in EG reduces the quality of the environment.

The literature review has identified areas requiring further research within the context of EU countries. Firstly, studies examining the impact of population aging (AG) on environmental quality (EQ) are limited, and existing findings exhibit inconsistencies. Additionally, the interaction between AG, healthcare expenditures (HE), renewable energy budgets (REB), and CO_2 emissions has not been sufficiently explored. In particular, there is a notable lack of studies investigating the effects of HE on REB and EQ.

Secondly, most existing research focuses on the relationship between EQ and HE. However, comprehensive analyses that directly assess the impact of HE on EQ remain insufficient. Spatial dependence makes it impossible to address environmental issues in isolation. Given the environmental policy interactions among EU countries, the use of spatial econometric modeling is essential.

Ignoring spatial relationships may lead to inaccurate estimations of environmental impacts. Previous studies have generally examined the relationships between environmental sustainability, healthcare expenditures, and an aging population. However, the majority of these studies have relied on panel data analysis or time series methods without considering spatial dependence or analyzing cross-country interactions. By incorporating spatial interactions among EU countries, this study fills a critical gap in the literature.

Thirdly, prior research has predominantly focused on OECD countries or specific regional groups, often overlooking EU countries. Considering the economic disparities among EU nations, treating them as a homogeneous group may compromise the accuracy of the findings. Moreover, studies focusing on a single country may limit the generalizability of policy recommendations.

Therefore, this study aims to analyze EU countries with similar economic and social indicators, providing more comprehensive and applicable insights into ENS and policy recommendations.

3. EMPIRICAL ANALYSIS

This section of the study will look at the regional implications on the EU member states as well as the relationship between AG, HE, REB, and EQ. Prior to discussing the application findings, the data and model will be presented, followed by an explanation of the research methods of the relevant subject.

3.1. Methodology

According to the statement at Tobler's First Geography Lesson "Everything is related to everything else, but near things are more related than distant things" (Tobler, 1970), all of the ascribed values of indicators in a given geographic region are interested in one another, but closer indicators havea stronger relationship than more distant ones. indicates that they are related in some way. One surface is not separated from another, in accordance with this principle. Ignoring geographical correlations in an economic study might provide biased conclusions when variables are spatially connected (Anselin, 1988).

There are three main methods of spatial panel data analysis. These methods are used as Spatial Lag Model (SLM), Spatial Error Model (SEM) and Spatial Durbin Model (SDM) which includes both SLM and SEM. The SLM model makes the assumption that a spatially weighted average of nearby dependent variables contributes to the value of the dependent variable seen at a particular location (Elhorst, 2012).

$$y_{it} = \sum_{j=1}^{N} w_{ij} y_{jt} + x_{it} + {}_{i} + \varepsilon_{it} \quad (1)$$

From the subscripts in the above equation; i countries ($i = 1,...,N$), t is time ($t = 1,...,T$) represents. $\sum_{j=1}^{N} w_{ij} y_{jt}$ the dependent variable y_{it}'s represent endogenous interaction effects. y_{jt} is the weighted average of dependent variables in neighboring countries. parametersThe spatial autoregressive coefficient measures the strength of the simultaneous spatial correlation between a region and its geographically neighboring regions. x_{it} refers to the matrix of explanatory variables. 's are vectors of parameters to be estimated. ε_{it} represents the error term. The error term is independent and identical, has zero mean and variance σ^2 it is suggesting that w_{ij} represents the spatial weight matrix.

Interaction effects between error components are included in the SEM model. When missing factors have an impact on both local and nearby regions, resulting in regional interaction effects, this model is employed. The following is the panel SEM model (Elhorst, 2012):

$$y_{it} = x_{it} + {}_{i} + \varepsilon_{it} \qquad (2)$$
$${}_{it} = \sum_{j=1}^{N} w_{ijjt} + \varepsilon_{it} \qquad (3)$$

signifies the spatial autocorrelation coefficient of the error term, measuring the influence of residuals from neighboring regions on the residuals of the local region. The primary difference between the coefficients and lies in how spatial dependence is incorporated into the regression equation. Other parameters remain as previously specified.

