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Aging Europe and Sustainability: Evidence from Panel Econometrics

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Abstract

This study analyzes the interaction among demographic aging, economic growth, and environmental sustainability in the European Union (EU). Rapid population aging increases fiscal pressures through pension and healthcare expenditures, constrains labor markets, and challenges conventional growth models. The environmental effects of aging are mixed: reduced mobility and consumption may lower emissions, while healthcare expansion and energy-inefficient housing may raise them. Using a dynamic panel econometric approach with Common Correlated Effects (CCE) estimators and PCA-based structural controls for 27 EU countries over 2000–2023, the findings confirm long-run co-integrating relationships. The results highlight the need to consider grey economy dynamics, tax compliance, and institutional trust in sustainability and welfare policies. The policy implications include promoting active aging, modernizing healthcare systems, improving energy-efficient housing, and strengthening intergenerational equity. Overall, demographic aging should be reframed not as a burden but as an opportunity for structural reform and sustainable transformation.

Keywords
Aging Europe, Panel Econometrics, Grey Economy, Sustainability

JEL Classification
J11, O52, H55, Q56

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Yaşlanan Avrupa ve Sürdürülebilirlik: Panel Ekonometri Analizi

Öz

Bu çalışma, Avrupa Birliği'nde (AB) demografik yaşlanmanın ekonomik büyüme, mali sürdürülebilirlik ve çevresel etkiler üzerindeki rolünü analiz etmektedir. AB ülkelerinde hızla artan yaşlı nüfus, emeklilik ve sağlık harcamaları nedeniyle kamu maliyesini baskı altına almakta, işgücü piyasalarını daraltmakta ve sürdürülebilir büyüme modellerini yeniden düşünmeyi zorunlu kılmaktadır. Bununla birlikte, yaşlanmanın çevresel etkileri çift yönlüdür: Daha düşük tüketim ve hareketlilik karbon emisyonlarını azaltırken, sağlık hizmetlerine yönelik artan talep ve enerji verimsiz konutların yaygınlığı emisyonları artırmaktadır. Çalışmada 2000–2023 döneminde 27 AB ülkesi için Dinamik Panel CCE yöntemi kullanılmış ve yaşlanma, ekonomik büyüme ve çevresel sürdürülebilirlik arasında uzun dönem ilişkilerin varlığı doğrulanmıştır. Bulgular, gri ekonomi ve vergi uyumu gibi faktörlerin de demografik dönüşümle yakından ilişkili olduğunu göstermektedir. Politik açıdan bulgular, aktif yaşlanma, enerji verimli konutlar, sürdürülebilir sağlık altyapısı ve kurumsal güvenin güçlendirilmesi gibi gereklilikleri ortaya koymaktadır.

Anahtar Kelimeler
Yaşlanan Avrupa,
Panel Veri Analizi,
Gri Ekonomi,
Sürdürülebilirlik

JEL Kodu
J11, O52, H55, Q56

1. Introduction

The European Union (EU) is undergoing one of the most significant demographic transformations in its modern history, characterized by rapidly rising life expectancy, declining fertility, and a sustained increase in the share of the elderly population. This structural demographic transformation has profound consequences for labor markets, public finances, social welfare systems, and long-term economic growth. However, its implications extend beyond conventional macroeconomic concerns: demographic aging interacts directly with environmental sustainability, climate transitions, and the dynamics of the grey economy. As nearly one-third of EU citizens are projected to be aged 65 or older by 2050, aging has become a defining structural force shaping Europe's developmental trajectory (Bloom et al., 2010; Börsch-Supan, 2013; European Commission, 2018).

The primary aim of this study is to examine how demographic aging influences economic growth and environmental sustainability across EU member states and to examine the extent to which institutional, fiscal, and structural factors particularly grey economy activity and tax capacity, mediate these relationships (Bengtsson & Scott, 2011; Maestas et al., 2016). Using a dynamic panel econometric model with Common Correlated Effects (CCE) estimators and PCA-based composite indicators for 27 EU countries between 2000-2023, the study investigates long-run interdependencies between aging, emissions, and economic performance, while accounting for shared shocks and structural heterogeneity across member states.

Understanding the demographic-economic-environmental nexus is crucial for designing long-term sustainability policies, especially in the context of the Green Deal, aging welfare systems, and shrinking labor markets. Fiscal pressures from pension and healthcare expenditures may constrain investment capacity and environmental policy implementation. At the same time, aging may produce both positive and negative environmental outcomes lower personal consumption but higher resource-intensive healthcare and inefficient residential energy use. The study is therefore important for informing public policy decisions related to welfare reform, environmental strategy, active aging programs, innovation investment, and grey economy containment (European Commission, 2020; OECD, 2024).

Although previous research has extensively examined the economic effects of aging, few studies have integrated demographic, fiscal, environmental, and grey economy dimensions within a single empirical framework (Albalate et al., 2023). This study contributes by combining sustainability and demographic economics through the Environmental Kuznets Curve (EKC) perspective and by applying advanced panel techniques (CCE, PCA compression) that capture common shocks such as COVID-19 and EU policy harmonization. Linking aging dynamics with informal economy pressures, tax capacity, and institutional resilience dimensions often overlooked in existing literature. Providing country-level long-run estimation results and policy-relevant comparative insights across the EU. Thus, the research differs from previous works by offering a multidimensional and data-driven interpretation of how demographic aging influences sustainable development within interconnected European economies.

This study contributes to the existing literature in several important ways. First, it extends the demographic aging literature by integrating economic growth, environmental sustainability, and grey economy dynamics within a single empirical framework. Second, unlike previous studies that focus primarily on fiscal or labor market effects, this paper highlights the sustainability dimension of aging through emissions, institutional capacity, and structural controls. Third, the use of long-span panel data for 27 EU countries combined with second-generation econometric techniques allows for a more realistic representation of interconnected European economies.

The remainder of the study is structured as follows: The next section summarizes the theoretical foundations and existing literature on demographic aging, sustainability, and the grey economy within the European context. Following this, the third section presents the data, analytical framework, and econometric methodology, including the CCE model and PCA-based structural controls. The fourth section discusses empirical results and comparative country-level findings. The final section offers conclusions and policy recommendations aimed at supporting sustainable aging, fiscal balance, and environmental transitions in the EU.

