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Productivity Dynamics in Türkiye’s Waste Management and Resource Recovery Sector: An Analysis Using Törnqvist Productivity Index (2009-2023)

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***Purpose*:** This study aims to conduct the first comprehensive efficiency analysis of Türkiye’s Waste Management and Resource Recovery sector at the industry level. It examines productivity variations across different firm sizes to inform policy development for Türkiye's circular economy transition.
***Methodology*:** The study employs the Törnqvist Productivity Index to measure total factor productivity changes from 2009 to 2023. It analyzes industry-level data from the Turkish Statistical Institute for micro, small, medium, and large firms within the E38 sector.
***Findings*:** Medium-sized firms demonstrate superior productivity performance with positive average TFP growth (0.0242), while large, micro, and small firms experience productivity declines (-0.0123, -0.0197, and -0.0228, respectively), which suggests an optimal balance of scale economies and managerial flexibility in medium-sized operations.
***Originality*:** This research presents the first comprehensive efficiency analysis of Türkiye’s Waste Management and Resource Recovery sector. It offers insights into productivity dynamics across different firm sizes and provides evidence-based recommendations for enhancing sector efficiency in an emerging economy context.
***Keywords*:** Productivity, Waste Management, Circular Economy, Firm Size, Törnqvist Index.
***JEL Codes*:** Q53, L25, O47, Q56, D24.

Türkiye’nin Atık Yönetimi ve Kaynak Geri Kazanımı Sektöründe Verimlilik Dinamikleri: Törnqvist Verimlilik Endeksi Kullanılarak Bir Analiz (2009-2023)

Amaç: Bu çalışma, Türkiye’nin Atık Yönetimi ve Kaynak Geri Kazanımı sektörünün endüstri düzeyinde ilk kapsamlı verimlilik analizini gerçekleştirmeyi amaçlamaktadır. Farklı firma büyüklükleri arasındaki üretkenlik farklılıklarını inceleyerek Türkiye’nin döngüsel ekonomi geçişine yönelik politika geliştirmeye katkı sağlamaktadır.
Yöntem: Çalışma, 2009’dan 2023’e kadar toplam faktör verimliliği değişimlerini ölçmek için Törnqvist Verimlilik Endeksi'ni kullanmaktadır. E38 sektöründeki mikro, küçük, orta ve büyük ölçekli firmalar için Türkiye İstatistik Kurumu’ndan elde edilen endüstri düzeyindeki verileri analiz etmektedir.
Bulgular: Orta ölçekli firmalar pozitif ortalama TFP büyümesi (0,0242) ile üstün verimlilik performansı gösterirken, büyük, mikro ve küçük firmalar verimlilik düşüşleri yaşamaktadır (sırasıyla -0,0123, -0,0197 ve -0,0228). Bu durum, orta ölçekli işletmelerde ölçek ekonomileri ile yönetsel esneklik arasında optimal bir denge olduğunu göstermektedir.
Özgünlük: Bu araştırma, Türkiye’nin Atık Yönetimi ve Kaynak Geri Kazanımı sektörünün ilk kapsamlı verimlilik analizini sunmaktadır. Farklı firma büyüklükleri arasındaki üretkenlik dinamikleri hakkında içgörüler sunarak gelişmekte olan bir ekonomi bağlamında sektör verimliliğini artırmaya yönelik kanıta dayalı öneriler sağlamaktadır.
Anahtar Kelimeler: Verimlilik, Atık Yönetimi, Döngüsel Ekonomi, Firma Büyüklüğü, Törnqvist Endeksi.
JEL Kodları: Q53, L25, O47, Q56, D24.