A more comprehensive model is created by integrating SLM and SEM into SDM. Panel SDM is obtained with this method proposed by LeSage and Pace (2008). Panel SDM is as follows:

$$y_{it} = \sum_{j=1}^{N} w_{ij} y_{jt} + x_{it} + {}_{i} + \lambda_t + \sum_{j=1}^{N} w_{ij} x_{jt} + \varepsilon_{it} \qquad (4)$$

is a vector of the explanatory factors' spatial autocorrelation coefficients. The other parameters are identical to those previously given. We apply Elhorst's (2012) specification tests to identify the model that best fits the data. To examine fixed effects (FE), we begin by estimating conventional panel data models and conducting the likelihood ratio (LR) test. Subsequently, we use Lagrange Multiplier (LM) tests—LM_{LAG} and LM_{ERR} —along with their robust versions, Robust- LM_{LAG} and Robust-LM_{ERR}, to assess whether the SLM or the SEM better represents the data compared to a model excluding spatial interaction effects. If the LM tests indicate that the spatial panel model is preferred over the non-spatial panel model, we then apply Wald and LR tests to confirm whether the spatial panel model provides a superior fit.

We first estimate the SDM model and then $H_0: \gamma = 0$ and $H_0: \gamma + \rho\beta = 0$ the hypotheses are tested with Wald and LR test. The first hypothesis says that the SDM model is valid and the second hypothesis says that the SEM model is valid. (Burridge, 1981). If both hypotheses are rejected, the SDM model best explains the data. For this reason, SDM is a more generalized form compared to the SLM and SEM model. However, a relevant statistical test needs to be performed to decide whether SDM can be applied to a particular regression analysis. CO_2 exhibit spatial spillover effects (Shahnazi & Shabani, 2021). The SDM specification of the model established in this study is presented as follows:

$$lnprCO2_{it} = \alpha + \rho\sum_{i=1}^{n} W_{ij} lnprCO2_{jt} + \beta_1 lnprAG_{it} + \beta_2 lnHE_{it} + \beta_3 lnprGDP_{it} + \beta_4 lnREB_{it} + \rho_1\sum_{i=1}^{n} W_{ij} lnprAG_{jt} + \rho_2\sum_{i=1}^{n} W_{ij} lnHE_{jt} + \rho_3\sum_{i=1}^{n} W_{ij} lnprGDP_{jt} + \rho_4\sum_{i=1}^{n} W_{ij} lnREB_{jt} + \mu_i + \lambda_t + \epsilon_{it} \quad (5)$$

In the above equation, the subscripts (i) and (t) represent the cross-sectional units (22) and time periods (16), respectively. While μ_i denotes the individual FE, λ_t represents the time FE, and ϵ_{it} denotes the random error term. (W) is defined as the spatial weight matrix. $W_{ij} lnprCO2_{jt}$ represents the spatially lagged value of the model's dependent variable. $W_{ij} lnprAG_{jt}$, $W_{ij} lnHE_{jt}$, $W_{ij} lnprGDP_{jt}$, and $W_{ij} lnREB_{jt}$ represent the spatially lagged terms of the independent variables. A spatial weight matrix that considers geographical distance is used to define spatial effects between units. The formulation of this matrix is as follows:

$$W = \left(1/d^2_{ij}\right) \quad (6)$$

Here, d^2_{ij} represents the distance between country (i) and another country (j). The queen contiguity method is adopted by considering only neighboring countries for each country. In this constructed matrix, countries that share a border are assigned a value of 1, while other countries (non-bordering ones) are assigned a value of 0. The values on the main diagonal of the matrix are zero. This is because a country is not considered a neighbor to itself. In this study, the spatial weight matrix employed in the spatial panel data analysis was constructed based on border adjacency. This method, widely used for modeling spatial dependence, captures spatial relationships by considering the interaction of a unit solely with the geographically adjacent units (Anselin, 2013). In the literature, weight matrices based on border adjacency are recognized as an effective approach for identifying spatial dependence (LeSage & Pace, 2009). Following this perspective, a binary spatial weight matrix was developed and utilized in the analysis, ensuring that each unit is connected only to its directly adjacent counterparts. This approach effectively represents spatial interactions at the regional level and enables a precise assessment of spatial autocorrelation.