2. Liteture

Population aging has become a defining demographic trend within the EU, generating profound implications for economic growth, social welfare systems, labor markets, and environmental sustainability. A substantial body of literature links aging to slower economic expansion due to declining labor participation and reduced productivity (Bloom et al., 2010; Börsch-Supan, 2013; European Commission, 2018). Southern and Eastern European economies, in particular, face more severe labor shortages and weaker institutional capacity (European Commission, 2020; Eurostat, 2025). At the firm level, aging workforces may limit innovation and entrepreneurial dynamism, while sectors such as healthcare confront increasing demand amid personnel shortages (Maestas et al., 2016).

To synthesize the theoretical mechanisms discussed in the literature, Figure 1 provides a conceptual overview illustrating how demographic aging influences fiscal pressure, labor dynamics, consumption patterns, and environmental outcomes.

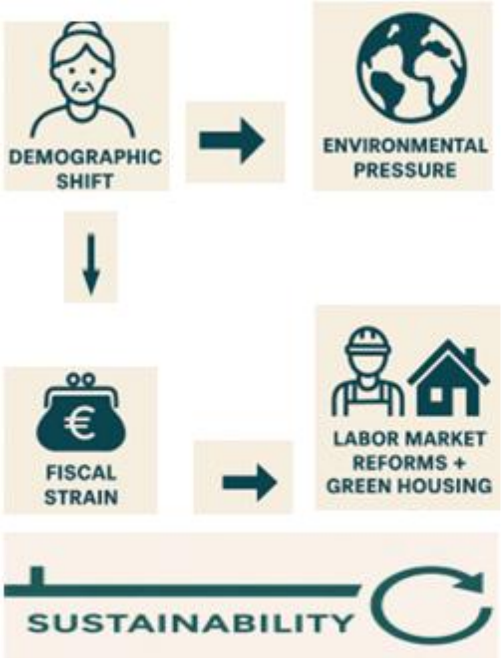

Figure 1. Aging and Sustainability Pathways created by the authors.

The figure provides a conceptual mapping that aligns with findings from Bloom et al. (2010), Börsch-Supan (2013), and Liddle & Lung (2010), and therefore strengthens the theoretical basis of the subject.

Fiscal sustainability is a central theme in aging research. Rising pension and healthcare expenditures generate structural pressure on public budgets, as smaller working populations fund increasing cohorts of retirees (Bengtsson & Scott, 2011; Maestas et al., 2016; OECD, 2024). The OECD (2024) highlights that population aging is the leading driver of long-term expenditure increases across advanced economies. Although pension reforms such as Sweden's notional defined contribution model and Germany's Riester reform have sought institutional adaptation, their long-term adequacy remains contested.

According to Eurostat projections, the share of the population aged 65 and over in the EU will increase steadily over the next decades, significantly transforming labor market conditions, public finance sustainability and long-term development planning (Eurostat, 2025). The magnitude of the demographic shift described above becomes more evident when examining projections of the old-age dependency ratio.

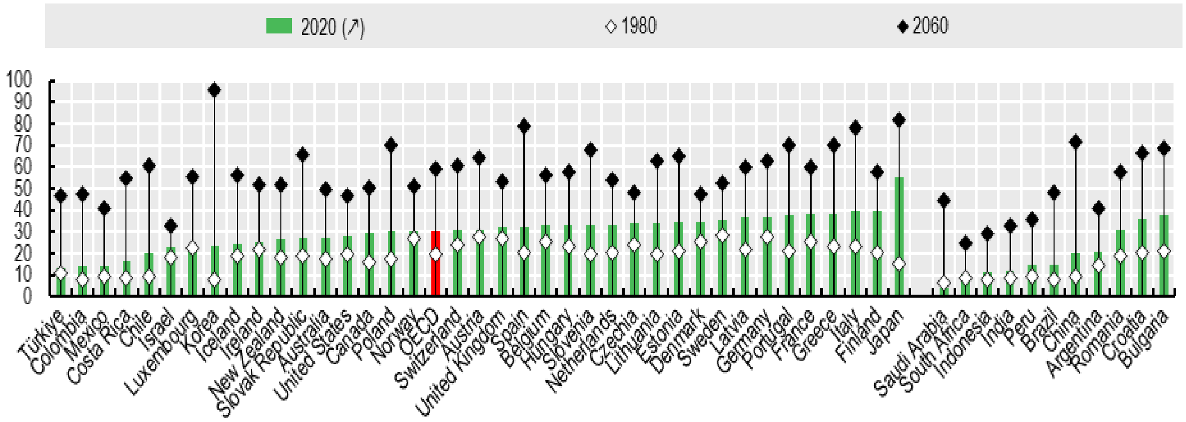

Figure 2. The Demographic Old Age to Working Age Ratio will Double over the Next Four Decades (Source: OECD, 2024: 71).

As shown in Figure 2, the proportion of the elderly population relative to the working-age population is expected to increase sharply across the EU over the coming decades.

The fiscal implications of population aging are also reflected in healthcare expenditures, which vary significantly across European countries. Figure 3 illustrates cross-country differences in per-capita health spending, highlighting how rising healthcare demand associated with aging contributes to increasing budgetary pressures.

