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Solid Waste Recovery, Co2 Productivity and Growth: An Empirical Analysis for Sustainable Development in Turkiye

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Abstract

This article seeks to explore the connection between solid waste recycling and economic growth through the lens of the circular economy perspective in Turkiye, considering the CO2 productivity index which had been reconstructed by using the PCA method (Principal Component Analysis) utilizing three different variables during the period spanning from 2000Q1 to 2021Q4. The findings revealed that recycling has a negative long-term impact on economic growth, indicating that policymakers should invest in modernizing infrastructure and optimizing logistics, provide financial support through subsidies and incentives, and foster public-private partnerships to enhance recycling's economic benefits. Furthermore, markets should be developed for recycled products with public procurement policies and consumer campaigns, considering the market volatility. Moreover, strengthening regulations, encouraging research and development, and enhancing governance and coordination will ensure effective recycling management and contribute to environmental sustainability and economic growth.

Keywords
Solid Waste Recovery,
Co2 Productivity,
Growth

JEL Classification
C22, Q53

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Turkiye'de Sürdürülebilir Kalkınma İçin Katı Atık Geri Dönüşümü, Co2 Verimliliği ve Büyüme: Ampirik Bir Analiz

Öz

Bu makale, Turkiye'de katı atık geri dönüşümü ve ekonomik büyüme arasındaki bağlantıyı, döngüsel ekonomi perspektifiyle, 2000Q1'den 2021Q4'e kadar olan dönemi kapsayan üç farklı değişken kullanılarak PCA (Temel Bileşen Analizi) yöntemiyle yeniden yapılandırılmış CO2 verimlilik endeksi göz önünde bulundurarak araştırmayı amaçlamaktadır. Bulgular, geri dönüşümün uzun vadede ekonomik büyüme üzerinde olumsuz bir etkisi olduğunu ortaya koymuştur. Bu durum, politika yapıcıların altyapıyı modernize etmeye ve lojistik süreçleri optimize etmeye yatırım yapmaları, sübvansiyonlar ve teşvikler yoluyla finansal destek sağlamaları ve geri dönüşümün ekonomik faydalarını artırmak için kamu-özel sektör ortaklıklarını teşvik etmeleri gerektiğini göstermektedir. Ayrıca, piyasa dalgalanmaları göz önüne alınarak, kamu alım politikaları ve tüketici kampanyaları ile geri dönüştürülmüş ürünler için pazarlar geliştirilmelidir. Bunun yanı sıra, düzenlemelerin güçlendirilmesi, araştırma ve geliştirmeye teşvik verilmesi, yönetim ve koordinasyonun iyileştirilmesi, etkili geri dönüşüm yönetimini sağlayacak ve çevresel sürdürülebilirlik ve ekonomik büyümeye katkıda bulunacaktır.

Anahtar Kelimeler
Katı Atık Geri Dönüşümü, Co2 Verimliliği, Büyüme

JEL Kodu
C22, Q53

1. Introduction

As per the World Bank’s "What a Waste 2.0" report, the persistent increase in global household solid waste, notably significant in low and middle-income countries (Kaza et al., 2018), is projected to reach 3.4 billion tons by 2050. Along with the conventional and unsustainable waste management methods, this increase in waste volume leads to 1.6 billion tons of carbon releases and escalates management costs. Hoornweg and Bhada-Tata (2012) expected an increase in these costs from $205 billion to $376 billion by 2025. The 2020 waste statistics of Turkiye compiled by the Turkish Statistical Institute (TÜİK) mirror these global challenges. In 2020, Turkiye produced 104.8 million tons of waste, of which 30.9 million tons were classified as hazardous, indicating a 10.5% rise from 2018. Of this waste, 56.3% was transported to authorized waste processing facilities, 4.2% to disposal sites, and 7.1% was stored on-site. A mere 0.1% was treated using alternative methods, with recycling units handling 7%, and municipalities or industrial zones handling 1.7%, underscoring the significance of effective waste management and recycling for sustainability.

The pressures of overpopulation, industrial advancement, urban expansion, and climate change necessitate immediate, sustainable solutions due to their effect on consumption patterns and waste production (Philippidis et al, 2019). Moreover, waste management is further complicated by the harmful effects of waste on living organisms, combined with climate change and socio-economic subtleties (Gardiner and Hajek, 2020). One of the major drivers of human-induced environmental and climate changes is the linear production and consumption system, characterized by the "take-make-use-dispose" model (Kuvvetli Yavaş, 2023). To address the deficiencies of the linear economy, waste management has become a global imperative, with a circular economy emphasizing sustainability and resource efficiency through reducing the production, consumption, and disposal of goods while enhancing well-being (World Bank, 2022). The theoretical framework is based on the ecological modernization theory, which posits that environmental concerns caused by economic activities can be alleviated by recuperating resource efficiency through technical innovations like the practices of circular economy (Ferronato et al., 2019).

