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Assessing the Cement-CO_2 Link in Türkiye: A RALS Cointegration Framework

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Abstract
This study explores the long-term connection between cement production and CO_2 emissions in Türkiye, one of the world's largest cement producers. The purpose is to evaluate the sector's contribution to national emissions while highlighting decarbonization strategies consistent with global net-zero targets. Using annual data for the period 1970–2023, the analysis employs the Fourier ADF unit root test, which accounts for multiple structural breaks and nonlinearities, as well as the RALS-ADL and RALS-EG2 cointegration tests, which address deviations from the normality assumption. The findings confirm a stable long-run cointegration relationship between cement output and CO_2 emissions, with an estimated elasticity of 0.45—indicating that a 1% increase in production results in a 0.45% rise in emissions. This suggests partial efficiency gains but underscores the need for structural reforms. The results highlight the importance of expanding alternative fuels, lowering clinker intensity, and improving energy efficiency, supported by stronger regulatory and policy frameworks, if Türkiye's cement sector is to align with international decarbonization pathways.

Keywords: Cement Production, CO_2 Emissions, Fourier ADF, RALS Cointegration, Decarbonization

Türkiye'de Çimento Üretimi-CO_2 İlişkisinin Değerlendirilmesi: RALS Eşbütünleşme Analizi

Öz
Bu çalışma, dünyanın en büyük çimento üreticilerinden biri olan Türkiye'de çimento üretimi ile CO_2 emisyonları arasındaki uzun vadeli ilişkiyi araştırmaktadır. Amaç, küresel net sıfır hedefleri ile uyumlu karbonsuzlaştırma stratejilerini vurgulayarak sektörün ulusal emisyonlara katkısını değerlendirmektir. 1970-2023 dönemine ait yıllık veriler kullanılarak yapılan analizde, çoklu yapısal kırılmaları ve doğrusal olmama durumunu dikkate alan Fourier ADF birim kök testi ile normallik varsayımından sapmaları dikkate alan RALS-ADL ve RALS-EG2 eşbütünleşme testleri uygulanmıştır. Bulgular, çimento üretimi ile CO_2 emisyonları arasında istikrarlı bir uzun dönemli ilişkiyi doğrulamaktadır ve uzun dönem esneklik katsayısı 0,45 olarak tahmin edilmiştir. Bu da çimento üretiminde %1'lik bir artışın emisyonlarda %0,45'lik bir artışa yol açtığını göstermektedir. Bu durum kısmi verimlilik kazanımlarına işaret etmekle birlikte yapısal reformlara olan ihtiyacın altını çizmektedir. Sonuçlar, Türkiye çimento sektörünün uluslararası karbonsuzlaştırma hedeflerine uyum sağlaması için daha güçlü düzenleyici ve politika çerçeveleriyle desteklenen alternatif yakıtların yaygınlaştırılmasının, klinker yoğunluğunun düşürülmesinin ve enerji verimliliğinin artırılmasının önemini vurgulamaktadır.

Anahtar Kelimeler: Çimento Üretimi, CO_2 Emisyonları, Fourier ADF, RALS Eşbütünleşme, Karbonsuzlaştırma

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Introduction

Cement manufacturing is widely recognized as one of the most carbon-intensive industries. The process requires vast amounts of raw materials and fuels such as petroleum coke, coal, natural gas, fuel oil, biomass, or even certain wastes, in addition to substantial inputs of electricity, heat, air, and water (Valderrama et al., 2012; Gálvez-Martos and Schoenberger, 2014). A key stage in production is the calcination of limestone ($CaCO_3$), where its conversion to lime (CaO) releases large volumes of carbon dioxide. This is compounded by the combustion of fossil fuels needed to reach kiln temperatures above 1,400 °C, making the process both energy-intensive and emission-heavy (Gibbs et al., 2011). Beyond occasional wastewater, solid waste, and noise, the dominant environmental burden of the sector stems from energy use and atmospheric emissions (Schorcht et al., 2013; Georgiopoulou and Lyberatos, 2018). Globally, cement production is estimated to account for about 5–7% of anthropogenic CO_2 emissions and nearly 3% of overall greenhouse gas (GHG) releases (Gálvez-Martos and Schoenberger, 2014), while representing roughly 12–15% of total industrial energy consumption (Aranda-Usón et al., 2012). On average, producing a single ton of cement consumes around 4.7 million British thermal units (BTU) of energy—roughly equivalent to burning 181 kg of coal—and emits close to one ton of CO_2 (Gibbs et al., 2011). These figures illustrate why the sector stands at the center of climate change debates and why it has become a critical target for GHG mitigation efforts.

Efforts to reduce emissions in the cement sector often focus on lowering the clinker-to-cement ratio, substituting wastes as raw materials or fuels, and upgrading production technologies (Hasanbeigi et al., 2012; Stafford et al., 2016). A widely adopted strategy in this context is the use of alternative fuels and raw materials (AFR), commonly referred to as co-processing, which is practiced in many countries around the world. Typical AFRs include refuse-derived fuel (RDF), waste oils, discarded tires, plastics, sewage sludge, solvents, waste paint, paper residues, wood, and agricultural biomass (Lamas et al., 2013). RDF, produced from the combustible fraction of municipal solid waste, is particularly attractive due to its relatively high calorific value, lower moisture content, and reduced nitrogen and sulfur levels compared to conventional fossil fuels (Hasanbeigi et al., 2012; Rahman et al., 2015). Waste oils, generated from automotive, marine, rail, agricultural, and industrial activities, are also increasingly used in cement kilns because of their high energy content (33–41 MJ/kg) and limited processing requirements. However, compared to crude-based heavy oils, they tend to contain higher concentrations of heavy metals, sulfur, phosphorus, and halogens (Rahman et al., 2015). Another option is dried sewage sludge, which can simultaneously act as both fuel and raw material, offering environmental co-benefits by reducing waste volumes and contributing to resource efficiency. Yet, sludge drying itself is highly energy-intensive, with energy demand varying according to the technology applied (Jungbluth et al., 2007; Valderrama et al., 2013). Hence, a careful evaluation of the environmental implications of sludge drying is required before its large-scale application (Haque et al., 2015).