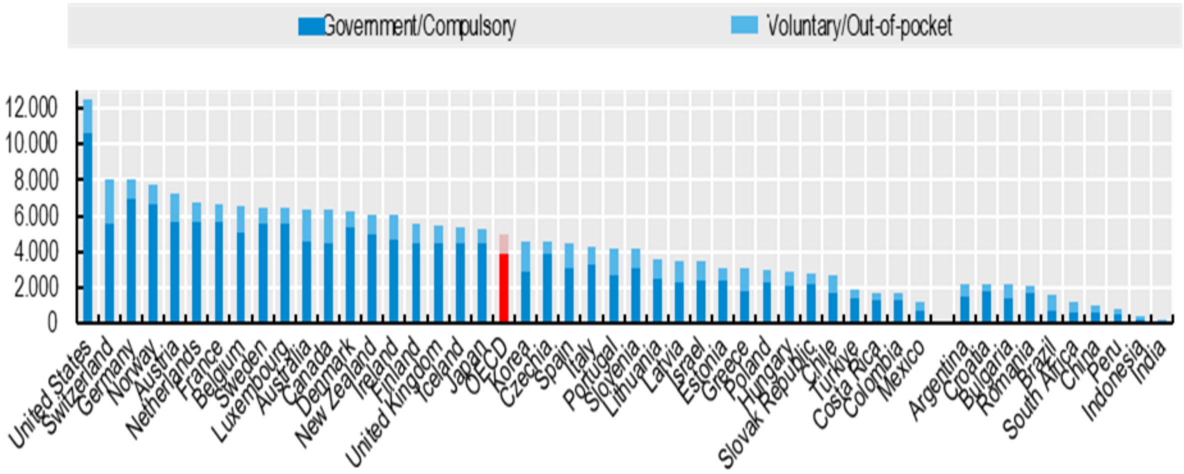

Figure 3. Large differences in health spending per capita across the OECD (Source: OECD 2024: 103) *Notes:* Values represent PPP-adjusted USD.

Figure 3 supports the argument that rising medical costs place growing stress on public budgets, potentially incentivizing informal labor and tax avoidance behaviors.

Recent research also links demographic dynamics to environmental outcomes. Liddle & Lung (2010) show that older populations tend to consume fewer resources and travel less, contributing to lower CO_2 emissions per capita. However, studies by Lenzen et al. (2020) and Zhao et al. (2025) and emphasize counter-effects such as increased healthcare-related emissions and higher energy consumption in single-occupancy elderly households, where older homes often lack modern insulation or efficiency technology. These findings suggest that demographic aging may either support or hinder sustainability depending on policy design.

Social and intergenerational dimensions complement these economic and environmental discussions. Bengtsson & Scott (2011) argue that aging reshapes solidarity, equity, and political behavior, influencing policy priorities and societal cohesion. Karatağ & Akyıldız (2019) highlight the emotional and identity-based complexity of retirement and aging processes. Furthermore, the literature increasingly acknowledges the role of technological innovation and digital aging in addressing sustainability challenges (Coughlin, 2020).

Despite these contributions, research gaps remain. Few studies have examined the interaction between aging, sustainability, fiscal stress, and grey-economy incentives within an integrated empirical model (Albalate et al., 2023; Schneider et al., 2015). This study addresses this gap by combining demographic, environmental, and institutional factors with panel econometric evidence from the EU.

3. European Grey Economies

The grey economy, referring to legally permissible but unregistered or untaxed economic activities, is an essential component of the demographic-fiscal sustainability debate in Europe. Grey economy expansion is often driven by high tax burdens, insufficient pension adequacy, weak institutional trust, and labor market exclusion factors closely linked to aging populations. The traditional Allingham–Sandmo model describes how individuals weigh tax compliance against the likelihood of detection and penalties; in aging societies this decision becomes increasingly sensitive as retired or underemployed older individuals seek supplemental income outside the formal system (Schneider et al., 2015; Arsic et al., 2015).

External shocks, such as the COVID-19 pandemic, have further intensified these pressures. As depicted in Figure 4, health spending surged in most OECD countries during and after the pandemic, exacerbating fiscal constraints and indirectly stimulating grey-economy participation due to shrinking formal labor capacity and rising financial stress.

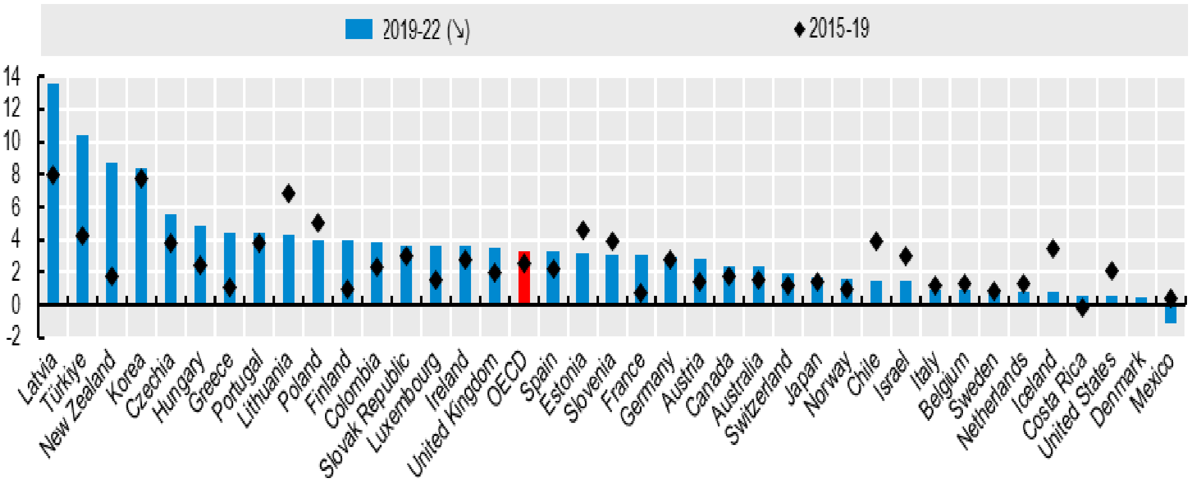

Figure 4. The emergence of COVID-19 led to increases in health spending in two-thirds of OECD countries (Source: OECD, 2024: 103).

OECD tax burden and social security contribution data reveal significant variation across EU economies. Countries such as Portugal, Italy, Greece, and Slovenia exhibit high pension expenditures, aging populations, and relatively elevated grey-economy activity. Fiscal pressures intensified during the COVID-19 pandemic, when healthcare costs surged while labor participation declined. These structural dynamics risk shrinking tax bases and reducing state capacity to finance environmental transformation (OECD, 2024).

The relationship between aging and the grey economy therefore produces a dual sustainability risks:

1. Fiscal sustainability risk, where expanding pension and healthcare demand collide with eroding tax income,
2. Environmental sustainability risk, where reduced public investment capacity constrains climate policy implementation.