The circular economy, initially centered on recycling, has since expanded to incorporate reduction and reuse, thus creating the 3R strategy. The European Union's 2008 Solid Waste Framework Directive further advanced this by establishing the 4R strategy encompassing reduce, reuse, recycle, and recover. In 2017, the comprehensive 10R principles were defined: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover (Moraga et al., 2019). By implementing these principles, the circular economy intends to replicate natural ecosystems and move from the linear economy to a regenerative model that considers products' entire life cycles (De Jesus et al., 2018). This study inspected the bond between the circular economy and economic evolution during the period spanning from 2000Q1 to 2021Q4.

The potential addition of this study to the existing literature is considering the CO2 productivity index reconstructed using the PCA method (Principal Component Analysis) utilizing three different variables. CO2 productivity is one of the environmental and resource efficiency indicators which includes indicators such as production and consumption-based CO2 emissions and efficiency, energy intensity and efficiency, total primary energy supply, renewable energy supply, the share of renewable energy in electricity production, per capita urban waste, and recycled urban waste. These indicators inspect the efficiency of economic activities involving energy, environmental services, and other natural resources, reflecting significant aspects of the transition to a resource-efficient and low-carbon economy. This study considers production-based carbon dioxide emissions and efficiency. Furthermore, it aims to mark significant contributions to the scholarly domain since macro-level aggregate research investigating the nexus between recycling of municipal solid waste and both economic and environmental indicators is notably scarce, with few existing studies attempting to understand the impacts of municipal solid waste recycling on economic expansion and environmental quality. This is the initial work that investigates the nexus between the circular economy and economic growth considering CO2 productivity.

Based on OECD data, Turkiye's production-based CO2 emissions rose from 201.22 (in 2000) to 391.19 million tons in 2021, following a fluctuating trend. However, OECD countries, especially the OECD Europe region, exhibited smaller fluctuations than Turkiye. Significant decreases during the 2009 economic crisis and the 2020 pandemic were observed. On another side, the production-based CO2 productivity measures the amount of CO2 emitted from burning coal, oil, natural gas, and other fuels; reflects efficient resource allocation in production through a high CO2 efficiency value, which is favorable. Turkiye's CO2 efficiency fluctuated between 4 and 6 from 2000 to 2021, showing only slight improvement, implying that production's fossil fuel efficiency has not notably improved due to factors such as inadequate domestic savings, short-term foreign investments, insufficient private enterprise, and export dependence on imports.

Figure (1) depicts the production-based CO2 productivity ($/kg) during the period spanning from 2000 to 2021. Turkiye's CO2 efficiency exceeds the overall OECD average but trails behind OECD European countries, indicating that despite performing well compared to the total OECD average, Turkiye still falls short compared to OECD European countries. Noteworthy is the continuous rise in CO2 efficiency among OECD member countries due to increased investments in renewable energy and the adoption of more efficient systems in the energy sector, driven by environmental pressures (Karadaş & Işık, 2019).

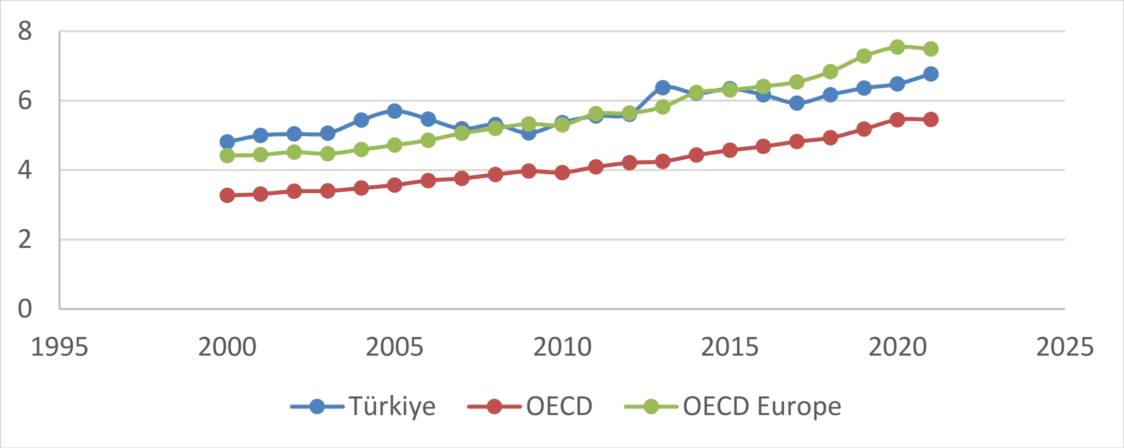

Figure 1. Production-based CO2 productivity ($/kg)

These indicators show a negative development in Turkiye, stemming from problems in obtaining clean energy and using this energy efficiently. Therefore, more studies and research are required to draw a roadmap for policymakers, thus the importance of this study. This study aims to mark significant contributions to the scholarly domain since macro-level aggregate research investigating the nexus between the recycling of municipal solid waste and both economic and environmental indicators is notably scarce, with few existing studies attempting to understand the impacts of municipal solid waste recycling on economic expansion and environmental quality. This is the initial work that investigates the nexus between the circular economy and economic growth considering CO2 productivity. This study is structured as follows: in the second section, an overview of the literature is provided. The third one explains the methodology. The fourth section presents empirical conclusions. The final one discussed conclusions and policy recommendations.