In the SLM, including the spatially lagged dependent variable as an independent variable introduces feedback effects, which create an endogeneity problem. Consequently, estimating model parameters using the ordinary least squares (OLS) method leads to inconsistent results. However, in this context, maximum likelihood estimation (MLE) can be employed to sustain consistent parameter estimates. It is necessary to maximize the log-likelihood (LR) function, which is:

$$lnL = \left(-\frac{NT}{2}\right)\ln\left(2\pi\sigma^2\right) + Tln\left|I_N \, \rho W\right| - \frac{1}{2\sigma^2}\sum_{i=1}^{N}\sum_{t=1}^{T}(y_{it} - \rho\sum_{j=1}^{N} w_{ij}y_{jt} - x_{it}\beta - \alpha_i)^2 \quad (7)$$

3.2. Model and Dataset

To measure the impact of population aging (AG), healthcare expenditures (HE), per capita GDP, and renewable energy budgets (REB) on environmental quality (EQ), data from 22 EU countries were used for the period between 2005 and 2020. The variables include per capita CO2 emissions (million tons), total population ages (> 65), current healthcare expenditures (% of GDP), per capita GDP (=2015 USD), and the renewable energy budget (million USD). Data on per capita CO2 emissions, the AG, HE, and per capita GDP were derived from the World Development Indicators (WDI), while REB were sourced from the OECD. All variables were used in their natural logarithmic forms. This log-log model allows for the interpretation of all variables in terms of elasticity, ensuring they are analyzed in the same unit. The EU countries included in the study are listed in the table below:

Table 3: EU Member State Group

Austria	Estonia	Greece	Latvia	Poland	Spain
Belgium	France	Hungary	Lithuania	Portugal	Sweden
Czech Rep.	Finland	Ireland	Luxembourg	Slovakia	
Denmark	Germany	Italy	Netherlands	Slovenia	
Note: Bulgaria, Croatia, Cyprus, Malta and Romania could not be included in the group of					

countries considered. Cyprus does not haveborders with EU countries that could create spatial effects due to its geographical location. Data from the other 5 countries could not be accessed in certain years. Since a balanced panel structure was preferred in the study, missing observations were remoandd.

Within the EU, EQ and an AG are two intrinsically linked variables. Maintaining a healthy environment is vital, particularly for older citizens, since access to clean water, unpolluted air, and green spaces is essential for both quality of life and public health. Meanwhile, the demographic shift toward an older population is reshaping economic and social structures by increasing the demand for healthcare services, social security, and infrastructure (Yang et al.,2022). As a result, sustainable environmental policies must not only preserve natural balance but also support the development of healthier and more active lifestyles among the elderly (Van de Kaa, 1999; Pascual-Saez et al., 2020). Spatial econometric models play a critical role in uncovering how economic outcomes in EU countries are affected by factors such as geographic location, regional interactions, and spatial dependencies. In these nations, the impact of economic, social, and environmental policies extends beyond national borders. Consequently, these models are seen as indispensable tools for both economic analysis and policy-making within the European Union (Vangerven & Crombez,2012).

This study explores the effect of AG, HE, GDP per capita, and REB on EQ by selecting 22 EU member countries. Due to the absence of data for certain variables, Bulgaria, Croatia, Cyprus, Malta, and Romania were omitted from the analysis. Since this study aims to maintain a balanced panel structure, these countries were not included. Additionally, Cyprus was excluded because it is not a geographical neighbor, which is a relevant factor given the study's focus on spatial effects. A comprehensive table displaying the variables is provided below.