At the same time, policy responses such as active-aging labor programs, energy-efficient housing retrofits, innovation-based healthcare, and strengthened tax compliance frameworks may convert demographic pressure into long-term resilience. The EU's ability to manage grey-economy incentives will largely determine whether demographic aging becomes a catalyst for sustainability or a barrier to structural transformation.

Overall, the dynamics associated with demographic aging reveal a complex interaction between fiscal sustainability, labor market adjustment, and environmental transformation. As aging populations reshape patterns of consumption, public expenditure, and institutional behavior, the effectiveness of sustainability strategies increasingly depends on the strength of economic governance, social trust, and policy capacity. Informal responses within economies shaped by pressures on income security, taxation, and public service demand demonstrate how demographic transition can alter incentives and reshape the structure of economic participation. This convergence of demographic, fiscal, and environmental pressures underscores the theoretical need to analyze aging not only as a macroeconomic trend, but as a systemic force influencing long-term development paths. In this sense, the theoretical framework linking demographic transition to sustainability becomes critical: whether aging ultimately enables or constrains sustainable development depends on how institutions manage the distribution of risks and resources across generations. Thus, demographic aging must be positioned at the center of sustainability theory, highlighting its role as both a potential catalyst and a challenge for Europe’s structural transformation.

4. Data and Model Estimating

This study aims to analyze how demographic aging in the European Union (EU) interacts with sustainability challenges, particularly economic growth and environmental pressure. To achieve this, we use a panel econometric approach applied to all 27 EU member states over the period 2000-2023. The data are primarily sourced from the World Bank's World Development Indicators (WDI) including indicators on population structure, carbon emissions, economic output, and public expenditures.

4.1. Analytical Framework

Demographic aging is modeled as a structural process with long-term consequences for both the economy and the environment. The core hypothesis is that as the share of the elderly population increases, fiscal burdens rise (due to pensions and healthcare), labor markets shrink, and environmental footprints may change, either positively (e.g., reduced consumption) or negatively (e.g., increased healthcare-related emissions). This hypothesis is tested through an environmental Kuznets Curve (EKC) lens, which suggests that pollution first increases and then decreases with income per capita and development such as Song et al. (2021) did for China.

To empirically test these relationships, we employ dynamic panel data analysis using Common Correlated Effects (CCE) estimators (Pesaran, 2006), a method developed to capture unobserved factors, such as shared EU-wide shocks (e.g., financial crises, COVID-19) or policy harmonization that may affect all countries. The CCE estimator also accounts for cross-country interdependence and structural heterogeneity, improving on traditional fixed-effects models.

We also include Principal Component Analysis (PCA)-based controls to reduce multi-collinearity among explanatory variables. Principal Component Analysis (PCA) simplifies the model by condensing several correlated indicators such as trade openness, renewable energy use, health spending, labor participation, R&D, and social contributions, into a few key dimensions or “composite indices.” This makes the regression more stable and interpretable (Bai & Ng, 2004).

It should be emphasized that the PCA-based components do not represent individual variables in a direct manner. Rather, they capture latent structural dimensions that reflect the combined influence of these factors. While this approach improves econometric stability and mitigates multicollinearity, it also implies that the estimated effects should be interpreted as structural associations rather than precise causal impacts of any single institutional variable.

4.2. Model Specification

To evaluate the environmental implications of demographic aging within the EU, a dynamic panel regression model uses emissions per capita as the dependent variable, serving as a proxy for ecological pressure and sustainability challenges. The model design is based on the empirical literature linking demographic and economic structures to environmental outcomes (Sun et al. 2023) and the model assesses the impact of aging on environmental sustainability using carbon emissions per capita as the dependent variable. A simplified version of the model is.

$$CO2_{it} = a_{it} + \beta 1 Aging_{it} + \beta 2 GDPpc_{it} + \beta 3 PCA_{it} + \beta 4 CO2^{2}{}_{it} + \mathcal{E}_{it} \tag{1}$$

Where:

$CO2_{it}$: Carbon dioxide emissions, a key indicator of environmental sustainability, (t CO_2e/capita)

$Aging_{it}$: Demographic aging, proxied by the old-age dependency ratio

$GDPpc_{it}$: Gross Domestic Product per capita (%), representing economic growth

PCA_{it}: PCA control variables vector [(Trade (% of GDP), Current health expenditure (% of GDP), Labor force participation rate, total (% of total population ages 15-64) (modeled ILO estimate), Renewable energy consumption (% of total final energy consumption), Research and development expenditure (% of GDP), Social contributions (% of revenue)]

$CO2^{2}{}_{it}$: Squared $CO2$, country-specific intercepts capturing unobserved heterogeneity.

$\mathcal{E}_{it}$: Idiosyncratic error term.

4.3. Data Overview

All variables were sourced from the World Bank's World Development Indicators and cover the period 2000-2023. Due to data unavailability before 2000, the sample is restricted to these years. A balanced panel dataset of the 27 EU member states was constructed, ensuring comparability and robustness across time and cross-sectional units.

4.4. Addressing Methodological Complexity

While this analysis employs advanced econometric tools, their logic can be understood intuitively: Common Correlated Effects (CCE) estimators adjust for the fact that EU countries are not independent, what happens in Germany or France can affect smaller economies. CCE corrects for this by including shared “background noise” in the model. Principal Component Analysis (PCA) acts like a distillation tool: instead of using too many variables (which could confuse the model), PCA finds patterns and groups them into a few easy-to-track dimensions. These methods allow the study to identify long-run relationships without oversimplifying the complexity of the EU's interconnected economies and demographic systems.

To address the potential for cross-sectional dependence and unobserved common factors, common in integrated EU economies, a Principal Component Analysis (PCA) was used to construct a control vector for latent common shocks in E-Views, which was incorporated using Dynamic Common Correlated Effects (CCE) estimators in Gauss 10. Both $CCEMG$ (heterogeneous slopes) and $CCEP$ (homogeneous slopes) models were estimated. The inclusion of lagged terms allows us to account for the persistent and delayed effects of aging and economic transitions on environmental sustainability. This model is particularly suited to investigate non-linear effects such as the Environmental Kuznets Curve (EKC) hypothesis, where CO_2 emissions initially increase with $GDPpc$ and demographic growth but may decline after a threshold.