To set the stage, the remainder of the paper is organized as follows. The next section presents the context of Türkiye and reviews the relevant literature. This is followed by the data and model specification, and then by the methodology section, which outlines the econometric framework employed in the analysis. The subsequent section reports the empirical findings, while the final sections discuss the policy implications and conclude the study.

Context of Türkiye and the Literature

According to TÜRKÇİMENTO (2023), Türkiye's total cement production increased by 9.9% in 2023, reaching 84.6 Mt. Domestic sales rose to 68.9 Mt, up from 58.3 Mt in 2022, marking an 18.2% annual increase. Türkiye has consistently ranked among the world's leading cement producers; in 2024, national output was approximately 82 Mt, placing the country behind China (1,900 Mt), India (450 Mt), the United States (86 Mt), and Vietnam (110 Mt) (USGS, 2025). The industry is wholly dependent on domestically sourced raw materials, which secures national self-sufficiency. In 2023, exports accounted for 18.6% of total output, positioning Türkiye as the world's second-largest cement exporter. Among shipments to more than 100 countries, the principal destinations were the United States, Israel, Syria, and Italy (TÜRKÇİMENTO, 2023). The relevant trends are depicted in Figure 1.

Cement production is carried out using two principal methods: the dry process and the wet process. In Türkiye, the dry process with pre-calcination is employed. This process requires significant energy use at every stage of the production line. Examination of the structural characteristics of the components reveals that, despite adequate insulation, a considerable amount of energy is lost through surface dissipation. For industries with such high energy requirements, maintaining continuity of supply, ensuring product quality, and minimizing energy costs are among the primary operational objectives (Söğüt, 2012). The Turkish cement sector ranks as the country's second-largest industrial energy consumer, accounting for 20% of total industrial energy use, following the iron and steel industry at 35% (Ates, 2015).

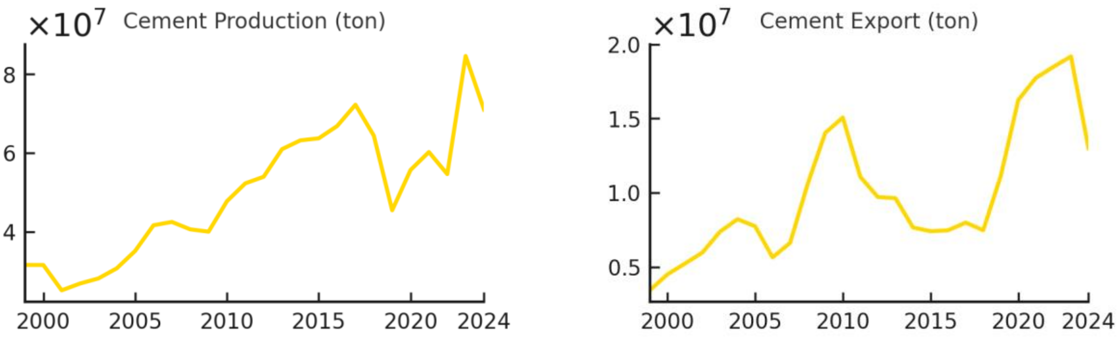

Figure 1. *Türkiye's Cement Production and Exports*

Source: TÜRKÇİMENTO database.

Cement production is widely recognized as one of the most carbon-intensive industrial processes. The bulk of emissions arises from the clinker production stage, where limestone calcination directly releases large volumes of CO_2, and the burning of fossil fuels like coal and petroleum coke leads to additional emissions. Together, these sources account for almost the entire carbon footprint of the industry, making clinker production the central target of decarbonization strategies. On a global scale, cement manufacturing is responsible for roughly 5% of anthropogenic CO_2 emissions, which significantly contribute to climate change. Although other GHGs, including methane (CH_4) and nitrous oxide (N_2O), have higher global warming potentials, their impact within cement production is relatively limited. Beyond process and combustion-related emissions, some kilns operate at extremely high flame temperatures that allow the co-incineration of waste oils, solvents, and other organic residues. While this practice can help reduce fossil fuel use, it may also release toxic metals and organic pollutants, raising concerns about technical feasibility and environmental safety. Consequently, the cement industry occupies a critical position in global climate mitigation efforts, where balancing energy demand, fuel choices, and emission reduction remains a pressing challenge (Worrell et al., 2001; Salas et. al., 2016). As shown in Table 1, Türkiye's clinker capacity has expanded substantially over the past two decades, rising from 33 Mt in 2000 to 92 Mt by 2020–2023.

Table 1. *Clinker Production Capacity in Türkiye (Mt)*

Year	*2000*	*2005*	*2010*	*2015*	*2020*	*2023*
Capacity (Mt)	33	55	65	69	92	92

Source: Adapted from USGS Reports.

Table 2. *Fuel Use and Calorific Values in Cement and Clinker Production*

	Fuel Type	*Calorific Value (GJ/t)*	*2003*	*2004*	*2005*
Türkiye*	Pet coke	31.38	18.42	18.35	19.20
	Coal	18.83			
			2010	**2015**	**2020**
Global**	Fossil Fuels	–	3.39	3.26	3.25

* cement industry, ** clinker production.

Source: Adapted from Oral and Saygin, 2019; TTGV, 2023.

Fuel use patterns further emphasize the challenge. As shown in Table 2, the Turkish cement industry relies predominantly on petroleum coke and coal, with weighted calorific values ranging between 18.35 and 19.20 GJ/t across different years. In contrast, global fossil fuel use in clinker production has been progressively reduced, declining from 3.39 GJ/t in 2010 to 3.25 GJ/t in 2020. This comparison highlights the relatively high emissions intensity of Türkiye's fuel mix and underscores the urgency of aligning with global net-zero pathways, where clinker production remains the central focus of emission-reduction strategies.

Research on cement industry emissions over the past quarter century can broadly be organized into four strands:

(i) Alternative binders and emission reduction strategies:

A number of studies have concentrated on replacing conventional Portland cement with substitutes that generate fewer emissions. Davidovits (1994) was among the first to advocate for geopolymeric cements as a low-carbon alternative. In a similar line, Worrell et al. (2001) analyzed CO_2 emissions from the cement sector worldwide and pointed to the benefits of using supplementary additives. Gartner (2004) also underlined the potential of hydraulic cements and artificial pozzolans to lower overall carbon intensity while maintaining equivalent performance.