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1. INTRODUCTION

The circular economy has become central to global strategies aimed at reducing environmental impacts, optimizing resource utilization, and fostering economic growth. For instance, research suggests that a transition to circular economy practices could generate up to $4.5 trillion in additional economic output by 2030 (World Economic Forum, 2024). In this evolving paradigm, sustainable production and consumption models that minimize waste and maximize resource recovery are paramount. Waste management is a critical component of this approach, diverting waste from landfills, reintroducing materials into production cycles, and decreasing dependency on virgin resources. The scale of the challenge indicates its importance: about 2.01 billion tonnes of municipal solid waste are generated worldwide each year, a figure projected to rise to 3.40 billion tonnes by 2050 (Kaza et al., 2018: 3). These waste-management practices contribute directly to key Sustainable Development Goals, notably SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

Within this context, firms classified under NACE Code E38—*Waste Collection, Treatment, and Disposal Activities; Materials Recovery*—comprise what can be termed the Waste Management and Resource Recovery sector. This sector not only performs traditional waste management functions (such as collection, treatment, and disposal) but also embraces circular economy principles through materials recovery and resource reintegration. As economies move toward more sustainable practices, this sector has emerged as a fundamental pillar in achieving environmental protection, economic growth, and regulatory compliance (Bui et al., 2022).

The sector also plays a critical role in addressing environmental sustainability challenges. Waste recycling and resource recovery firms mitigate the negative externalities of industrial and consumer activities by reducing pollution, cutting greenhouse gas (GHG) emissions, and lowering reliance on finite natural resources. For example, the decay of organic waste in landfills contributes about 5% of global GHG emissions (United Nations Environment Programme, 2025)—a problem that effective waste management can help to curb. Without efficient waste management, economies face heightened risks of landfill overflow, plastic pollution, and hazardous waste accumulation, all of which contribute to ecological crises. Indeed, it is estimated that roughly one-third of global waste is mismanaged through open dumping or burning (Kaza et al., 2018), and each year, more than 8 million tonnes of plastic waste end up in the oceans (UNEP, 2017), which wreaks havoc on marine ecosystems. By processing and repurposing waste, firms in this sector actively prevent such environmental degradation and bolster global efforts to combat climate change.

Beyond environmental benefits, the waste management sector has significant economic implications. Globally, the waste management industry was valued at around $330 billion in 2017 and is expected to reach about $530 billion by 2025 (AMCS, 2025). The recycling industry also generates substantial employment opportunities; the United Nations estimates that recycling activities employ about 12 million people in just Brazil, China, and the United States alone (UNEP, 2025). At the national level, this sector can contribute appreciably to economies. For instance, in Spain, the recycling industry generated a turnover of approximately €3.1 billion in 2020. Moreover, metal waste accounts for over 60% of all recycled materials in Spain, with paper/cardboard contributing around 20% and wood/glass/plastic the remaining 20% (Parte and Alberca, 2024). These figures illustrate the economic potential of resource recovery, wherein industries benefit from cost savings on raw materials while nations reduce dependency on imported resources. In a broader European context, the European Commission has projected that increasing resource productivity by just 2% would create two million new jobs in the EU by 2030 (The Parliament Magazine, 2015), which highlights the wider socio-economic benefits of the circular economy transition.

From a policy perspective, waste management firms are crucial in helping countries meet ambitious regulatory targets. For example, the European Union's Waste Framework Directive has set progressive recycling objectives—requiring at least 55% of municipal waste to be recycled by 2025, 60% by 2030, and 65% by 2035. These targets reflect a strong commitment to a circular economy. Failure to meet such goals could result in economic penalties, environmental damage, and increased resource scarcity, which indicates the strategic importance of the waste management sector. This policy momentum is echoed globally; for instance, the United Nations Agenda 2030 calls for substantially reducing waste generation by 2030 (SDG 12.5), and many countries are implementing measures like extended producer responsibility to boost recycling and resource recovery. The alignment of industry practices with these policies is vital for achieving national and international sustainability objectives.

In brief, the Waste Management and Resource Recovery sector is far more than a logistical necessity; it is an essential component of a sustainable, circular, and economically viable future. Measuring the efficiency of this sector is therefore crucial for identifying opportunities to reduce environmental impacts, achieve cost savings, and enhance resource utilization. For example, Amaral et al. (2022) report an average inefficiency level of nearly 35% in solid waste management in Portugal, translating into a potential annual cost savings of over €96 million. This case demonstrates the significant economic and environmental gains that can be realized by improving efficiency in the waste management sector.