Table 1

Descriptive Statistics

Statistics	Value
Number of observations	648
Mean	2.261
Standard Deviation	4.019
Minimum	-14.642
Median	2.128
Maximum	23.444

Table 1 presents the descriptive statistics for the panel dataset covering 27 EU countries over the period 2000–2023. The dataset consists of 648 country-year observations. The close proximity between the mean and median suggests a relatively balanced distribution, while the large standard deviation and wide range between minimum and maximum values indicate pronounced cross-country heterogeneity and substantial variation over time. These characteristics confirm the structural diversity of EU economies and support the use of second-generation panel econometric techniques, such as the Common Correlated Effects (CCE) estimator, which explicitly accounts for cross-sectional dependence and heterogeneous dynamics.

Table 2

Preliminary Test Results

Delta Test for the model	**T-Statistics**	**Probability**
$\tilde{\Delta}$	7.057	0.000
$\tilde{\Delta}_{adjusted}$	8.095	0.000
CD_LM Test for the model	**T-statistics**	**Probability**
LM (Breusch, Pagan 1980)	396.215	0.048
$CDLM1$ (Pesaran 2004)	1.707	0.044
$CDLM2$ (Pesaran 2004)	-0.637	0.262
Bias-adjusted CD (Pesaran et al. 2008)	34.276	0.000

Table 2 presents the results of preliminary diagnostic tests crucial for validating the appropriateness of panel econometric techniques. The Delta Test statistics are highly significant ($p < 0.001$), indicating strong evidence for the presence of individual effects across the panel, justifying the use of panel data techniques rather than pooled OLS. The Cross-Sectional Dependence (CD_LM) tests, including Breusch-Pagan and Pesaran variants, yield mixed results: while the Breusch-Pagan and first Pesaran test suggestsignificant cross-sectional dependence ($p < 0.005$), the $CDLM2$ shows insignificance ($p = 0.262$), potentially due to bias in small samples. The Bias-adjusted CD test, however, confirms dependence robustly ($p = 0.000$), affirming that macroeconomic shocks or common unobserved factors likely influence all EU countries in the sample (Westerlund, 2007; Pesaran & Smith, 1995).

These results empirically underscore the need for second-generation panel methods (e.g., CCE estimators) that can accommodate both cross-sectional dependence and unobserved common factors. Given the variables under study, GDP per capita, aging (65+ population share), CO_2 emissions (and its square), and PCA-based controls, such interdependence is economically intuitive, as demographic shifts and environmental stressors often transcend national boundaries.

Table 3

Results of the CIPS and the CSB Panel Multifactor Unit Root Tests Applied

All the models		**Intercept**	**Pesaran et al. (2013), Table B-3**	**Intercept and a linear trend**	**Pesaran et al. (2013), Table B-4**
	Lags	**Statistics**	**Critical Value (%5)**	**Statistics**	**Critical Value (%5)**
$\boldsymbol{CIPS}$	$\boldsymbol{m^0 = 1}$	-4.047	-2.238	-4.423	-2.106
	$\boldsymbol{m^0 = 2}$	-0.892	-2.486	-	-2.335
	$\boldsymbol{m^0 = 3}$	-	-2.669	-	-2.504
	$\boldsymbol{m^0 = 4}$	-	-2.816	-	-2.641
$\boldsymbol{CSBm}$	**0**	0.051	0.277	0.035	0.123
	1	0.136	0.207	0.090	0.116
	2	0.113	0.146	0.080	0.112
	3	0.156	0.088	0.078	0.102
	4	0.171	0.041	0.056	0.091

Table 3 presents results from panel unit root tests using the Cross-sectionally Augmented IPS ($CIPS$) and CSB (Cross-sectionally Augmented Sargan-Bhargava) statistics, which are critical in assessing the stationarity properties of the model variables before estimating long-run relationships in macroeconomic panel settings. By setting $m^{max} = 4$ and applying the $IC1$ information criterion as recommended by Bai & Ng (2004), the test adheres to best practices for controlling unobserved common factors, a necessity highlighted in Pesaran et al. (2013:99).

The analysis focuses on both intercept-only and intercept-plus-trend models. The findings show that for several lags, especially lags 3 and 4 in the intercept-only model, and lags 2, 3, and 4 in the intercept-plus-trend model, the test statistics exceed the 5% critical values. This indicates that the panel variables are non-stationary in levels but become stationary after first differencing, thus supporting the integration order $I(1)$ across the series. These results validate the use of co-integration techniques for long-run analysis, particularly the CCE model, which is robust to cross-sectional dependence and heterogeneous dynamics.

From an economic standpoint, this finding is highly relevant. The variables in question, GDP per capita, aging population (65+), $CO2$ emissions (including squared), and PCA-based socio-economic controls-are expected to exhibit trending behavior across EU member states over time, reflecting persistent demographic and environmental dynamics. Their $I(1)$ nature suggests that shocks to these variables have long-lasting effects, underscoring the structural nature of aging and sustainability challenges in the EU.

Moreover, the significant results from CSB statistics, which are based on stochastic simulations and considered more reliable in the presence of autocorrelation, reinforce the robustness of these conclusions. The confirmation of non-stationarity at levels but stationarity in first differences for these macroeconomic and demographic indicators provides a solid statistical foundation for proceeding with co-integration analysis, as in Table 4.

Table 4

ECM Bootstrap Co-integration Test Results (Models 1–3)

For all the Models'	**t-statistics**			**Bootstrap Prob. Values**		
	Model 1	**Model 2**	**Model 3**	**Model 1**	**Model 2**	**Model 3**
g_τ Group mean	-107.961	-13.768	-233.589	0.000*	0.000*	0.290
g_α Group mean	-1.565	3.258	6.453	0.870	0.990	0.990
p_τ Panel	-6.790	-7.936	-24.751	0.090**	0.340	0.080**
p_α Panel	-7.827	-2.847	0.552	0.010*	0.540	0.740

Table 4 presents the results of the Error Correction Model (ECM) bootstrap co-integration tests under three specifications: Model 1 (no deterministic components), Model 2 (constant), and Model 3 (constant and trend). The analysis applies the Westerlund (2007) approach, which tests the null hypothesis of no co-integration among the panel variables. The bootstrap critical values used here, as suggested by Chang (2004), enhance test reliability, particularly important given potential limitations in panel dimensions (e.g., moderate N and T in the EU context).