(ii) Life-cycle assessment (LCA) applications:

Another significant body of work employs life-cycle methodologies to evaluate environmental impacts. Huntzinger and Eatmon (2009) compared traditional production with alternative processes and concluded that environmental life-cycle assessment (ELCA) provides a comprehensive framework for identifying risks and optimizing production. Extending this approach, Valderrama et. al. (2012) reported that indicators such as eutrophication, acidification, and cumulative exergy demand show a declining trend when LCA is applied. From a country perspective, Green and Stern (2017) examined China and found that emissions from fossil fuel use and cement manufacturing more than doubled between 2001 and 2006.

(iii) Energy modeling using LEAP:

The Long-range Energy Alternatives Planning (LEAP) framework has also been widely adopted to simulate future emission pathways. Applications include those by Bose (1996), Shin et al. (2005), Song et al. (2007), Wang et al. (2011)**,** Dagher and Ruble (2011), Udomsri et al. (2010), Bautista (2012), Rahmadi et al. (2013), Kumar and Madlener (2016), Aized et al. (2018), Liu et al. (2017), Mirjat et al. (2017), and Oral and Saygin (2019). Collectively, these works confirm LEAP's suitability for exploring energy–emission interactions and scenario analysis in the cement industry.

(iv) Türkiye-focused contributions:

In Türkiye, scholarship has been narrower in scope, concentrating mainly on environmental and efficiency aspects. Doğan and Karpuzcu (2010) considered the broader ecological consequences of cement production, while Yildirim et al. (2011) evaluated stabilization techniques for by-products. Okandan et. al. (2011) assessed the CO_2 potential of the sector, and Söğüt (2012) together with Gürsel and Meral (2012) investigated the exergetic efficiency of cement production systems. Waste management and sustainable production were examined by Bayar and Talinli (2013) and Ekincioglu et al. (2013), while Ozer et al. (2013) and Ates (2015) applied the LEAP model domestically to explore the relationship between CO_2 emissions, energy demand, and electricity consumption in heavy industries. On material efficiency, Ulusu et al. (2016) studied pumice-based blended cements, and Özkan and Ulutas (2017) conducted efficiency analyses of cement production outputs. Civancık and Yetiş (2018) then analyzed mercury emissions from cement plants, emphasizing pollutant-specific challenges. Most recently, Bildirici (2020) investigated the links between cement production, air quality, mortality rates, and economic growth in Türkiye and other major producers, using regime-switching econometric models. This study underscores the health and environmental burdens of cement-related emissions and reinforces the urgency of adopting cleaner technologies, alternative fuels, and stronger regulatory frameworks.

In Türkiye, research on cement industry emissions has concentrated mainly on waste management, efficiency improvements, or pollutant-specific assessments, with limited attention to dynamic econometric modeling of CO_2 emissions. Previous domestic studies employing LEAP rely on scenario-based projections, which, while useful for long-term planning, do not capture causal linkages or asymmetric responses in actual production and emission data.

To address this gap, the present study employs the Fourier Augmented Dickey–Fuller (F-ADF) unit root test alongside the RALS-ADL (Residual Augmented Least Squares – Autoregressive Distributed Lag) and RALS-EG2 (Residual Augmented Least Squares – Engle and Granger Type 2) cointegration tests to examine the long-run relationship between cement production and CO_2 emissions in Türkiye. This provides a novel contribution to the Turkish context, where empirical econometric evidence on cement-related emissions is scarce. Beyond its national relevance, the study also offers broader policy insights by situating Türkiye's emission dynamics within global decarbonization efforts and the net-zero pathway.

Data and Model

This section presents the variables, data sources, and model specification. The analysis centers on the relationship between cement production and CO_2 emissions in Türkiye for the period 1970–2023. The general form of the model employed to investigate this relationship is outlined as follows:

$$CO = f(CP) \quad (1)$$

$$lnCO_t = \gamma_0 + \gamma_1 lnCP_t + \varepsilon_{1t} \quad (2)$$

Where *CO* is the carbon dioxide (CO_2) emissions (total) (Mt CO2e) and *CP* is the cement production (tonnes). The series of the *CP* is obtained from "United States Geological Survey (USGS) Data Bank". The series of the *CO* is obtained from "World Development Indicators". It should be noted that the baseline econometric specification is intentionally parsimonious and captures the long-run association between *CO* and *CP* only. Variables such as total energy use, fuel mix composition, clinker substitution ratio, and plant-level technological upgrading are discussed extensively in the conceptual and policy sections because they are central channels through which cement output affects emissions. However, they are not explicitly included in the econometric model, mainly due to the lack of sufficiently long and consistent annual series. Accordingly, the estimated coefficient should be interpreted as an aggregate long-run elasticity, while recognizing that part of this relationship is mediated by omitted sector-specific mechanisms such as fuel switching, clinker reduction, and energy-efficiency improvements.

This study aims to provide a robust empirical analysis by accounting for potential multiple structural breaks, nonlinearities, and deviations from the normality assumption. To this end, the F-ADF unit root test and the RALS-ADL and RALS-EG2 cointegration tests are employed. The following section presents the theoretical background of these applied tests.

Methodology

This section outlines the theoretical foundation of the cointegration and unit root tests applied in the study. It first reviews the conventional linear unit root test and the nonlinear Fourier-based approach, followed by the RALS cointegration framework used to analyze the long-run relationship between the variables.

Fourier ADF Unit Root Test (F-ADF)

In time series analysis, a critical step in exploring relationships between variables is identifying the type of stochastic process each series follows. To determine these stochastic characteristics—particularly whether the series is stationary and the degree of stationarity—it is essential to choose the appropriate model when conducting unit root tests. This involves considering factors such as the presence, timing, and nature of potential structural breaks in the data, as well as whether the series behaves in a linear or nonlinear manner.