Table 4: Table Containing Detailed Information of Variables

Variables	Indicator	Measurement	Expectation	Source	References
lnprCO2	Environmental Quality (EQ)	Million tonnes of carbon dioxide per person	.	WDI	.
lnprAG	Population aging (AG)	Total population aged > 65	Negative	WDI	Chu, 2024; Sui et al., 2024; Yang & Wang, 2020
lnHE	Health Expenditures (HE)	Current health expenditures (GDP%)	Positive	WDI	Karaaslan & Çamkaya, 2022; Apergis et al., 2018
lnprGDP	GDP per capita (Economic growth, EG)	US dollars (= 2015)	Positive	WDI	Çobanogulları 2024; Narayan & Narayan, 2008; Qureshi, 2015
lnREB	Renewable	Million US	Negative	OECD	Ahmad et al.

	energy budget (REB)	Dollars (=2015 and PPP)			2022; Yang et al., 2022

The variables in the table represent EQ and the socio-economic and energy-based factors influencing it. The expected effect of each variable is assessed based on previous studies in the literature. Below is an interpretation of the expected impact of each variable on EQ. AG is expected to enhance EQ by reducing CO_2 emissions, as older populations tend to consume less energy and adopt more environmentally conscious lifestyles. This positive relationship has been confirmed in studies by Chu (2024), Sui et al. (2024), and Yang & Wang (2020), supporting the notion that AG positively contributes to ENS. The impact of HE on EQ is complex. Besides, the energy consumption and medical waste produced by the healthcare sector can cause to environmental degradation. On the other hand, eco-friendly healthcare infrastructure and energy-efficient practices can improve EQ. The expected positive effect of this variable can be explained by the idea that a healthier population is more likely to support ENS initiatives. Similar results have been reported by Apergis et al. (2018) and Karaaslan & Çamkaya (2022). EG typically leads to environmental degradation due to higher energy consumption and industrial activities. Studies by Çobanoğulları (2024), Narayan and Narayan (2008), and Qureshi (2015) indicate that a rise in GDP per capita leads to higher CO_2 emissions, thereby reducing EQ. Therefore, EG is expected to have a negative impact on EQ. Investments in RE contribute to improving EQ by reducing fossil fuel consumption and CO_2 emissions. Studies by Ahmad et al. (2022) and Yang et al. (2022) confirm the positive effect of REB on EQ. Consequently, this variable is expected to have a favorable impact AG on ENS.

Overall, these variables exert different effects on EQ. While AG and REB positively influence EQ, HE and GDP per capita negatively affect EQ. These findings highlight the need to carefully balance energy consumption, population dynamics, and EG to achieve sustainable development goals. Increasing investments in RE and promoting eco-friendly healthcare infrastructure play a vital role in enhancing EQ in the long term.

One effective way to gain prior insight into variables is through correlation analysis (Tosunoğlu, 2024). This statistical method examines the degree and direction of the relationship between variables, allowing researchers to identify patterns and associations. By measuring how one variable changes in response to another, correlation analysis provides valuable preliminary information about potential interactions. This understanding can help guide further analysis, refine hypotheses, and improve the accuracy of predictive models in various fields of research. The table below displays descriptive statistics and the correlation relationships among the variables.

Table 5: Descriptive statistics and correlation matrix of the variables (N=352)

	lnprCO2	lnprAG	lnHE	lnprGDP	lnREB
lnprCO2	1				
lnprAG	0.18*** (0.0009)	1			
lnHE	0.53*** (0.0000)	0.34*** (0.0000)	1		
lnprGDP	0.11*** (0.0430)	-0.08 (0.1339)	0.44*** (0.0000)	1	
lnREB	0.93*** (0.0000)	0.28*** (0.0000)	0.71*** (0.0000)	0.34*** (0.0000)	1
Mean	4.21	-1.75	2.11	10.24	7.50
Std. deviation	1.24	0.16	0.22	0.60	1.50
Minimum	1.96	-2.24	1.56	9.05	4.16
Maximum	6.74	-1.45	2.55	11.63	10.9

Notes: Asterisks indicate significance: ***, **, and * denote 1%, 5%, and 10% levels, respectively. Parentheses show p-values.

The study's variables' descriptive statistics were examined to provide preliminary information, revealing that the variables did not contain any outliers.