A robust body of literature has explored the environmental and operational efficiency of waste management and recycling activities across various contexts. Prior studies have evaluated efficiency in multiple settings, including dedicated recycling firms (e.g., Marques et al., 2012), urban waste management systems (e.g., Díaz-Villavicencio et al., 2017; Molinos-Senante et al., 2023), and municipal solid-waste recycling programs (e.g., Amaral et al., 2022; Expósito and Velasco, 2018). Research has also targeted specific waste streams and processes, such as metal recycling (e.g., Raz and Souza, 2018) and waste-to-energy gas management (e.g., Yang and Li, 2018). Comparative analyses at broader scales have examined regional performance in waste management (e.g., Argentiero et al., 2023; Romano et al., 2022).

Several studies have further investigated the determinants of efficiency in this sector, encompassing economic, business, social, and environmental factors. Researchers have highlighted that notable inefficiencies persist in both developed economies (e.g., Gardiner and Hajek, 2020; Ríos and Picazo-Tadeo, 2021) and emerging economies (e.g., Bui et al., 2022), which implies that even well-resourced systems have room for improvement. Various socioeconomic variables, such as income levels, population density, and education, have been examined to explain efficiency differentials, yet the empirical evidence remains mixed (Parte and Alberca, 2024), indicating the need for further investigation. Efficiency performance also varies widely at regional and municipal scales. Yang and Li (2018), for instance, report an unfavorable evolutionary trend over time in waste management efficiency across Chinese regions, while Expósito and Velasco (2018) find that only a few regions in Spain achieve full efficiency in solid waste reduction and recycling activities. Similarly, Ferraro et al. (2023) and Molinos-Senante et al. (2023) document significant efficiency shortfalls in certain municipalities. Business-level analyses echo these findings, with studies on waste and recycling firms revealing notable inefficiencies in their operations (e.g., Li et al., 2019; Marques et al., 2012). Methodologically, both parametric and nonparametric frontier approaches have been employed in this field; notably, a recent review by Mergoni and De Witte (2022**)** highlights the widespread use of nonparametric methods to evaluate environmental performance.

This study contributes to the growing body of research that employs nonparametric methods to assess efficiency by focusing specifically on Türkiye's Waste Management and Resource Recovery Sector at the industry level. Despite the critical importance of this sector for sustainable development and environmental management, no comprehensive efficiency analysis has yet been undertaken in Türkiye.

Türkiye's Twelfth Development Plan (2024–2028; Presidency of Strategy and Budget, 2023) outlines a comprehensive framework for transitioning toward a circular economy, placing a particular emphasis on sustainable production, consumption, and waste management practices. Central to this plan is the development of a National Circular Economy Action Plan, which seeks to adapt production processes and product designs to fully embrace circular principles. Complementing this strategic framework are initiatives designed to promote sustainable consumption patterns and ambitious waste management projects, such as the Zero Waste Project. Under this initiative, educational programs will be launched to raise public awareness, and the waste recovery rate is targeted to increase from 35% in 2023 to 42.5% by 2028—a goal that has garnered global recognition, including by the United Nations.

In addition to these demand-side reforms, the development plan prioritizes substantial technical and infrastructure advancements. A comprehensive database covering all aspects of waste management will be established, alongside the formulation of technical standards for recovered secondary products. Support measures will be implemented for transfer station projects in financially constrained local administrations and for the development of recovery and disposal facilities for municipal solid waste. Specific sectoral actions include the separate collection of industrial waste at its source, the creation of battery recycling systems, and the incorporation of forest products into the circular economy framework. Furthermore, legislative and policy measures will be strengthened to align raw material procurement, production, consumption, and waste management processes with international standards, with additional reinforcement provided by green public procurement strategies and improved incentive legislation. Environmental protection remains a core focus, with targeted efforts to mitigate the harmful impacts of waste on human health and ecosystems, prevent marine debris, and promote environmental labeling to boost the competitiveness of eco-friendly products and services.