Enders and Granger (1998) emphasized that incorrectly specifying the dynamics of a time series can cause standard unit root and cointegration tests to yield misleading conclusions. Similarly, Perron (1989) found that structural breaks, if ignored, can bias traditional unit root tests, often resulting in a failure to reject the unit root hypothesis even when the series is actually stationary. Cuestas and Garratt (2011) further argued that applying linear unit root tests to nonlinear series can lead to similar biases, again increasing the likelihood of incorrectly accepting the presence of a unit root. In this regard, the stationarity properties of the series were determined using the ADF test as a linear unit root test and the F-ADF test as a nonlinear unit root test. In unit root tests based on Fourier functions, the number, form, or location of structural breaks is not of significance. This is because Fourier functions are capable of modeling unpredictable changes in the series. This characteristic provides a significant advantage for these tests.

F-ADF unit root test, developed by Christopoulos and León-Ledesma (2010) and an extension of the ADF type unit root test with Fourier functions, is a unit root test that considers both abrupt changes and smooth structural breaks, where the number, location, and form of structural breaks are not of significance. In the F-ADF test, the first step involves estimating the model for the time series used in the analysis and obtaining the residuals from the model. Subsequently, the ADF unit root test is applied to the obtained residuals. When constructing the test model, structural breaks are incorporated using a trigonometric function that allows for temporary smooth changes in the mean.

The application of the F-ADF test consists of three main stages. The first stage involves determining the optimal frequency (k*). For this purpose, Eq. (3) is estimated for each integer value of *k* from 1 to 5 using the Ordinary Least Squares (OLS) method, and *k* value of the model that yields the least of sum of the squares residuals is selected as the optimal frequency.

$$y_t = \alpha_0 + \alpha_1 sin\left(\frac{2\pi kt}{T}\right) + \alpha_2 cos\left(\frac{2\pi kt}{T}\right) + v_t \tag{3}$$

Where *k* is the frequency, *T* is the sample size. Additionally, the terms $sin(2\pi kt/T)$ and $cos(2\pi kt/T)$ are trigonometric terms that incorporate structural changes in the deterministic component of the model. Subsequently, the residuals of the model are obtained using Eq. (4):

$$\hat{v}_t = y_t - \left[\hat{\alpha}_0 + \hat{\alpha}_1 sin\left(\frac{2\pi k^* t}{T}\right) + \hat{\alpha}_2 cos\left(\frac{2\pi k^* t}{T}\right)\right] \tag{4}$$

In the second stage of the test, after identifying the optimal lag length, a unit root test is conducted on the residuals derived from the model specified in Eq. (4). The following model is used in the F-ADF unit root test developed by Christopoulos and León-Ledesma (2010):

$$\Delta v_t = \delta_1 \vartheta_{t-1} + \sum_{j=1}^{p} \theta_j \Delta v_{t-j} + u_t \tag{5}$$

In this test, the null hypothesis indicating the presence of a unit root is stated as $H_0: \delta_1 = 0$, and it is tested against the alternative hypothesis $H_1: \delta_1 \neq 0$. The asymptotic distribution of the test statistics calculated here depends on the optimal frequency (k), which is the frequency of the Fourier series (Becker et al., 2006). The calculated test statistic is compared with the critical values constructed for different *k* values in the range of 1 to 5, as presented by Christopoulos and León-Ledesma (2010).

In the second stage, if the null hypothesis indicating the presence of a unit root is rejected, the third stage involves testing the statistical significance of the parameters of the trigonometric terms in the model. At this stage, the null hypothesis $H_0: \alpha_1 = \alpha_2 = 0$, which expresses the significance of the α_1 and α_2 in Eq. (3), is tested against the alternative hypothesis $H_1: \alpha_1 = \alpha_2 \neq 0$ using the F-test ($F_\mu(\hat{k})$). The test statistics obtained from the F-test are compared with the critical values provided by Becker et al. (2006).

RALS Cointegration Tests

Traditional residual-based cointegration tests typically assume that the error terms in the regression follow a normal distribution. The test statistics and their critical values are derived under this assumption. However, these tests may miss valuable insights when the error terms deviate from normality. Despite this, the asymptotic distributions of the test statistics remain unchanged even in the absence of normality. As a result, conventional cointegration tests continue to be applied, regardless of whether the normality assumption holds (Oh et al., 2020).

Lee et al. (2015) argue that even though the asymptotic distribution of test statistics might remain unchanged under non-normality, this issue should not be ignored. To address this, the RALS approach, proposed by Im and Schmidt (2008), is used to test for unit roots in the presence of non-normally distributed residuals.

To overcome this limitation, incorporating information from non-normal error terms into cointegration analysis can improve estimator efficiency and increase the power of cointegration tests (Lee et al., 2015). In this regard, Lee et al. (2015) developed two modified cointegration tests—RALS-ADL and RALS-EG2. These tests apply the RALS framework to conventional single-equation cointegration methods. Specifically, the RALS-ADL test is based on Eq. (6), which reformulates the conditional error correction model (ECM) into an ADL structure, following the approach of Banerjee et al. (1998).

$$\Delta p_t = \gamma_p + \alpha_p p_{t-1} + \lambda f_{t-1} + \varphi \Delta f_t + e_t \tag{6}$$

The RALS-EG2 test is based on the residual-based cointegration test developed by Engle and Granger (EG) (1987). The EG cointegration test relies on the t-statistics derived from the null hypothesis of $\delta = 0$ in the ADF regression outlined below:

$$\Delta \hat{u}_t = \delta \hat{u}_{t-1} + \varepsilon_t \tag{7}$$

RALS cointegration tests utilize the second and third moments of residual series $\hat{e}_t$, derived from traditional cointegration tests, by creating a new term, $\hat{w}_t$. This term was computed using Eq. (8), based on the second and third moments of the error terms from the corresponding cointegration test.