An analysis of the correlation matrix indicated that the correlations between lnprCO2 and lnprAG, lnHE, lnprGDP, and lnREB were statistically significant at the 0.05 significance level, with all relationships being positive. The correlation coefficients between lnREB and lnHE, as well as between lnREB and lnprCO2, were 0.93 and 0.53, respectively, indicating a strong correlation. Additionally, the correlations between lnprAG and lnprGDP, as well as between lnprAG and lnprCO2, were 0.18 and 0.11, respectively. Moreover, the correlation between lnHE and lnREB was found to be statistically significant, with a high and positive coefficient of 0.71.

The model employed in this study is grounded in the existing literature. In addition to being developed from prior research, it was further refined by Yang et al. (2022), who used this model to analyze panel effects in G7 countries. However, this study extends the analysis by considering not only panel effects but also spatial effects within EU countries. The functional form of the model subject to this study is given in the following equation.

$$lnprCO2 = f(lnprAG, lnHE, lnprGDP, lnREB) \quad (8)$$

Included in the model lnprCO2 is the dependent variable and represents CO2 per capita (EQ). Included in the model lnprAG population aging, lnHE healthcare expenses, lnprGDP GDP per capita and lnREB renewable energy budget constitutes the independent variables of the model. The variables were converted into their natural logarithmic forms, transforming the analysis into a log-log model. This transformation linearizes the estimator equations, making the analysis more straightforward (Tosunoğlu, 2025). Additionally, it enables a clearer interpretation of the results in terms of elasticity, providing valuable insights into the relationships between variables.

3.3. Results and Discussion

Spatial panel analyses were handled using the available data in this section of the study. So as to identify the appropriate econometric model, the presence of spatial effects was first examined using LM tests. Next, pooled OLS, FE, and random effects models were compared using LR and Hausman tests. The queen border method was utilized to determine the relationship between EU member states based on the model employed in the investigation. Elhorst's codes and MATLAB were utilized for the analyses. Before presenting the findings of the spatial panel data analysis, specific specification tests outlined in Elhorst's (2012) methodology are conducted to determine the appropriate model. The specification tests used for model selection are as follows:

Table 6: Test Result of Model Selection Spesification Tests

Tests	Hypotesis	Statistics
LM_{LAG}	H_0: There is no spatially lagged dependent variable.	Pooled OLS: 19.9*** Spatial panel fixed effect: 71.4*** Spatial-time-period panel fixed effects: 25.2***
LM_{ERR}	H_0: The error term exhibits no spatial autocorrelation.	Pooled OLS: 1.77 Spatial panel fixed effect: 29.1*** Spatial-time-period panel fixed effects: 22.4***
LM_{LAG} (Robust)	H_0: There is no spatially lagged dependent variable.	Pooled OLS: 22.3*** Spatial panel fixed effect: 49.28*** Spatial-time-period panel fixed effects: 2.83*
LM_{ERR} (Robust)	H_0: The error term exhibits no spatial autocorrelation.	Pooled OLS: 4.05*** Spatial panel fixed effect: 6.97*** Spatial-time-period panel fixed effects: 0.04

Table 6: Test Result of Model Selection Spesification Tests (Continued)

Tests	Hypotesis	Statistics
Hausman	H_0: The difference in coefficients is not systematic.	SLM: -77.8*** SEM: 216.1***
LR_{LAG}	H_0: The SDM can be simplified into the SLM.	Spatial panel fixed effect: 1635.7*** Spatial panel random effect: 1424.9***
LR_{ERR}	H_0: The SDM can be simplified into the SEM.	Spatial panel fixed effect: 1598.3***

		Spatial panel random effect: 1444.9***
Wald lag (W_{LAG})	H_0: The SDM can be simplified into the SLM.	Spatial panel fixed effect: 0.53*** Spatial panel random effect: 0.38***
Wald error (W_{ERR})	H_0: The SDM can be simplified into the SEM.	Spatial panel fixed effect: 0.55*** Spatial panel random effect: 0.57***
Note: Asterisks indicate significance: ***, **, and * denote 1%, 5%, and 10% levels, respectively.		