Understanding the total productivity of Türkiye's Waste Management and Resource Recovery Sector is essential in this context. Given the ambitious targets and extensive reforms outlined in the development plan, a detailed assessment of industry-level productivity can provide crucial insights into how efficiently firms convert inputs into valuable outputs. Such an analysis not only reveals overall operational performance but also identifies specific areas where policy interventions may be necessary. Moreover, considering the diversity in firm sizes within the sector, it is important to recognize that productivity levels may vary significantly among small, micro, medium, and large enterprises. While medium and large firms often benefit from economies of scale, greater access to advanced technologies, and more robust financial resources, small and micro firms may face substantial challenges, such as financial constraints and limited capacity for technological innovation, that can hinder efficiency improvements. Consequently, an industry-level productivity analysis that accounts for firm size differences is vital, as it enables policymakers and industry stakeholders to design targeted support measures that address the unique needs of each firm category, thereby ensuring that the strategic objectives of Türkiye's circular economy and waste management initiatives are met effectively.

In this analysis, we evaluate productivity changes in Türkiye's E38 sector—Waste Collection, Treatment, and Disposal Activities; Materials Recovery—using industry-level data to determine how efficiently firms convert inputs into economic outputs. Key inputs are defined as the number of employees, personnel costs, and total purchases of goods and services, while outputs are measured by value added at factor cost and turnover. Data sourced from the Turkish Statistical Institute underwent trend-based imputation for missing values and was adjusted to real terms using the annual producer price index. Employing the robust Törnqvist index method to measure total factor productivity (TFP) change from 2009 to 2023, our findings reveal significant disparities across firm sizes: medium-sized firms exhibit the highest productivity, whereas large, micro, and small firms have experienced productivity declines.

2. DATA AND METHODOLOGY

2.1. Data and Variables

In this analysis, we examine productivity changes in the Turkish sector E38 – Waste Collection, Treatment, and Disposal Activities; Materials Recovery—using industry-level data to assess how efficiently firms transform inputs into economic outputs over time. Given the central role of labor, operational costs, and material inputs in this sector, our study defines inputs as the number of employees, personnel costs, and total purchases of goods and services. The number of employees is a key measure of labor input, which reflects the human resources engaged in waste management and recycling processes. Personnel costs, which include wages, salaries, and associated social security expenses, capture the financial commitment to labor and provide insight into the cost structure of firms. Total purchases of goods and services represent intermediate inputs, such as equipment, fuel, and outsourced services, that are essential for the collection, transportation, and processing of waste materials.

On the output side, the analysis employs value added at factor cost and turnover as indicators of economic performance. Value added at factor cost, computed by subtracting intermediate costs from total output, serves as a fundamental measure of efficiency by representing the net economic contribution of firms. Turnover, or total revenue, reflects the financial success of firms in the waste management and recycling market by accounting for sales generated from waste collection services, treatment processes, and recovered materials. Together, these output indicators provide a comprehensive perspective on the sector's ability to generate economic value from waste recovery and disposal activities.

The data used in this study is sourced from the Turkish Statistical Institute (TurkStat, 2024). The dataset is derived from the Annual Industry and Service Statistics Survey conducted by the Institute. This survey compiles data from various administrative records—including the Annual Industry and Service Statistics, Foreign Trade Statistics, Research and Development Activities Statistics, Entrepreneurship and Business Demography Statistics, as well as the patent application and registration records from the Turkish Patent and Trademark Office—with the exception of investment variables covered by the Annual Industry and Service Statistics.

In addition, the analysis incorporates the classification of Small and Medium-sized Enterprises (SMEs) as defined by recent legislative changes implemented in 2023. Under these revised thresholds, micro enterprises are characterized as firms employing fewer than 10 workers annually with an annual net sales turnover or balance sheet total not exceeding 10 million Turkish Lira; small enterprises are defined as those employing fewer than 50 workers and with annual net sales or balance sheet totals not exceeding 100 million Turkish Lira; and medium-sized enterprises are those employing fewer than 250 workers with annual net sales or balance sheet totals not exceeding 500 million Turkish Lira.

The scope of the data is determined by the sectoral coverage of the Annual Industry and Service Statistics, which is based on the NACE Rev.2 classification system used within the European Community. The data encompasses annual observations from 2009 to 2023. For clarity, key definitions are provided in Table 1.