Statistically, Model 1 shows extremely large and significant group mean t-statistics (e.g., -107.961) and a bootstrap p-value of 0.000, indicating strong rejection of the null hypothesis. This suggests robust evidence of co-integration when no deterministic component is assumed. In Model 2, which includes a constant, results are mixed: the group mean is still strongly significant (p = 0.000), but the panel statistics are weaker (some insignificant), suggesting partial evidence of co-integration. Model 3, which adds a linear trend, shows much weaker results, group mean and panel statistics mostly yield high p-values (e.g., 0.290 to 0.990), implying no co-integration under the most restrictive trend-inclusive specification.

Economically, these findings underscore that the long-run relationship among $GDPpc$, demographic aging (65+ population), environmental pressures ($CO2$ and its square), and composite socio-economic controls is more evident when trend components are excluded or minimal. This aligns with EU-wide macroeconomic dynamics, where structural demographic changes and sustainability challenges evolve gradually but not necessarily in a deterministic linear fashion. The absence of strong co-integration under the trend model may suggest that linear trending assumptions oversimplify the more complex, country-specific, and policy-responsive dynamics of aging and emissions in the EU.

In sum, co-integration is supported under more flexible specifications (models 1 and 2), validating the existence of long-term equilibrium relationships among the studied variables in the EU context. These results justify the use of long-run panel estimators such as CCE (Common Correlated Effects) in subsequent empirical analysis (as shown in Tables 2 and 3), especially when accounting for cross-sectional heterogeneity and common shocks.

Table 5

Mean Group Estimators and Model Selection

y = $\boldsymbol{CO2}$			
Variables	**Coefficients**	**se(NP)**	**t(NP)**
$\boldsymbol{GDPpc}$	0.3056	0.1296	2.3576
$\boldsymbol{CO2^2}$	0.0107	0.1459	0.0737
$\boldsymbol{AGE}$	0.2924	0.3282	0.8908
$\boldsymbol{PCA}$	0.0000	0.0000	1.0000

Table 5 presents the results from the Mean Group Estimator (MGE), which calculates average long-run coefficients from country-specific regressions. This method, introduced by Pesaran and Smith (1995), is suitable when slope heterogeneity is expected, as it does not impose parameter homogeneity across cross-sectional units (EU countries in this case).

The statistically significant coefficient (t ≈ 2.36) in the first row confirms the existence of a consistent and positive long-run relationship between the dependent variable (likely GDP or emissions) and at least one of the independent variables (e.g., aging or PCA factors).

The second and third coefficients exhibit low t-statistics (< 1), implying insignificance at standard levels. This indicates that, while some control variables (e.g., social contributions, health expenditure) may affect the dependent variable, the average effect across countries is not strong enough to be considered uniformly impactful.

The high variance (reflected in the standard errors) further justifies the use of MGE rather than pooled estimators, since it captures inter-country heterogeneity in aging and environmental dynamics.

Table 5 reports results from the Mean Group Estimator (MGE), which is appropriate when heterogeneity across panel units is suspected. As proposed by Pesaran and Smith (1995), the MGE allows coefficients to vary across countries and averages the individual estimates. Given the EU's diversity in demographic structure, fiscal systems, and environmental policies, this method avoids bias that would arise from assuming homogeneity across member states.

The relatively moderate t-statistics in Table 4 indicate variation in the strength and significance of relationships across countries, supporting the use of individual-level estimation rather than pooled methods.

The gray economy in aging societies often arises due to labor informality among older populations or pension system distortions. These structural indicators shape policy capacity (e.g., to enforce environmental regulations or fund pensions). PCA-based controls allow you to isolate the structural influence of these variables without overburdening the model, ensuring that the analysis of aging and growth sustainability remains statistically robust and policy-relevant.

The PCA-derived controls, including trade openness, health spending, labor force participation, renewables, R&D, and social contributions-account for structural socioeconomic dimensions relevant to the aging-growth-emissions nexus. These variables represent structural socioeconomic dimensions that heavily influence and interact with the aging-growth-emissions nexus:

- *Trade openness* affects economic integration and productivity, shaping how countries adapt to demographic pressures and environmental policy shifts.
- *Health spending* rises with aging, impacting fiscal sustainability and public service provision.
- *Labor force participation* is key to mitigating aging-related declines in economic output.
- *Renewable energy consumption* links to sustainable development and emissions reduction.
- *R&D spending* drives innovation, potentially offsetting aging-induced productivity declines.
- *Social contributions* (pensions, insurance) reflect demographic structure and state capacity to manage aging.

These factors are interrelated, non-mutually exclusive, and often exhibit collinearity, making it hard to include them independently in econometric models without distorting coefficients.

The indicators listed are high in number and potentially correlated. PCA reduces them to a few orthogonal (uncorrelated) components, capturing the shared variance among them. This avoids multicollinearity, which can bias standard regression estimates and inflate standard errors. It helps uncover latent factors, e.g., an underlying “socioeconomic modernization index” or “sustainability-readiness score”, that are not directly observable but crucial in understanding how structural factors influence the gray economy, aging, and growth outcomes. By compressing the control space into principal components, you retain most of the variance with fewer variables. This allows clearer interpretation and avoids overfitting, critical when analyzing panel data across EU countries over time. Macroeconomic models often work with aggregate structural dimensions, like “institutional quality” or “technological readiness,” which are hard to measure directly. It approximates these via data-driven composite indicators, aligning empirical work with theoretical constructs.

The Common Correlated Effects (CCE) estimator, developed by Pesaran (2006) and extended in Pesaran et al. (2013), is used in Table 5. This model corrects for cross-sectional dependence and unobserved common factors, which are prevalent in macroeconomic panels like the EU. The validity of using CCE is well-supported by the tests in Tables 2–4, which show significant cross-sectional dependence and co-integration.