The table above displays the results of specification tests used to determine the appropriate model, following the approach outlined by Elhorst (2012). Initially, traditional panel data models (Pooled OLS, FE, and spatial-time-period FE) are estimated using the LR method. In the SLM, feedback effects arise bacause of the inclusion of the spatially lagged dependent variable as an independent variable, leading to an endogeneity problem. Consequently, estimating model parameters using the ordinary OLS method results in inconsistent estimates. To address this issue and obtain consistent estimates, the maximum likelihood estimator is applied. Additionally, after performing LM tests, the LR test is used to compare the models.

Next, LM tests are handled to assess the presence of spatial effects (Elhorst, 2012). The calculated LM statistic is evaluated using the chi-square (χ^2) distribution. The results of the LM spatial lag test indicate that the null hypothesis (H_0)—stating that there is no spatially lagged dependent variable—is rejected at the 1% significance level in the pooled OLS, spatial FE, and spatial-time-period FE models. This suggests that the spatially lagged value of the dependent variable should be included in the model, confirming the presence of spatial effects.

Regarding the LM spatial error test, the H_0—asserting that there is no spatial autocorrelation in the error term—cannot be rejected in the pooled OLS model. However, it is rejected at the 1% significance level in both the spatial FE and spatial-time-period FE models, indicating spatial dependence in the error terms of these models. Since both the LM_{LAG} and LM_{ERR} tests are significant, robust tests are performed for further validation. The results reveal that the H_0 is rejected at the 1% significance level in both the LM_{LAG} and LM_{ERR} tests. However, in the spatial-time-period FE model, the LM_{LAG} test rejects the H_0 at the 10% significance level, while the LM_{ERR} test does not reject it. Overall, the LM tests confirm the presence of spatial effects, but they do not provide conclusive evidence regarding whether the SLM or SEM should be preferred. Given that both models are significant, the results point to the SDM.

The SDM is a spatial panel econometric model that includes the spatial lag of the dependent variable as well as the spatial lags of the independent variables. This model offers greater flexibility by accounting for the effects of independent variables in neighboring regions. However, additional tests are required to assess the validity of the SDM compared to alternative mo*d*els.

In both the LR and Wald tests, the null hypotheses propose that the SDM can be simplified to either the SEM or the SLM The test results reject the H_0 in all cases, displaying that the SDM is preferable to both the SEM and SLM.

Another crucial specification test is the Hausman test, which compares FE and random effects models to identify the appropriate model. The H_0, which states that there is no systematic difference between the coefficients, is rejected in this analysis, confirming that the FE model is more suitable. Therefore, FE models are particularly appropriate for cross-sections involving social and economic cooperation, such as EU countries, further supporting the preference for this model. The subsequent section presents traditional panel data analyses conducted without spatial data analysis.

Table 7: Prediction Results Without Spatial İnteraction

The dependent variable: lnprCO2	**Pooled OLS**	**Panel Fixed Effects**	
Determinants	**Base**	**Spatial**	**Spatial and Time- Period**
Constant	-15.8*** (t-stat: -41.3)	.	.
lnprAG	-0.64*** (t-stat: -4.98)	-1.56*** (t-stat: -22.6)	-0.49*** (t-stat: -4.23)
lnHE	-0.79*** (t-stat: -6.19)	0.04 (t-stat: 0.77)	0.20*** (t-stat: 3.93)
lnprGDP	0.41*** (t-stat: 11.7)	0.75*** (t-stat: 12.6)	0.68*** (t-stat: 13.3)
lnREB	0.04** (t-stat: 2.52)	-0.13*** (t-stat: -5.21)	-0.04* (t-stat: -1.91)
σ^2	0.12	0.0061	0.0040

R^2	0.40	0.65	0.35
logL	-117.9	400.9	.
Note: Asterisks indicate significance: ***, **, and * denote 1%, 5%, and 10% levels, respectively.			