2. Review of Literature

There is a remarkable lack of macro-level research investigating the nexus between municipal solid waste recycling and its weight on both environmental outcomes and economic development, especially for Turkiye. Miçooğulları & Moalla (2023) analyze the weight of solid waste recycling on economic evolution in Turkiye; however, this study contributes to the circular economy literature by incorporating the CO2 productivity index, reconstructed using PCA.

Korhonen et al. (2018) define a circular economy (CE) as an economy designed to maximize the service derived from linear material and energy productivity flows by utilizing renewable energy sources, cyclical material flows, and cascading energy flows, thus contributing to the environmental, economic, and social dimensions of sustainable development. However, the study criticizes the current concept of sustainable sustainability, primarily developed and led by practitioners such as policymakers and corporations, for its superficial and unstructured scientific basis. Current practices include product reuse, remanufacturing, recycling, remanufacturing, refurbishment, repair, serialization, modernization, and the use of renewable energy throughout the product value chain. The study identifies six critical challenges that must be addressed to truly contribute to global net sustainability: Thermodynamic limits, temporal and spatial system limits, limits imposed by the physical scale of the economy (including the rebound effect, Jevon's paradox, and the boomerang effect), dependency and lock-in, management and governance limits, and cultural and social definitions of waste. Despite the green economy's potential to attract the business community to sustainability initiatives and introduce new consumption practices such as the sharing economy, the study emphasizes the need for a critical scientific approach and further research to resolve these challenges and ensure that the green economy makes a meaningful contribution.

De Jesus et al. (2021) discuss that transitioning to a Circular Economy (CE) involves structural change driven by transformative eco-innovation (EI). Synthesizing 20 years of CE research through a “systematic review of systematic reviews, their research addresses the gap of understanding and explicitly defining the dynamics of eco-innovation (EI) within the Circular Economy (CE), offering a thorough framework for promoting circular innovation strategies and highlighting significant trends in recycling and recovery, systemic innovations, and business-model innovations. The authors aim to enhance the conceptual and practical understanding of how EI can effectively drive the transition to a sustainable CE, by proposing the advancement of "circular innovation studies" as a dedicated research agenda. The authors identify major trends in innovations related to business-model innovations, recycling and recovery strategies, and systemic or transformative innovations, connecting these trends to supply and demand side innovations, spurring innovations linked to product manufacturing, design, logistics, reverse logistics, and end-of-life management and recovery. Their paper notes that the conceptual understanding of EI dynamics within CE remains largely implicit, limiting the potential to advance knowledge in this area, arguing that addressing this limitation is crucial for progressing in innovation for CE, proposing a dedicated "circular innovation studies" agenda to explore and resolve these challenges.

McDowall et al. (2017) compare how China and Europe have adopted and implemented Circular Economy (CE) policies, highlighting that while both regions share a common conceptual basis focused on enhancing resource efficiency, their approaches differ significantly. Whereas Europe's CE focuses more on waste management and resource efficiency, emphasizing business opportunities; China's CE policies are broader, incorporating pollution control and resource efficiency to address environmental challenges from rapid industrialization. Their paper examines historical development, policy focus, and governance methods in both regions, noting Europe's decentralized, member-state-driven approach versus China's use of experimental zones and targeted responsibility systems. Regarding Circular Economy (CE) policies, the authors identify several lessons that China and Europe can learn from each other. For Europe, China's coordinated experimentation of specific zones and location-specific indicators serves as a model for amplifying successful initiatives and incorporating CE principles into land-use planning. For China, the insights gained from Europe's experience in managing consumption through eco-design, promoting product repairability, innovative business models, and compulsory product durability labeling are valuable. Moreover, Europe's more comprehensive indicators regarding CE, namely, patents in recycling technologies, could improve China's indicator systems. Furthermore, the shared indicators, standards, and mutual learning can be instrumental in improving both regions in areas like product design, recycling standards, and policy effectiveness, leveraging their trade flows to advance global CE practices.