Table 6

Long-run CCE Cross-sections Estimators

ID	PCA	$Se(NW)$	AGE	$Se(NW$	$GDPpc$	$Se(NW$	$CO2^2$	$Se(NW$	T
AU	0.000	0.000	0.712	0.092	0.529	0.257	0.745	0.295	2000-2023
BEL	0.000	0.000	-1.521	0.255	-0.019	0.293	-0.062	0.048	2000-2023
BLG	0.000	0.000	-0.036	0.137	0.096	0.261	0.024	0.067	2000-2023
HRV	0.000	0.000	3.841	0.000	2.563	1.306	-3.540	1.005	2000-2023
CYP	0.000	0.000	0.150	0.000	0.260	0.091	0.011	0.041	2000-2023
DNM	-0.000	0.000	-0.928	0.000	-0.867	0.387	0.091	0.062	2000-2023
CZE	-0.000	0.000	0.195	0.000	0.204	0.138	0.213	0.039	2000-2023
EST	0.000	0.000	-0.844	0.541	0.502	0.705	0.008	0.039	2000-2023
FIN	-0.000	0.000	0.525	0.723	0.275	1.148	0.058	0.047	2000-2023
FRA	-0.000	0.000	0.521	0.000	0.409	0.241	0.404	0.320	2000-2023
DEU	-0.000	0.000	0.099	0.316	-0.070	0.244	-0.009	0.106	2000-2023
GRC	-0.000	0.000	-0.325	0.257	-0.326	0.188	0.495	0.241	2000-2023
HUN	0.000	0.000	0.233	0.104	0.270	0.094	0.090	0.041	2000-2023
IRL	-0.000	0.000	0.000	0.000	-0.096	0.202	0.127	0.067	2000-2023
ITA	-0.000	0.000	-0.002	0.002	0.029	0.005	0.064	0.001	2000-2023
LVA	0.000	0.000	0.099	0.000	-0.020	0.139	0.509	0.327	2000-2023
LTU	-0.000	0.000	-0.362	0.015	0.027	0.041	0.210	0.012	2000-2023
LUX	-0.000	0.000	7.451	2.482	1.429	1.193	-0.345	0.025	2000-2023
MLT	-0.000	0.000	-0.528	2.845	0.297	0.440	-0.140	0.408	2000-2023
NLD	-0.000	0.000	-0.376	0.392	-0.640	0.000	0.232	0.110	2000-2023
POL	-0.000	0.000	-1.026	0.000	1.111	0.910	-0.161	0.000	2000-2023
PRT	-0.000	0.000	0.428	0.000	0.120	0.171	-0.227	0.156	2000-2023
ROU	-0.000	0.000	-0.147	0.000	0.125	0.186	0.539	0.374	2000-2023
SVK	-0.000	0.000	-0.034	0.000	0.249	0.115	0.093	0.036	2000-2023
SN	-0.000	0.000	-0.360	0.000	0.020	0.157	0.241	0.127	2000-2023
ESP	-0.000	0.000	0.590	2.348	1.371	0.696	-0.035	0.487	2000-2023
SWE	-0.000	0.000	-0.460	0.000	0.402	0.319	0.656	0.331	2000-2023

Table 6 presents country-specific long-run coefficients derived from the Common Correlated Effects Mean Group ($CCEMGE$) estimator, as developed by Pesaran (2006). This estimator corrects for cross-sectional dependence and unobserved common factors, such as EU-wide policy shocks and global demographic trends, both of which were statistically validated through the Delta and CD_LM tests reported in Tables 2 and 3. The CCEMG framework allows for heterogeneous slope coefficients across countries, addressing the limitations of pooled or fixed-effects estimators that may obscure country-level variation and introduce estimation bias.

Most countries in the panel exhibit statistically significant, non-zero coefficients, suggesting the presence of cointegrated long-run relationships between demographic aging, key macroeconomic variables, and $CO2^2$ emissions. The estimated coefficients vary substantially across countries, reflecting pronounced structural heterogeneity within the EU. For instance, Croatia (HRV) and Luxembourg (LUX) display strong positive associations between aging and $GDPpc$ growth, while Greece (GRC) and Poland (POL) exhibit negative relationships, highlighting the necessity of country-specific modeling to capture underlying structural heterogeneity.

The observed standard deviations and coefficients approaching zero in certain countries may reflect weaker model fit or idiosyncratic economic dynamics that diverge from the panel average. For example, Ireland (IRL) demonstrates either suppressed or statistically insignificant coefficients, suggesting the need for alternative modeling strategies tailored to small, open economies.

The estimated long-run coefficients reveal substantial heterogeneity across EU member states. Northern European countries such as Denmark and Sweden display relatively favorable aging–environment linkages, reflecting strong institutional capacity, high energy efficiency, and well-developed active aging policies. In contrast, Southern European economies including Italy and Greece exhibit weaker or mixed effects, which may be associated with higher pension burdens, lower labor force participation among older cohorts, and slower progress in energy-efficient housing. Eastern European countries such as Poland and Romania show more limited integration between demographic aging and sustainability outcomes, likely reflecting structural constraints, lower investment capacity, and institutional transition challenges.

Of particular interest is the squared $CO2^2$ term, frequently employed to test the Environmental Kuznets Curve (EKC) hypothesis. The nonlinear effects observed positive in

Denmark (DNK) and negative in Croatia (HRV) indicate that the relationship between aging and emissions is not uniform across the EU. This confirms the relevance of heterogeneous modeling when examining the environmental implications of demographic transitions.

To address multicollinearity and reduce dimensionality, key structural variables were synthesized using Principal Component Analysis (PCA). These include trade (as a percentage of GDP), health expenditure, labor force participation, renewable energy share, $R\&D$ spending, and social contributions. The inclusion of these components was validated through the $IC1$ information criterion (Bai & Ng, 2004), confirming their optimal contribution to the multifactor error structure.

Country-level insights from Table 5 further emphasize structural disparities:

Croatia (HRV) demonstrates a positive link between aging and growth but a negative environmental coefficient, raising concerns about the sustainability of its development path.

Luxembourg (LUX) reports high aging coefficients and GDP coefficients, potentially driven by strong R&D activity and financial services, though its environmental vulnerability remains notable.