The above table (7) displays the estimation findings of the econometric model established without spatial interaction, obtained using traditional panel data analysis methods through the LR method. Using these outputs, LM tests from the specification tests presented in Table 6 were obtained. According to the specification tests, spatial effects were detected in the established model. As indicated by the LM_{LAG} and LM_{ERR} statistics, SDM is estimated in a comparative manner with other models. The SDM findings, which include the comparative results of the models, are as follows:

Table 8: Spatial Interactive Prediction Results With Comparisons

The dependent variable: lnprCO2	**Spatial Panel Fixed Effects**		**Spatial Panel Random Effects**	
Determinants	**SLM**	**SEM**	**SLM**	**SEM**
Constant	.	.	-14.85***	-18.15***
lnprAG	-0.98***	-1.18***	-1.13***	-1.15***
lnHE	0.13***	0.11**	0.10**	0.10*
lnprGDP	0.50***	0.48***	0.56***	0.45***
lnREB	-0.06***	-0.07***	-0.08***	-0.06***
W*lnprCO2 (W_{LAG})	0.53***	.	0.38***	.
θ (W_{ERR})	.	.	0.01***	26.02***
ϕ	.	0.55***	.	0.57***
$σ^2$	0.004	0.005	0.005	0.005
R^2	0.98	0.96	0.97	0.97
logL	445.4	426.7	339.9	350.1
Note: Asterisks indicate significance: ***, **, and * denote 1%, 5%, and 10% levels, respectively.				

The table above displays the results of comparative estimation considering spatial effects. Based on these results, the LR, Wald, and Hausman tests in Table 6 were conducted to determine the appropriate model specification.

The LR and Wald tests suggest that the SDM model is the most suitable. Meanwhile, the Hausman test displays a preference for the FE model. Consequently, the choice must be made between the SLM and the SEM within the fixed effects framework.

To identify the more appropriate model, the log-likelihood (logL) statistic is also considered. A higher logL value indicates a model's superior performance in explaining the observed data. When comparing the SLM and SEM, the FE spatial lag model is preferred since its logL value (445.4) is higher than that of SEM (426.7). Based on these model specification tests, the coefficients are interpreted using the fixed effects SLM.

The findings show that the coefficients are statistically significant at the 1% significance level. Given that a log-log model is employed, the coefficients represent elasticities. Specifically, a 1% increase in lnprAG leads to a 0.98% decrease in lnprCO2, suggesting that population aging enhances environmental quality. This outcome may be attributed to lower energy consumption and more environmentally conscious behaviors among older individuals. Conversely, a 1% increase in lnHE results in a 0.13% increase in lnprCO2, implying that higher health expenditures negatively impact environmental quality. This relationship could stem from energy consumption in healthcare facilities, the operation of medical devices, and waste management processes. Additionally, a 1% increase in lnprGDP leads to a 0.50% rise in lnprCO2, indicating that GDP per capitia diminishes environmental quality. In contrast, a 1% increase in lnREB reduces lnprCO2 by 0.06%, suggesting that expanding the renewable energy budget improves environmental quality by decreasing fossil fuel consumption. Finally, the spatial effect across EU countries is found to be statistically significant, with a spatial effect coefficient of 0.53.

4. CONCLUSION AND POLICY RECOMMENDATIONS

This paper researhes the effects of AG, HE, GDP per capita, and REB on EQ across 22 EU member countries from 2005 to 2020, using the spatial panel econometric data analysis method. The diagnostic tests conducted for model specification display that the fixed effect-SLM the most appropriate. The constructed model reveals the exintence of spatial interactions among EU countries. The existence of spatial effects underscores the significance of regional disparities and interactions between countries. The findings indicate that while AG and REB enhance EQ, healthcare expenditures and GDP per capita negatively affect EQ.

Compared to prior literature, the results of this study align with previous findings that an aging population improves EQ (Chu, 2024; Sui et al., 2024; Yang

& Wang, 2020). Furthermore, the negative impact of per capita GDP on EQ observed in this study is consistent with previous research (Çobanogulları, 2024; Narayan & Narayan, 2008; Qureshi, 2015). Additionally, studies by Ahmad et al. (2022) and Yang et al. (2022) support this study's findings that REB positively impact EQ. However, since the presence of spatial effects has not been explored in the existing literature, it is not possible to draw a comparison in this regard. In this study, the spatial data analysis method was employed based on the assumption that factors such as health expenditures, an aging population, and environmental sustainability are not confined within the boundaries of individual countries, but rather exhibit significant spillover effects on neighboring countries. While conventional panel data methods typically neglect these spatial interdependencies, spatial econometric models provide a more holistic and nuanced analysis of these cross-country interactions. Ignoring spatial dependence could result in incomplete or biased assessments regarding the impact of healthcare expenditures on carbon emissions or the role of an aging population in environmental sustainability. Therefore, examining spatial interactions among European Union countries constitutes one of the distinctive contributions of this research to the existing literature.