Morseletto (2023) demonstrates that economies have always comprised a mix of circular and linear practices in varying proportions, highlighting the linear–circular contrast in the circular economy literature, by scrutinizing emblematic examples, dispelling misconceptions, enriching understanding of both frameworks, and identifying factors that influence an economy's tendency towards circularity or linearity, such as profit, scarcity, circumstances, and business opportunities. Moreover, the study scrutinizes forces that perpetuate the linear economy and its impacts and investigates why circularity is essential and the obstacles that favor a throwaway society, such as joblessness, overproduction, and fast consumption; proposing three pathways to promote circular solutions and dismantle linear economy drivers which are: ‘lessening,’ ‘sharing,’ and ‘valorizing’. Potting et al. (2017) explored ways to measure progress in transitioning towards a circular economy in product chains, formulating a conceptual framework regarding innovation’s role and applying it to several cases. They reported that the Dutch Ministry of Infrastructure and the Environment characterizes a circular economy as an economic system centered on the reusability of products and their constituents, materials' recycling, and natural resources' conservation while creating added value in every link of the system, aiming to promote the CE transition by improving the closing of product and material chains. Potting et al. reported that a product chain tracks products' lifecycle from resource extraction to waste treatment. Furthermore, recovering materials from discarded products is energy-intensive and often results in lower-quality recycled materials, used in products with lower quality requirements, and this extends the material chain beyond a single product. The goal of a circular economy is to recycle materials without quality loss, eliminating the need for new resources and waste.

Utilizing quarterly data during the period spanning from 1990 to 2017, and employing bootstrapping ARDL modeling, Razzaq et al. (2021) examine the impact of municipal solid waste (MSW) recycling on environmental quality and economic evolution in the United States. The results revealed that in the long run (short run), a 1% increase in MSW recycling contributes to a 0.317% (0.157%) increase in economic growth and a 0.209% (0.087%) reduction in carbon emissions. Furthermore, in the long run (short run) a 1% improvement in energy efficiency boosts economic evolution by 0.489% (0.281%) and decreases carbon emissions by 0.285% (0.197%). Moreover, in the long run, higher per capita income and population growth lead to increased emissions by 0.197% and 0.401%. Their findings highlight the significance of policy interventions in MSW recycling to enhance economic evolution and reduce carbon releases, being confirmed by a unidirectional causality running from MSW recycling to economic evolution, carbon releases, and energy efficiency. Many studies in the economic literature underscored the economic and environmental benefits of effective MSW management, especially through recycling and composting. For instance, Magazzino et al. (2020) found a bidirectional causality between GDP and MSW generation utilizing Granger causality and machine learning methods on Swiss data during the period spanning from 1990 to 2017, highlighting the importance of recycling and composting in reducing GHG emissions. Ayodele et al. (2018) revealed that recycling in Nigeria could save 89.99 tons (1046.43 GWh) of energy annually, and the electricity savings from recycling could power about 9.8 million people, generate economic benefits of 11.71 million USD (equivalent to about 16,562 jobs annually), and reduce GHG emissions by 307.364 tons CO2eq.

Kristanto and Koven (2019) reported that composting generates 25,700 kg CO2-eq/day, while controlled landfills generate 129,000 kg CO2-eq/day in the best-case MSW management scenario in Indonesia. Liu et al. (2020) revealed that a 1% increase in recycling leads to a 0.4% job growth in the overall solid waste and recycling in Florida, USA, utilizing fixed effect regression during the period spanning from 2001 to 2022. Jiménez, Domínguez and Vega-Azamar (2018) revealed that recycled aggregate concrete could decrease annual CO2-eq emissions by 22,343 tons, utilizing field and inventory data for life cycle assessment (LCA) in Yucatan and Mexico. Xin et al. (2020) found that sorting and recycling kitchen waste and recyclables, combined with incinerating the residue, could reduce emissions by 70.82% in Beijing and China. Highlighting the need for green development, Caiyi et al. (2022) examine the nexus between the growth of China's e-commerce industry and solid waste emissions, revealing existing of the Environmental Kuznets Curve (EKC) quadratic relationship in various regions of China. Moreover, they revealed that while e-commerce growth initially increases solid waste, it can eventually lead to reductions if managed properly. Furthermore, the results revealed that trade openness helps reduce emissions in central China, while FDI contributes to increasing solid waste emissions in central and western China; recommending developing a green industrial chain, optimizing delivery environments, and promoting recycling systems to mitigate the environmental impact of e-commerce.

In OECD countries, Shah et al. (2023) evaluated the impact of economic evolution, industrialization, and foreign direct investment (FDI) on municipal solid waste (MSW), and examined technology’s role in managing waste, exploring how technology and industrialization mediate the effects of economic growth on waste generation during the period spanning from 2000 to 2020. The conclusions revealed that economic growth, industrialization, and FDI (with less significant impact) increase waste in OECD economies; with a crucial role of research and development in reducing waste generation. Moreover, the results revealed that the later stages of economic growth do not help reduce waste; suggesting that OECD countries need proper mechanisms and taxes to manage industrialization and economic activities to reduce waste, alongside leveraging technology for better waste management. Broadly, research shows that industrialization and technological advancements play significant roles in the of production solid waste and its environmental effects, with recycling and solid waste management, stimulating economic evolution and lowering carbon emissions.