$$\hat{w}_t = h(\hat{e}_t) - \hat{K} - \hat{e}_t \hat{D}_2, \qquad t = 1, \dots, T \tag{8}$$

where $h(\hat{e}_t) = [\hat{e}_t^2, \hat{e}_t^3]', \hat{K} = \frac{1}{T}\sum_{t=1}^{T} h(\hat{e}_t)$ and $\hat{D}_2 = \frac{1}{T}\sum_{t=1}^{T} h'(\hat{e}_t)$. By letting $\hat{m}_j = \frac{1}{T}\sum_{t=1}^{T} \hat{e}_t^j$ where $j = 2{,}3$, the newly added term $\hat{w}_t$ can be expressed as:

$$\hat{w}_t = [\hat{e}_t^2 - \hat{m}_2, \hat{e}_t^3 - \hat{m}_3 - 3\hat{m}_2 \hat{e}_t]' \tag{9}$$

Thus, RALS-ADL and RALS-EG2 cointegration tests can be expressed with the following formulations:

$$\Delta p_t = d_t + \delta p_{t-1} + \lambda f_{t-1} + \varphi \Delta f_t + \hat{w}_t' \psi + v_t \tag{10}$$

$$\Delta \hat{u}_t = c + \delta \hat{u}_{t-1} + \kappa \Delta f_t + \hat{w}_t' \psi + \varsigma_t \tag{11}$$

In Eq. (10), d_t indicates a deterministic term which includes either a constant ($d_t = \alpha$) or a constant and linear trend ($d_t = \alpha + \varrho t$). In Eq. (11), c is a constant, and $\hat{u}_t$ is the residual from the least squares estimation of the long-run regression in the Engle and Granger (1987) cointegration test. In the literature, lags of Δp_t and Δf_t are generally included to account for potential serial correlation in v_t in the RALS-ADL test. Likewise, lags of $\Delta \hat{u}_t$ are allowed in the RALS-EG2 regression (Oh et al., 2020).

In the application of the RALS-ADL and RALS-EG2 cointegration tests, the null hypothesis, which states the absence of cointegration, is tested against the alternative hypothesis, which asserts the presence of cointegration. The hypotheses are as follows:

$$H_0: \delta = 0$$

$$H_1: \delta < 0$$

The null hypothesis is tested using the t-statistics calculated from Eq. (10) for RALS-ADL and Eq. (11) for RALS-EG2. In both RALS cointegration tests, the critical values depend on the long-run correlation coefficient, denoted by ρ^2. The empirical critical values for various ranges of ρ^2 are provided in Lee et al. (2015). ρ^2 is calculated using Eq. (12) for the RALS-ADL test and Eq. (13) for the RALS-EG2 test.

$$\rho^2 = \frac{\sigma_{ev}^2}{\sigma_{ee}\sigma_{vv}} \tag{12}$$

$$\rho^2 = \frac{\sigma_{\varepsilon\varsigma}^2}{\sigma_{\varepsilon\varepsilon}\sigma_{\varsigma\varsigma}} \tag{13}$$

There are compelling reasons to employ RALS cointegration tests when examining long-term relationships among variables in this study. Most notably, the RALS approach enhances test robustness by incorporating information from higher-order moments, which becomes particularly valuable when residuals deviate from normality. Specifically, the term $\hat{w}_t$ in Eq. (8) is constructed based on moment conditions related to heteroscedasticity and zero-normalized kurtosis—key characteristics of normally distributed data. In cases of non-normality, these moment conditions produce irreducible stationary components that can be represented as stationary common variables, as noted by Hansen (1995). Including these components in the regression helps reduce the error variance and, in turn, improves the strength and reliability of the test. Additionally, the RALS procedure offers a practical advantage: it is simple to implement and does not require prior specification of a functional form, a known density function, or the identification of a particular type of non-normality (Oh et al., 2020).

Findings

The integration order of the variables was evaluated prior to investigating their long-term relationship. Because cointegration analysis requires variables to be integrated of the same order, the ADF unit root test was initially applied to assess their stationarity properties. The results, presented in Table 3, show that both lnCO and lnCP are stationary at first difference, [I(1)]. However, conventional unit root tests may produce biased results, as they often fail to reject the unit root hypothesis when structural breaks are present. To address this issue, the stochastic properties of the series were also examined using the F-ADF test, which allows for multiple smooth or abrupt breaks. According to the F-ADF results, also shown in Table 3, the level values of lnCO and lnCP are non-stationary, confirming the presence of unit roots in both variables.

Table 3. *The Results of Unit Root Tests*

Variables	*ADF*		*F-ADF*		
	Level	First Differences			
	Test Statistic (p-values) [opt. lag]	Test Statistic (p-values) [opt. lag]	Opt. Freq. (k)	F-ADF Test Statistic	F-test Statistic ($F_\mu(\hat{k})$)
lnCO	-1.459 (0.483) [4]	-4.602* (0.000) [5]	1	-3.049	156.784
lnCP	-1.276 (0.328) [3]	-3.425** (0.023) [3]	1	-2.264	63.486

* and ** denote the rejection of the null hypothesis at the 1 and 5% levels, respectively.

The F-ADF unit root test results indicate that the null hypothesis of a unit root cannot be rejected for the level values of all variables. Similarly, the ADF test confirms that both lnCO and lnCP contain unit roots at their levels, fully consistent with the Fourier-based results. However, when applied to the first differences, the ADF test shows that the variables are stationary, [I(1)]. Therefore, the long-term relationship between lnCO and lnCP, both integrated of order one, was analyzed using the RALS cointegration tests, with the results reported in Table 4.

Table 4. *The Results of RALS-ADL and RALS-EG2 Cointegration Tests*

Jarque-Bera (p-value)	ρ^2	*RALS-ADL Test Statistic*	*Jarque-Bera (p-value)*	ρ^2	*RALS-EG2 Test Statistic*
547.458 (0.0000)	0.9378	-3.6653**	586.344 (0.0000)	0.9393	-3.8991**

** denotes the rejection of the null hypothesis at the 5%. The null hypothesis states that there is no cointegration between the variables.

Table 5. *The Estimated Long-term Coefficients Based on RALS*

Variables	*Coefficient*	*t-statistic*	*p-value*
Constant	-3.1935*	-3.9772	0.0002
trend	0.0217*	9.3863	0.0000
lnCP	0.4510*	8.9671	0.0000
w_2	-4.2558**	-2.1544	0.0361
w_3	-95.922*	-2.9855	0.0044

* and ** denote the statistically significance of the coefficients at the 1 and 5%, respectively.