This study has certain limitations. Firstly, the analysis covers only the period from 2005 to 2020. This temporal limitation primarily stems from constraints in data availability and the necessity of maintaining a balanced panel structure. Additionally, since the year 2020 marked a critical turning point due to the significant impact of the COVID-19 pandemic on global health expenditures, the analysis was intentionally restricted to pre-pandemic data to ensure the integrity and consistency of the results. Another limitation relates to the cross-sectional scope of the study. Croatia, Cyprus, Bulgaria, Malta, and Romania were excluded from the analysis to better capture spatial effects and maintain a balanced panel structure. Cyprus was excluded specifically due to its geographical isolation from other European Union countries, thus preventing any potential spatial interactions. For the remaining four countries, certain data points were unavailable for specific years. To preserve the balanced panel structure, these missing observations were appropriately addressed

The finding that AG enhances EQ suggests the need to promote sustainable lifestyles among the elderly population. Moreover, policies aimed at improving access to eco-friendly transportation and energy use for older individuals could be implemented. Given that REB positively impact EQ, both governments and the private sector should promote RE production, expand infrastructure investments, and support research and development in this field. To reduce the environmental impact of the healthcare sector, sustainable practices such as energy efficiency and waste management should be adopted. Additionally, green hospital initiatives should be encouraged. Considering that per capita GDP growth negatively affects EQ, it is essential to maintain EG while ensuring ENS. This can be achieved by promoting green technologies, supporting a circular economy, and adopting low-carbon production processes.

It is well known that aging populations are more vulnerable to environmental impacts. Therefore, prioritizing environmental protection and developing policies that promote ENS in aging societies is essential. Sustainable transportation alternatives are particularly crucial for older populations, as they often rely on transportation to access healthcare services. One of the largest indirect costs in healthcare economics is related to transportation, which typically increases fossil fuel consumption and CO2 emissions, posing a significant challenge to ENS. Investing in electric vehicles, public transportation, and age-friendly transportation options can help establish environmentally friendly transportation systems. This, in turn, can facilitate the transition to RE and support ENS. Moreover, the positive impact of REB on EQ, as identified in this study, highlights the necessity of increasing investments in RE and expanding eco-friendly energy systems. In this context, governments should provide incentives for RE and offer financial support for technologies that reduce CO_2 emissions.

Given the spatial interactions among EU countries, this study emphasizes the need to strengthen cross-border cooperation in environmental protection and energy policies. Aligning joint climate goals and carbon neutrality strategies in a coordinated manner is crucial for achieving sustainable environmental outcomes across the EU. Future research could extend the analysis by incorporating additional data sources for Bulgaria, Croatia, Cyprus, Malta, and Romania, which were excluded due to data limitations. Including these Eastern European countries would provide a more comprehensive understanding of spatial spillover effects, improving the generalizability of the findings. Expanding datasets to cover these missing countries could enhance the depth and inclusivity of future studies.

5. CONFLICT OF INTEREST STATEMENT

Authors don't have any competing interests.

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7. AUTHOR CONTRIBUTIONS

İHP, MT, TA: Idea;

MT, İHP: Design;
İHP, MT: Supervision;
MT: Collection and/or processing of resources;
MT: Analysis and/or interpretation;
İHP: Literature review;
İHP, MT: Author of the article;
İHP, MT: Critical review

8. ETHICS COMMITTEE STATEMENT

The study adhered to the ethics committee's principles, and necessary permissions were obtained in accordance with intellectual property and copyright regulations**.**

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