3. Methodology

3.1. Model and Data Set

The primarily intention of this study is to scrutinize the effects of municipal solid waste recycling on the growth of the Turkish economy. Utilizing the autoregressive distributed lag model for the period spanning from 2000Q1 to 2021Q4, it delves into the connection between recycling activities and Turkish economic growth within a circular economy framework, considering a CO2 productivity index (IND) reconstructed via Principal Component Analysis (PCA) based on three variables outlined in Table 1. Utilizing the ARDL method is expedient due to its flexibility in handling variables of mixed integration orders I(0) and I(1) even with small sample sizes, with error correction representation allowing for the identification of long-run equilibrium while capturing short-run dynamics within a single framework.

Table 1

PCA Index Construction

Variable	Unit	Source
production-based CO2 emissions	millions of tons	OECD
production-based CO2 productivity	GDP per unit of energy-related CO2 releases measured in US dollars per kilogram, 2015	OECD
production-based CO2 intensity	energy-related CO2 per capita in tons	OECD

To accomplish these goals, a model has been formulated utilizing quarterly data covering the period spanning from 2000Q1 to 2021Q4 (Miçooğulları & Moalla, 2023, Razzaq et al. 2021), as presented in Equation (1):

$$\ln GDP_t = \beta_0 + \beta_1 \ln RCY_t + \beta_2 \ln GFC_t + \beta_3 \ln LBR_t + \beta_4 \ln EC_t + IND + \varepsilon_t \tag{1}$$

In Equation (1), GDP refers to the gross domestic product, expressed as per capita GDP in constant 2015 US dollars; RCY indicates recycling, quantified by the annual amount of municipal solid waste collected and processed in kilotons; GFC refers to the capital component, indicated by gross fixed capital formation in constant 2015 US dollars; LBR signifies the labor component, measured by the labor force participation rate for individuals aged 15 and older; finally, EC stands for energy consumption from renewables, measured in terawatt-hours (TWh) equivalent. GDP, GFC and LBR are sourced from the World Bank-World Development Indicators (WDI); RCY from the TURKSTAT-Municipal Waste Statistics database; and EF from the Our World in Data database. Each of these variables is measured in different units, necessitating a standardized unit to account for distributional differences. Adhering to the approach of prior literature, all variables (except for IND) have been log-transformed to facilitate interpretation and enable elasticity-based analysis (Ehrlich, 1996; Shahbaz et al., 2020). The IND variable was included in its linear form because of its nature which is a composite index reconstructed through PCA. The IND variable is dimensionless and already normalized, providing a consistent and interpretable measure of environmental efficiency. Moreover, its linear form allows its coefficient to reflect the absolute impact of a one-unit change in the index ln(GDP), rather than a percentage-based elasticity. Any changes applied before or after the analysis should be carefully considered since PCA-derived components are susceptible to how the data is transformed. Furthermore, PCA is not scale-invariant, meaning that the units of measurement and the range of the original variables can significantly influence the reveals; indicating that applying transformations—such as logarithmic scaling—must be done cautiously to avoid distorting the relationships and variance structure captured by the principal components to ensure results remain valid and interpretable (Abegaz et al., 2018).

3.2. Constructing an Index Using Principal Component Analysis (PCA)

PCA is a commonly used statistical method for dimensionality reduction and data summarization. It transforms a set of variables that may be correlated into a set of linearly uncorrelated variables termed principal components, which capture the maximum variance in the data. To construct an index using PCA, the dataset should be standardized to warrant that each variable has a mean of zero and a standard deviation of one, as PCA is sensitive to the scales of the variables as shown in the following equation:

$$z_{ij} = \frac{x_{ij} - \mu_j}{\sigma_j} \tag{2}$$

where z_{ij} is the standardized value of variable j for observation i, x_{ij} is the original value, μ_j is the mean, and σ_j is the standard deviation. Then, to capture the relationships between the variables, the covariance matrix of the standardized variables C is calculated as

$$C = \frac{1}{n-1} Z^T Z \tag{3}$$

where Z is the matrix of standardized variables and n is the number of observations. Then, the eigenvalues and eigenvectors of the covariance matrix are calculated. The eigenvectors v represent the direction of each principal component while the eigenvalues λ denotes the amount of variance enlightened by each principal component as expressed in the following relationship:

$$Cv = \lambda v \tag{4}$$

By projecting the standardized data onto the eigenvectors, then:

$$P = ZV \tag{5}$$

where P and V denote the matrix of principal components and the matrix of eigenvectors respectively. By looking at the eigenvalues and choosing components that together account for a significant portion of the total variance, the principal components that explain most of the variance in the data could be selected. Moreover, by taking a weighted sum of the selected principal components, where the weights are scaled in proportion to the variance explained by each component, the index could be formed as follows:

$$\text{Index } = w_1 PC_1 + w_2 PC_2 + \cdots + w_k PC_k \tag{6}$$

Where $PC_i$and w_i denote the selected principal components and the corresponding weights respectively. The resulting index simplifies the dataset while retaining its most critical information by capturing the essential information from the original variables. Utilizing PCA to construct an index is a robust and statistically sound method for summarizing complex datasets into a single informative measure; offering several advantages, including dimensionality reduction, de-noising, and improved interpretability (Everitt & Hothorn, 2006).