An examination of the Jarque–Bera test statistics shows that the models do not satisfy the normality assumption. Therefore, in testing for cointegration, the traditional ADL (τ_{ADL}) and EG2 (τ_{EG2}) statistics were replaced with the RALS-ADL ($\tau_{RALS-ADL}$)) and RALS-EG2 ($\tau_{RALS-EG2}$) statistics. As reported in Table 4, the null hypothesis of no cointegration is rejected by both tests, indicating a long-term relationship between the variables. For these cointegration relationships to be meaningful, however, the long-run coefficients of the independent variables must also be statistically significant. Accordingly, the RALS method, which is robust to deviations from normality, was used to estimate the long-run coefficients, and the results are presented in Table 5.

The coefficients in Table 5 represent the long-term elasticity of the independent variable with respect to the dependent variable, and they are statistically significant. Accordingly, the long-term elasticity of *CO* with respect to *CP* is estimated at 0.45, meaning that a 1% increase in cement production leads to a 0.45% increase in CO_2 emissions.

Discussion

The adoption of alternative fuels in the Turkish cement sector has remained limited compared to international standards. According to Saka (2020), the industry currently substitutes around 7% of its energy demand with wastes through co-processing, while the European Union has achieved an average substitution rate of approximately 44%. This significant gap highlights both the untapped technical potential and the policy opportunity for Türkiye to accelerate the use of alternative fuels. Increasing substitution would not only reduce dependence on imported fossil fuels but also yield substantial environmental gains in line with global decarbonization efforts. A key element in this transition is the utilization of municipal solid waste, particularly for the production of RDF. The prevailing model in Türkiye involves municipalities or private investors establishing waste-processing facilities—responsible for sorting, drying, and preparing additional fuels—which are then purchased by cement plants. In this arrangement, municipalities redirect the costs saved from reduced landfill volumes as contributions to these facilities, eliminating the need for direct public subsidies. Long-term contracts between waste processors and cement plants ensure supply security, while simultaneously converting waste into a valuable energy source. This framework, if scaled up, could significantly expand AFR integration in Türkiye, helping the sector converge with European benchmarks and contribute more effectively to national and global climate targets.

Table 6. *Calorific Values of Alternative Fuel Wastes*

Fuel Type	***Energy (kcal/kg)***
Petcoke (baseline)	~7,500
Used tyre	5,500
Husk	4,760
Industrial plastic	4,350
Waste oil	3,500
Scrap paper	3,400
Contaminated waste	3,400
RDF plastic	2,800
Sewage sludge	2,000

Source: Ekincioglu et al. 2013.

Decarbonizing the cement industry requires a portfolio of complementary strategies rather than reliance on a single solution. One promising direction is the progressive substitution of fossil fuels with cleaner alternatives such as hydrogen, biomass, and RDF, which can significantly cut fuel-related emissions while also reducing dependence on imported coal and petroleum coke. Hydrogen, in particular, offers long-term potential as a high-temperature fuel in rotary kilns, especially when used in combination with waste-derived fuels like end-of-life tires and municipal biomass. The comparative calorific values of commonly used alternative fuels are presented in Table 6, illustrating their energy potential relative to petcoke. Parallel to fuel switching, recycling construction and demolition waste represents a valuable pathway for lowering the clinker footprint. By processing CaO-rich concrete waste through mineral carbonation, both raw material needs and process emissions can be reduced, while simultaneously creating opportunities for carbon capture and storage within the production cycle. These approaches, combined with advances in carbon capture technologies such as oxy-fuel combustion and the use of microalgae for flue gas treatment, highlight a diversified route toward deep decarbonization. Together, they underscore that emission reduction in the cement sector must integrate cleaner fuels, waste valorization, and innovative capture methods, supported by regulatory frameworks and industrial investment, if the industry is to align with global net-zero ambitions (TTGV, 2023).

The empirical findings further reinforce these strategic directions. The econometric analysis demonstrates a long-run cointegration relationship between cement production and CO_2 emissions, confirming that emission dynamics in Türkiye are structurally tied to output growth. More specifically, the estimated long-run elasticity of 0.45 implies that a 1% increase in cement production is associated with a 0.45% increase in CO_2 emissions. Although this coefficient is below unity and therefore suggests partial decoupling, it also indicates that output expansion still generates a substantial emissions response. From a policy perspective, this result implies that future production growth cannot be reconciled with decarbonization targets through scale expansion alone. Instead, the emissions intensity of each additional unit of output must be reduced through concrete instruments such as greater substitution of coal and petcoke with alternative fuels (e.g., RDF, biomass, and waste-derived inputs), a lower clinker-to-cement ratio through supplementary cementitious materials, and stronger energy-efficiency investments in kilns and waste-heat recovery systems. In this sense, the estimated elasticity provides an empirical basis for prioritizing policies that directly target the technological and material composition of cement production rather than relying only on general environmental commitments.

The present findings can also be interpreted more clearly when situated within the broader literature. At the global level, Worrell et al. (2001) emphasize that cement production remains structurally carbon-intensive because emissions are deeply embedded in both clinker chemistry and fossil-fuel combustion. From a country perspective, Green and Stern (2017) show that in China, emissions from fossil fuel use and cement manufacturing increased sharply during periods of rapid industrial expansion, underscoring how output growth can translate into a substantial environmental burden when cleaner technologies and fuel substitution remain limited. For Türkiye, Bildirici (2020) likewise highlights the environmental and social costs associated with cement-related emissions in a comparative framework that includes both advanced and emerging economies. Read together with the elasticity estimate obtained here, these studies suggest that Türkiye has achieved only partial decoupling rather than a structural break between production growth and emissions. In comparative terms, developed-country settings generally have greater scope to weaken the cement–emissions nexus through higher alternative-fuel substitution, broader clinker reduction practices, and stricter environmental regulation, whereas Türkiye appears closer to the pattern observed in emerging producers, where output increases still generate a visible rise in emissions. This comparison should be interpreted cautiously, since the present study does not estimate country-specific elasticities in a multi-country framework; nevertheless, it helps position the Turkish evidence within the wider cement decarbonization literature.