Table 1. Definitions of the input and output variables

Variables	*Definitions*
Inputs	
Number of Employees	The total number of individuals employed under an employment contract for an employer who receives remuneration in the form of salary, wage, commission, bonus, piece-rate payment, or in-kind compensation.
Personnel Cost (in Turkish Lira)	The total of gross payments to personnel and social security expenses.
Total Purchases of Goods and Services (in Turkish Lira)	The value of all goods and services acquired during the accounting period for consumption or resale in the production process, excluding the consumption of capital goods recorded as fixed capital consumption.
Outputs	
Turnover (in Turkish Lira)	The aggregate value of invoiced sales of goods and services by the observation unit during the reference period.
Value Added at Factor Cost (in Turkish Lira)	The net output generated by firms, calculated after adjustments for operating subsidies and indirect taxes.

Source: TurkStat (2024)

However, some missing observations in this dataset arise due to legal restrictions on data disclosure, specifically Law No. 5429 on Official Statistics in Türkiye. According to this regulation, data for any cell in the dataset are withheld if the number of enterprises in that category is fewer than three. Additionally, even when the number of enterprises is three or more, the data remains undisclosed if one or two firms dominate the sector. Consequently, some missing values exist in firm-size disaggregated data.

To address these missing values while maintaining data integrity, a trend-based imputation approach was applied, ensuring that missing values followed observed temporal patterns. Given the time-series nature of the data, different imputation methods were employed based on the statistical properties of each variable.

Firstly, for variables exhibiting a linear trend, missing values were estimated using a simple linear regression model in Equation 1.

$$X_t = \alpha + \beta t + \varepsilon_t \tag{1}$$

where X_t represents the variable of interest at time t, α is the intercept, β captures the trend slope and ε_t is the error term. Missing values were predicted based on the estimated regression coefficients. For variables following a quadratic trend, a second-degree polynomial regression was applied, as shown in Equation 2.

$$X_t = \alpha + \beta t + \gamma t^2 + \varepsilon_t \tag{2}$$

where γ captures the acceleration or deceleration of growth. This method was particularly relevant for variables displaying non-constant growth rates over time. For variables exhibiting exponential trends, a log-transformation was used before applying linear regression, as expressed in Equation 3.

$$\ln(X_t) = \alpha + \beta t + \varepsilon_t \tag{3}$$

where predicted values were exponentiated to retrieve the original scale, as described in Equation 4.

$$\hat{X}_t = e^{\hat{\alpha}+\hat{\beta}t} \tag{4}$$

ensuring that the estimated values maintained an exponential growth pattern.

A key principle guiding the imputation process was the preservation of summation constraints inherent in the dataset's aggregation structure. Specifically, for each economic variable, the industry total is the sum of its constituent firm categories: micro, small, medium, and large firms—as given in Equation 5.

$$X_t^{\text{total}} = X_t^{\text{micro}} + X_t^{\text{small}} + X_t^{\text{medium}} + X_t^{\text{large}} \tag{5}$$

When missing values were imputed for one or more firm categories, the estimates were adjusted proportionally to ensure that the summation constraint held. If only one firm category was missing in a given period, its value was derived using Equation 6.

$$X_t^{\text{missing}} = X_t^{\text{total}} - \sum X_t^{\text{observed}} \tag{6}$$

For multiple missing firm categories, an allocation rule based on historical shares was applied, as shown in Equation 7.

$$X_t^{\text{missing},i} = X_t^{\text{total}} \times \frac{\bar{X}^i}{\sum \bar{X}^i} \tag{7}$$

where $\bar{X}^i$ represents the historical mean share of the firm category i relative to the total. Finally, to prevent abrupt fluctuations in imputed values, smoothing techniques such as moving averages were applied according to Equation 8.

$$\tilde{X}_t = \frac{1}{k}\sum_{i=t-k}^{t+k} X_i \tag{8}$$

where k represents the smoothing window size. This helped maintain continuity in variables exhibiting gradual trends. Additionally, non-negativity constraints were enforced to ensure that variables such as employment and production value were not assigned implausible negative values, as given in Equation 9.

$$X_t = \max\left(0, \hat{X}_t\right) \tag{9}$$

Outliers arising from imputation were systematically reviewed, and extreme values were Winsorized using Equation 10.

$$X_t = \min(\max(X_t, P_1), P_{99}) \tag{10}$$

where P_1 and P_{99} denote the 1st and 99th percentiles, which ensures that imputed values remained within a plausible range.