3.3. Unit Root and Cointegration Tests

In time series analysis, unit roots pose a considerable challenge, often impeding the accurate understanding of fluctuations and stationarity properties within a series. The statistical features of the series such as mean and variance can change over time when a time series implies non-stationarity, exhibiting a unit root and complicating the modeling and forecasting processes. Various unit root tests have been developed to address these challenges, among them the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests; which identify the stationary characteristics of time series datasets and determine whether differencing is required to achieve stationarity. The ADF test builds on the original Dickey-Fuller test by addressing issues of autocorrelation in the error terms by including lagged differences of the dependent variable as additional regressors, allowing for a more accurate evaluation of the series' stationarity by ensuring that the residuals are white noise as presented in equation (7):

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \sum_{i=1}^{k} \delta_i \Delta y_{t-i} + \epsilon_t \tag{7}$$

Where Δy_t is the first difference of the series, α is the intercept, βt represents the trend component, γy_{t-1} is the lagged level of the series, and $\sum_{i=1}^{k} \delta_i \Delta y_{t-i}$ includes lagged differences to capture autocorrelation. Conversely, the PP test builds on the ADF test by providing more flexible assumptions regarding error terms, and adjusting the test statistics to account for serial correlation and heteroskedasticity in the errors without adding lagged difference terms. This makes the PP test more robust in circumstances where error terms have weak interdependence and non-uniform distribution, as indicated in equation (8):

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \epsilon_t \tag{8}$$

However, both the ADF and PP tests have limitations as they overlook structural breaks that occur due to significant events such as economic crises, policy changes, or technological advancements, and can cause shifts in the underlying data generation process. Disregarding these breaks can lead to incorrect conclusions about the presence of unit roots, since the series may appear non-stationary because of the breaks rather than an inherent unit root. The Zivot-Andrews (ZA) unit root test, proposed by Zivot and Andrews (2002), has been employed in this study to overcome this limitation, since that it enables one intrinsic structural break in the time series, providing a more accurate analysis of stationarity in the presence of structural changes as defined by the following model:

$$\Delta y_t = \mu + \theta DU_t + \beta t + \gamma y_{t-1} + \sum_{i=1}^{k} \delta_i \Delta y_{t-i} + \epsilon_t \tag{9}$$

Here, DU_t is a dummy variable representing the structural break, which equals 1 if t is greater than the break date and 0 otherwise. ZA test’s null hypothesis posits the presence of a unit root in the variable, indicating non-stationarity, while the alternative hypothesis signifies that the variable is stationary around a structural break. Incorporating the ZA test in this study guarantees a more reliable identification of stationarity properties despite structural breaks, thereby providing a thorough understanding of the time series data. After conducting the ZA test, the Autoregressive Distributed Lag (ARDL) bounds testing approach developed by Pesaran and Shin (1999) and Pesaran et al. (2001) will be conducted to test the existence of a long-run relationship between variables, especially useful when variables are integrated of different orders, i.e., I(0), I(1), or a combination of both, but not I(2). The ARDL model can be specified as:

$$\Delta Y_t = \alpha + \beta t + \theta Y_{t-1} + \sum_{i=1}^{p} \phi_i \Delta Y_{t-i} + \sum_{j=0}^{q} \psi_j \Delta X_{t-j} + \epsilon_t \tag{10}$$

where Δ denotes the first difference operator, Y_t is the dependent variable, X_{t-j} are the independent variables, α is the intercept, β is the trend component (if included), θ, ϕ_i, and ψ_j are the coefficients, and ϵ_t is the error term. The bounds testing procedure entails estimating the ARDL model using ordinary least squares (OLS) for the selected lag orders, conducting an F-test for the joint significance of the coefficients of the lagged level variables in order to test the null hypothesis $H_1: \theta \neq 0$ against the alternative hypothesis $H_1: \theta \neq 0$, and comparing the calculated F-statistic with the critical value bounds provided by Pesaran et al. (2001). an error correction model (ECM) is estimated to capture the short-run dynamics and speed of adjustment towards the long-run equilibrium, if a long-run relationship is established. It can be specified as:

$$\Delta Y_t = \alpha + \sum_{i=1}^{p} \phi_i \Delta Y_{t-i} + \sum_{j=0}^{q} \psi_j \Delta X_{t-j} + \lambda ECM_{t-1} + \epsilon_t \tag{11}$$

where ECM_{t-1} is the error correction term derived from the long-run nexus.

4. Findings and Discussion

4.1. Results of the Zivot-Andrews Unit Root Tests

To locate the structural breaks within the series, the Zivot-Andrews (Z-A) unit root test has been applied.