Despite its methodological strengths, this study is subject to several limitations. First, the econometric model is deliberately specified as a bivariate long-run framework between cement production and CO_2 emissions. Although this parsimonious structure is suitable for identifying the aggregate long-run association, it does not explicitly incorporate sector-specific drivers such as energy consumption, fuel mix composition, clinker substitution ratios, or technological modernization. These factors are highly relevant for interpreting the mechanisms behind the estimated elasticity, but consistent long-span annual data for Türkiye are limited. Therefore, the results should be read as capturing the overall emissions response to cement output rather than the separate marginal effects of individual decarbonization channels. Second, the reliance on aggregate annual data restricts the ability to capture seasonal fluctuations, short-term shocks, or plant-level heterogeneity that may influence emission dynamics. Third, while the F-ADF and RALS cointegration framework provide robustness against structural breaks, nonlinearities, and deviations from normality, they do not fully account for all potential regime shifts arising from regulatory reforms, carbon pricing mechanisms, or international trade shocks. Finally, the study is focused exclusively on the Turkish case, which limits the scope for direct cross-country comparisons or broader generalization of results.

Conclusion

Achieving meaningful emission reductions in the cement sector ultimately depends on policy frameworks that incentivize innovation and create favorable market conditions. Clear regulations on waste management and fuel substitution, combined with financial incentives for co-processing and recycling, can accelerate the uptake of alternative fuels and raw materials. At the same time, public–private partnerships are essential for developing the infrastructure needed to process municipal waste into usable RDF and to scale up carbon capture technologies. By aligning national policies with global net-zero targets, Türkiye can not only reduce the carbon intensity of its cement industry but also strengthen energy security, lower import dependency, and position itself as a competitive exporter in a low-carbon global economy.

To achieve these goals, the sector must adopt a portfolio of interrelated strategies: (i) alternative fuels, where RDF, biomass, waste oils, sewage sludge, and eventually hydrogen can progressively replace coal and petcoke; (ii) alternative raw materials, with industrial by-products such as slag, pyrite ash, or phosphogypsum reducing reliance on virgin resources; (iii) lowering the clinker factor, through the integration of supplementary cementitious materials like blast furnace slag, fly ash, and microsilica to cut process-related emissions; (iv) energy efficiency, by deploying waste heat recovery systems, modern kiln technologies, and improved energy management to lower both thermal and electrical demand; and (v) recycled and alternative materials in ready-mixed concrete, where recovered aggregates, water, and industrial by-products extend emission savings across the value chain. Together, these measures highlight that deep decarbonization in cement production depends not on a single pathway but on the coordinated adoption of complementary solutions supported by effective policy and investment frameworks.

Future research could address current limitations in several ways. First, extending the empirical model to include energy-related and clinker-related variables—such as total thermal energy use, electricity consumption, alternative fuel share, petcoke/coal dependence, clinker-to-cement ratio, and supplementary cementitious material use—would allow a more direct identification of the mechanisms through which production affects emissions. Second, expanding the analysis to higher-frequency datasets (e.g., quarterly energy use or monthly production records) would provide a finer understanding of short-term volatility and policy shocks. Third, comparative studies across major cement-producing economies could shed light on structural differences in fuel mixes, technology adoption, and carbon reduction strategies. Methodologically, future work may also extend the Fourier-based and RALS approaches by integrating additional structural break tests, multivariate or panel cointegration methods, and forecasting frameworks to capture nonlinearities more comprehensively. Finally, incorporating additional environmental indicators such as NO_x, SO_2, or particulate matter, alongside CO_2, would provide a more comprehensive picture of cement-industry externalities and strengthen the policy relevance of the findings.

Ethical Statement

During the preparation of the study titled *"Assessing the Cement-CO2 Link in Türkiye: A RALS Cointegration Framework"*, scientific principles, ethical standards, and citation rules were strictly followed; no falsification was made on the collected data, and this study has not been submitted to any other academic publication venue for evaluation. Ethics committee approval is not required for this research.

Etik Beyan

"Türkiye'de Çimento Üretimi-CO_2 İlişkisinin Değerlendirilmesi: RALS Eşbütünleşme Analizi" başlıklı çalışmanın yazım sürecinde bilimsel kurallara, etik ve alıntı kurallarına uyulmuş; toplanan veriler üzerinde herhangi bir tahrifat yapılmamış ve bu çalışma herhangi başka bir akademik yayın ortamına değerlendirme için gönderilmemiştir. Bu araştırmada etik kurul kararı zorunluluğu bulunmamaktadır.

Statement of Authors' Contribution Rate

The authors contributed equally to the study.

Araştırmacıların Katkı Oranı Beyanı

Yazarların çalışmadaki katkı oranları eşittir.

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There is no potential conflict of interest in this study.

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Bu makalenin yazımında yapay zeka ve türleri kullanılmamıştır.

Data Sharing Statement

We declare that the data of this study may be shared upon reasonable request for the purpose of verifying the findings, in accordance with the conditions specified in the relevant section of the "ethical principles and publication policy."