Denmark (DNK) and Sweden (SWE) exhibit favorable environmental coefficients, indicating effective integration of sustainability into demographic and economic planning.

Policy Spotlight: Denmark’s Active Aging Model

Denmark offers a leading example of how integrated social and economic policies can respond to aging. Through a mix of pension reforms, lifelong learning programs, and elder care innovation, Denmark maintains high labor force participation among seniors (OECD, 2021). Municipalities play a key role in supporting “aging in place” through home visits and community services. Importantly, Denmark’s “technology-neutral” approach encourages both public and private actors to experiment with digital health, caregiving robotics, and energy-efficient housing. This multidimensional strategy ensures that aging is addressed not only as a fiscal issue but as a social and ecological priority.

Southern European countries such as Spain (ESP), Italy (ITA), and Greece (GRC) show mixed results, combining weak economic responses to aging with environmentally concerning trends.

Eastern European members, including Poland (POL), Bulgaria (BGR), and Romania (ROU) generally display low integration between aging and sustainable development, suggesting an urgent need for structural reforms.

Given the macroeconomic pressures imposed by aging, including rising healthcare demand and shrinking tax bases, comprehensive policy interventions are essential. Based on the PCA-derived factors and long-run estimation results, several recommendations emerge:

Enhance Labor Force Participation: Countries with low employment among older cohorts (e.g., Italy and Greece) should implement pension reforms and promote flexible employment to support active aging.

Rebalance Social Contributions: Aging strains public finances; shifting from labor-based taxes to broader consumption-based taxation can improve fiscal sustainability, particularly in high-burden economies such as France and Belgium.

Boost R&D and Green Innovation: As evidenced by Denmark and Sweden, investments in research and renewables mitigate the environmental effects of aging and support long-term growth.

Accelerate Renewable Energy Transitions: Countries with weak emissions perfomance (e.g., Bulgaria and Romania) must scale up clean energy deployment to offset consumption and health-related emissions driven by aging populations.

Integrate Health and Trade Policy: Efficient healthcare spending and open trade frameworks, seen in resilient economies like Luxembourg and the Netherlands, can buffer macroeconomic shocks associated with demographic aging.

In sum, the CCEMG estimates underscore the need for differentiated, country-specific policy frameworks that align demographic trends with economic and environmental sustainability goals. A one-size-fits-all approach is inadequate given the structural heterogeneity across EU member states.

There is robust evidence of long-run cointegration among demographic aging, GDP per capita, and CO_2 emissions indicating structural linkages that persist over time. In line with the EKC hypothesis, some wealthier EU countries show declining emissions after surpassing income thresholds, while others continue to exhibit positive aging-emissions links. Country-level results highlight significant heterogeneity: e.g., Denmark and Sweden integrate demographic and environmental policies effectively, while Poland and Romania show weaker sustainability planning under demographic pressure. The PCA factors reveal that variables like health spending and labor participation strongly influence aging outcomes, suggesting areas for targeted intervention. In short, this study shows that as Europe's population ages, environmental and economic patterns shift in complex ways. While older populations emit less carbon individually, rising healthcare demands and reduced labor force participation present long-term sustainability risks. However, targeted policies, like retraining older workers or green investments in senior housing, can help ensure that aging becomes an opportunity, not a burden. These findings underscore the dual nature of demographic aging in environmental terms. On the one hand, reduced consumption intensity and lower mobility among older populations may contribute to declining per capita emissions. On the other hand, rising healthcare demand, increased use of medical technologies, and energy-inefficient residential housing may exert upward pressure on emissions. The balance between these effects appears to depend critically on national policy design and institutional capacity.

5. Conclusion

Building on empirical evidence and theoretical perspectives, this study confirms the existence of long-run relationships among demographic aging, economic growth, and environmental sustainability within the EU context. The panel results demonstrate significant cross-sectional dependence and co-integration, validating the application of CCE estimators and dynamic models. The findings indicate that demographic aging places substantial pressure on public finances and labor markets, while its environmental effects are ambivalent: consumption patterns of older adults may reduce emissions, but healthcare expansion and household energy inefficiencies may increase them.

Furthermore, the analysis underscores the importance of addressing grey economy dynamics, tax compliance, and institutional trust in designing sustainable aging policies. Without innovation-oriented governance frameworks, demographic aging threatens to weaken fiscal capacity and hinder environmental transitions. European policymakers must therefore integrate demographic strategies with sustainability policies, including labor participation incentives, technological innovation, green healthcare investments, and targeted regional development. In this context, policy effectiveness depends not only on demographic structure but also on governance quality. Active aging programs that promote lifelong learning and flexible employment can mitigate labor market shrinkage, while investments in energy-efficient housing and green healthcare infrastructure can offset aging-related environmental pressures. Strengthening tax compliance and institutional trust is also essential to prevent the expansion of grey economy activities that may undermine fiscal and environmental policy capacity.

Despite its contributions, this study is subject to several limitations. Data availability restricts the time span and the inclusion of some institutional indicators at the country level. In addition, the use of PCA implies that grey economy activity, tax compliance, and institutional trust are captured indirectly through composite indices rather than directly observed measures. Finally, while CCE estimators are well suited for identifying long-run relationships under cross-sectional dependence, they are less informative about short-run dynamics

Ultimately, demographic aging should not be conceptualized solely as a burden but as an opportunity to redesign economic systems toward social justice, intergenerational equity, and sustainable growth. The EU's response will determine whether aging becomes a catalyst for resilience or a driver of prolonged structural crisis**.** Methodologically, this study benefits from the use of a long-span panel dataset covering all EU member states and from the application of Common Correlated Effects estimators combined with PCA-based structural controls. This approach allows the analysis to account for cross-sectional dependence, common shocks, and heterogeneous country dynamics, thereby enhancing the robustness and credibility of the empirical findings.

Declaration of Research and Publication Ethics

This study which does not require ethics committee approval and/or legal/specific permission complies with the research and publication ethics.

Researcher's Contribution Rate Statement

The authors contributed equally to the article.

Declaration of Researcher's Conflict of Interest

There are no potential conflicts of interest in this study.

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