Table 2

Consequences of Zivot-Andrews Unit Root Test

Variables	**Level**		**First Difference**		
	Model: Constant		Model: Constant		
	t- statis.(Prop.)	Break Period	t-statis. (Prop.)	Break Period	Decision
lnGDP	-3.181 (0.576)	2009Q1	-6.870 (<0.01)	2007Q1	I(1)
lnRCY	-4.501 (0.043)	2004Q1	-6.830 (<0.01)	2002Q1	I(1)
lnGFC	-5.584 (< 0.01)	2009Q1	-6.988 (<0.01)	2001Q1	I(0)
lnLBR	-2.781 (0.796)	2008Q4	-4.881 (<0.01)	2003Q2	I(1)
lnEC	-5.611 (< 0.01)	2008Q4	-8.201 (< 0.01)	2006Q1	I(0)
IND	-1.651 (0.99)	2015Q1	-6.760 (<0.01)	2017Q1	I(1)

Note. I(0) denotes stationarity at the level, while I(1) denotes stationarity at the first difference.

In Table (2), The Zivot-Andrews Unit Root Test conclusions reveal the stationarity characteristics of the selected variables, considering structural breaks. The GDP (lnGDP), recycling (lnRCY), labor force participation rate (lnLBR), and CO2 productivity index (IND) are non-stationary at their levels but become stationary after first differencing. Specifically, lnGDP and lnRCY show structural breaks in 2009Q1 and 2004Q1, respectively, at their levels, and in 2007Q1 and 2002Q1, respectively, at their first differences. lnLBR and IND also become stationary after first differencing, with structural breaks in 2008Q4 and 2015Q1, respectively, at their levels, and in 2003Q2 and 2017Q1, respectively, at their first differences. Conversely, the natural logarithms of gross fixed capital formation (lnGFC) and energy consumption (lnEC) are stationary at their levels, with structural breaks in 2009Q1 and 2008Q4, respectively, indicating they are I(0) variables.

4.2. ARDL Long-Term and Short-Term Estimates

The bounds test for the ARDL model, which is suitable for variables integrated at either I(0) or I(1) order (Pesaran et al., 2001), was employed to investigate the potential long-term relationships among the analyzed variables. Based on the Akaike Information Criterion, the optimal lag length is 8 (AIC: -28.97280), and the model's optimal lag selection is (8,6,8,1,8,8). Table (3) shows the results of the bounds test, indicating that the F-statistic exceeds critical values at all levels, suggesting a long-term cointegration of the variables.

Table 3

Bounds Test Results

F-stat	**10%level I(0)- I(1)**	**5%level I(0)- I(1)**	**1%level I(0)- I(1)**
29.032	2.303-3.154	2.550- 3.606	3.351-4.587

Note. I(0) denotes stationary bounds, whereas I(1) denotes non-stationary bounds.

It is essential to evaluate the results of the diagnostic tests, before examining the short- and long-term coefficients. With a probability value of 0.4049, the Serial Correlation LM test yielded an F-statistic of 0.71, indicating no serial correlation and thus confirming the independence of error terms over subsequent periods. Moreover, with a probability value of 0.897, the heteroskedasticity test produced an F-statistic of 0.017, suggesting that the model does not exhibit significant heteroskedasticity. Additionally, the model remains stable over the specified period, confirmed by the CUSUM and CUSUMSQ graphs (Figure 2).

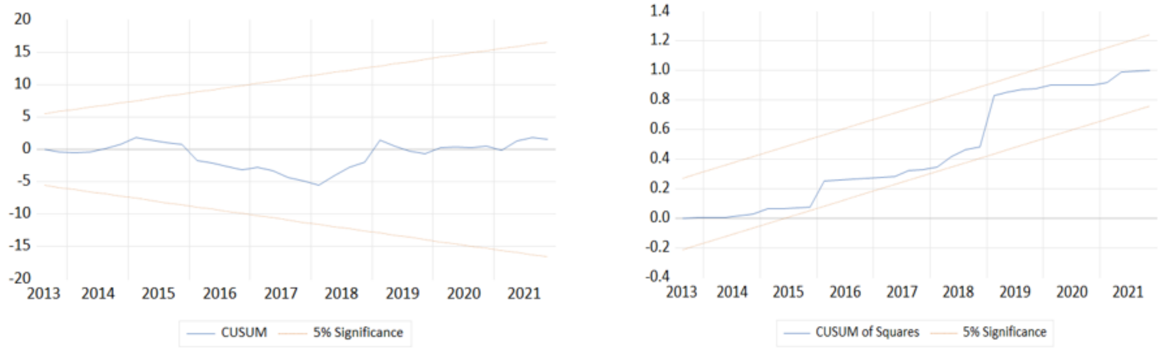

Figure 2. CUSUM and CUSUMsq Results

Identifying the cointegration nexus between the variables enables the analysis of the predicted long-term and short-term elasticities.