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GENİŞLETİLMİŞ ÖZET

Küresel düzeyde karbon salımlarının yaklaşık %7'si çimento üretiminden kaynaklanmaktadır. Bu yüksek oran, hem klinker üretiminde gerçekleşen kimyasal reaksiyonlar hem de yüksek sıcaklık gereksinimi nedeniyle yoğun fosil yakıt kullanımı gibi süreçsel nedenlerden ileri gelmektedir. Türkiye, dünyada önde gelen çimento üreticilerinden biri olmakla birlikte, sektördeki karbonsuzlaşma çabaları henüz sınırlı düzeydedir. Bu bağlamda, Türkiye'nin ulusal iklim hedefleriyle uyumlu bir şekilde çimento sektörünün dönüşümünü sağlamak, hem çevresel hem de ekonomik açıdan stratejik bir öneme sahiptir. Bu çalışmada, Türkiye'de çimento üretimi ile karbon dioksit (CO_2) emisyonları arasındaki uzun dönemli yapısal ilişkiyi ortaya koymak hedeflenmektedir. 1970–2023 dönemini kapsayan bu analiz, çimento sektörünün çevresel etkisini sayısal verilerle açıklamayı ve politika geliştirme süreçlerine ampirik katkı sunmayı amaçlamaktadır. Bu araştırmanın temel amacı, Türkiye'de çimento üretimi ile CO_2 emisyonları arasında uzun dönemli bir eşbütünleşme (koentegrasyon) ilişkisinin olup olmadığını incelemektir. Ayrıca, çimento üretimindeki artışın karbon emisyonları üzerindeki uzun vadeli etkisi, yani uzun dönem esnekliği hesaplanarak sektörün karbonsuzlaşma potansiyeli değerlendirilmektedir. Geleneksel doğrusal analizlerin ötesine geçilerek, yapısal kırılmalar, doğrusal olmayan dinamikler ve normallik varsayımından sapmalar gibi olasılıklara karşı daha sağlam sonuçlar üretebilen ekonometrik yöntemler tercih edilmiştir. Çalışmada iki aşamalı bir yöntem izlenmiştir. İlk olarak, çimento üretimi (CP) ve karbon emisyonu (CO) serilerinin durağanlık özellikleri incelenmiştir. Bu kapsamda, hem geleneksel Augmented Dickey-Fuller (ADF) testi hem de yapısal kırılmalar ve doğrusal olmayan süreçleri dikkate alan Fourier tabanlı ADF (F-ADF) testi uygulanmıştır. Elde edilen bulgular, her iki serinin birinci farklarında durağan olduklarını, yani I(1) seviyesinde bütünleşik olduklarını göstermiştir. İkinci aşamada ise, bu değişkenler arasında uzun dönemli bir ilişkinin var olup olmadığını test etmek amacıyla, kalıntıların normal dağılımdan sapmaları dikkate alan ve daha yüksek moment bilgilerini değerlendiren RALS-ADL ve RALS-EG2 eşbütünleşme testleri uygulanmıştır. Bu testler, geleneksel tek denklemli eşbütünleşme analizlerinin daha güçlü versiyonları olup, özellikle kalıntıların çarpıklık (skewness) ve basıklık (kurtosis) içerdiği durumlarda daha güvenilir sonuçlar sunmaktadır. Ayrıca, RALS yaklaşımı ile uzun dönemli katsayı tahminleri de elde edilmiştir. RALS-ADL ve RALS-EG2 testlerine göre, %5 anlamlılık düzeyinde değişkenler arasında eşbütünleşme ilişkisinin olmadığını ifade eden sıfır hipotezi reddedilmektedir. Bu sonuçlar, çimento üretimi ile karbon emisyonları arasında uzun dönemli bir ilişkinin bulunduğunu ortaya koymaktadır. Ayrıca, uzun dönem katsayı tahminlerine göre, karbon emisyonlarının çimento üretimine karşı uzun dönemli esnekliği 0.45 olarak bulunmuştur. Bu bulgu, çimento üretiminde meydana gelen %1'lik bir artışın karbon emisyonlarını %0.45 oranında artırdığını göstermektedir. Dolayısıyla, üretim artışı doğrudan ve güçlü bir şekilde emisyon artışına yol açmakta, ancak artış orantısal olarak daha düşük gerçekleşmektedir. Bu durum, belirli verimlilik kazanımlarının sağlandığını, fakat emisyonların üretimden tamamen ayrışmadığını (decoupling) göstermektedir. Türkiye'nin mevcut durumda alternatif yakıt kullanım oranı Avrupa Birliği ortalamasının oldukça altındadır. 2020 itibarıyla bu oran Türkiye'de yaklaşık %7 seviyesindeyken, AB ortalaması %44 civarındadır. Bu büyük fark, hem teknik kapasite hem de politika yapımı açısından önemli bir potansiyelin varlığına işaret etmektedir. RDF (Refuse Derived Fuel) gibi atık bazlı yakıtların kullanımının artırılması, hem çevresel hem de enerji güvenliği açısından stratejik katkılar sağlayabilir. Buna ek olarak, klinker faktörünün düşürülmesi, enerji verimliliği yatırımları, atık ısı geri kazanımı, mikrosilika ve uçucu kül gibi ikincil hammaddelerin entegrasyonu da sektördeki karbon yoğunluğunu azaltmada kritik rol oynamaktadır. Ayrıca, atık betonun geri dönüştürülmesi ve mineral karbonlaştırma tekniklerinin geliştirilmesi, döngüsel ekonomi yaklaşımlarını destekleyen ilave çözümler sunmaktadır. Bu çalışma, Türkiye'de çimento üretimi ile CO_2 emisyonları arasında uzun dönemli yapısal bir ilişki olduğunu ortaya koymaktadır. Emisyonlar, üretim artışına karşı daha az oranda artış gösterse de, sektör hâlen yüksek karbon bağımlılığı taşımaktadır. Dolayısıyla, yalnızca marjinal verimlilik artışlarıyla karbon ayak izinin anlamlı şekilde azaltılması mümkün görünmemektedir. Gerçek bir karbonsuzlaşma için, alternatif yakıt kullanımı, hammadde dönüşümü, enerji verimliliği ve karbon yakalama gibi çok boyutlu ve birbirini tamamlayan stratejilerin birlikte hayata geçirilmesi gerekmektedir. Politika yapıcıların, atık yönetimi, geri dönüşüm ve alternatif yakıt teşvikleri konusunda daha net ve etkin düzenlemeler oluşturması, özel sektörün ise bu dönüşümde aktif rol alarak yatırım yapması kritik önemdedir. Gelecek araştırmalar, bu çalışmanın sınırlarını aşarak daha yüksek frekanslı verilerle (örneğin aylık üretim ve enerji tüketimi), karşılaştırmalı ülke analizleriyle ve diğer kirletici türlerini de içeren kapsamlı modellerle sektördeki çevresel etkileri daha detaylı ortaya koyabilir. Böylece, Türkiye'nin çimento sektöründe düşük karbonlu üretim vizyonuna ulaşması daha somut bir zemine oturtulabilir.