Table 4

Long-Term and Short-Term ARDL Cointegration Results

Dependent Variable: GDP, Model: ARDL (8,6,8,1,8,8)			
Variable	Coefficient	t-statistics	Prop.
Long Run			
RCY	-0.065	-7.695	0.0000
GFC	0.025	4.420	0.0001
LBR	0.109	7.204	0.0000
EC	-0.003	-3.436	0.0015

IND	0.039	8.188	0.0000
Short Run			
Constant	0.874	4.546	0.0001
ΔGDP(-1)	-0.027	-0.438	0.6641
ΔRCY	-0.131	-6.692	0.0000
ΔGFC	0.294	37.320	0.0000
ΔLBR	0.579	16.150	0.0000
ΔEC	-0.001	-4.005	0.0003
ΔIND	0.036	8.242	0.0000
ECM(-1)	-0.047	-15.429	0.0000

The conclusions of the long-term and short-term predictions are presented in Table (4). The outcomes revealed that recycling (RCY) negatively affects GDP with an elasticity of -0.065. Gross fixed capital formation (GFC) and labor (LBR) have a significant positive influence on GDP. Energy consumption (EC) has a small negative impact, while CO2 productivity significantly boosts GDP with an elasticity of 0.039. In the short run, recycling (ΔRCY), gross fixed capital formation (ΔGFC), labor (ΔLBR), energy consumption (ΔEC), and CO2 productivity (ΔIND) all significantly impact GDP. The error correction term (ECM) shows a significant negative adjustment coefficient, indicating a rapid adjustment to long-run equilibrium. The negative nexus between recycling and economic evolution can be attributed to the fact that economic growth metrics can be burdened by the considerable initial investments in infrastructure, technology, and public education for recycling programs. GDP growth can initially decline due to the costs associated with establishing facilities, the logistics of collecting and processing recyclables, and implementing changes in production processes. When infrastructure is not optimized, the process of recycling can sometimes be less efficient than traditional waste disposal methods, which can lead to higher operational costs and lower economic returns. Genc et al. (2019) estimated the recycling cost of plastic waste using data from a recycling center that processed approximately 695 tons of plastic waste, revealing that the unit cost of recycling was calculated at US$0.40 per kg, compared to a predicted cost of US$0.25 per kg if municipalities segregated all plastic waste.

Moreover, the strict environmental regulations promoting recycling often lead to higher operational costs for businesses, requiring further investments in cleaner technologies and processes, which can temporarily impact economic growth. Another reason may be that the municipalities often face financial and logistical challenges in in establishing effective waste management systems. Moreover, recycling program effectiveness often depends on the collaboration between public and private sectors, and without proper coordination or investment from either party, the economic benefits of recycling can be diminished. (Bayram et al., 2019) reported that there are several challenges in Turkiye's waste management system, including insufficient legislative frameworks, inadequate infrastructure, and the need for better waste management practices and facilities.

As of 2002, merely 12 of 3140 municipalities possessed proper waste disposal facilities, including 12 regular storage and 4 composting facilities, revealing a notable infrastructure gap. Turkiye's traditional waste disposal method has been historically conducted through open dumping, creating critical health, safety, and environmental issues. A considerable amount of domestic solid waste is stored uncontrollably, leading to pollution of forests, creek beds, and seashores, causing groundwater and air pollution. The first regulations on solid waste management were introduced in 1930, but it wasn't until 1991 with the Solid Waste Control Regulation that comprehensive rules were established. Despite these regulations, enforcement and implementation remain weak, coupled with an ineffective legislative system, fail to provide local governments with the essential legal, administrative, and technical support needed for local governments to successfully implement waste management projects. The legislative frameworks need to be aligned with European Union standards, demanding more rigorous and comprehensive waste management practices. Rapid population growth, industrialization, urbanization, and changing consumption habits have significantly increased the amount of waste generated, necessitating improved recycling facilities to manage various types of waste effectively.

5. Conclusions and Remarks

This paper has scrutinized the influence of solid waste recycling on economic evolution within the circular economy perspective of the Turkish economy, considering the CO2 productivity index reconstructed using the PCA method (Principal Component Analysis) utilizing three different variables from 2000Q1 to 2021Q4. The outcomes revealed a negative nexus between the recycling and the economic evolution. To enhance the economic benefits of recycling, policymakers should invest in efficient recycling infrastructure by modernizing facilities and optimizing collection and transportation logistics. Financial backing through subsidies, grants, and tax incentives can help offset initial setup costs and stimulate investment in recycling technologies. Indorsing public-private partnerships by fostering collaboration and clearly defining roles can harness resources and expertise for effective program implementation. The regulatory framework should be strengthened with balanced regulations and compliance support to lessen the financial burden on businesses. Increasing demand for recycled products and developing the market can be achieved through public procurement policies, consumer awareness campaigns, and quality standards, along with addressing market volatility with price stabilization mechanisms and market diversification. Furthermore, for informed policy decisions, comprehensive data collection systems and regular reporting should be developed. Moreover, to raise awareness and participation in recycling, public education campaigns and behavioral incentives should be implemented, along with supporting research and development through innovation grants and pilot projects.

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

Since the author is the sole author of the article, the contribution rate is 100%.

Declaration of Researcher’s Conflict of Interest

There are no potential conflicts of interest in this study.

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