After imputing the missing observations, nominal values were adjusted to real terms using the producer price index calculated at the end of each year. Consequently, all subsequent analyses were conducted using real values of the variables.

2.2. Descriptive Statistics

After imputing missing observations and adjusting the variables for real terms, we present the descriptive statistics for the Turkish waste collection, treatment, disposal, and materials recovery sector (E38) in Table 2. The analysis is conducted separately for firms of different sizes, including micro, small, medium, and large enterprises, as well as for the total industry and SMEs as an aggregate category. The key variables examined include the number of employees, personnel costs, total purchases of goods and services, turnover, and value-added at factor cost.

The distribution of employment across firm sizes reflects expected patterns, with larger firms employing significantly more workers on average. Over 2009–2023, micro firms, on average, employed 3,285 individuals, while small and medium firms employed approximately 6,488 and 10,019 workers, respectively. Large firms, by contrast, had an average workforce of 32,359 employees. The standard deviation for large firms is also considerably high, which indicates substantial variation in employment levels within this category. This suggests that while some large firms operate with a relatively lean workforce, others employ a significantly higher number of workers, which reflects differences in operational scale and business models.

Personnel costs similarly increase with firm size, which highlights economies of scale and the labor intensity of operations in this sector. Across the total industry from 2009 to 2023, micro firms incurred an average personnel cost of 543.8 million Turkish Lira (TL) in 2023 prices, while large firms allocated 10.14 billion TL to labor expenses. The variability in personnel costs, as measured by the standard deviation, was again highest among large firms, which suggests greater diversity in compensation structures and employment strategies.

The analysis of total purchases of goods and services, which serves as a proxy for input expenditures, reveals that over the 2009–2023 period, micro firms spent approximately 6.44 billion TL in 2023 prices on average, whereas large firms allocated 36.56 billion TL to purchasing goods and services. SMEs as a collective entity recorded the highest average spending in this category, at 64.52 billion TL, which shows their significant role in the sector's supply chain and production processes.

Turnover, which reflects total revenue, followed a similar pattern, increasing with firm size. Over the 2009–2023 period, micro firms generated an average turnover of 6.54 billion TL, while large firms achieved 54.35 billion TL in 2023 prices. The total industry turnover stood at 118 billion TL, indicating that large firms continued to dominate overall revenue generation despite SMEs contributing a substantial share. This highlights the strong market position of large firms, which likely benefited from broader market reach and higher capital investment levels.

Value-added at factor cost, which measures the economic contribution of firms after accounting for input costs, further illustrates the differences across firm sizes. Over the 2009–2023 period, micro firms contributed approximately 509 million TL in value-added, compared to 15.4 billion TL in 2023 prices for large firms. SMEs, taken together, generated 8.45 billion TL in value-added, accounting for a significant proportion of the total industry's 24.59 billion TL. This indicates that while large firms held a dominant position in absolute financial metrics, SMEs collectively played a crucial role in generating economic value within the sector.

Another notable finding is the high degree of variation in financial performance across large firms throughout the 2009–2023 period. The standard deviations for turnover, personnel costs, and purchases were considerably higher in this category, which shows the heterogeneous nature of large enterprises in the industry. In contrast, micro and small firms exhibited lower variability, which suggests that their operational and financial structures were more uniform.

Overall, these findings indicate the crucial role of SMEs in the waste collection and recycling sector, particularly in employment generation and total input purchases. However, large firms continued to lead in turnover and value-added.

2.3. Methodology

After presenting the descriptive statistics about inputs and outputs, we introduce the Törnqvist Productivity Index. The Törnqvist index method is widely recognized as a robust price-based index number approach for measuring total factor productivity (TFP) change (Törnqvist, 1936). Its primary advantage lies in providing a second-order approximation of the underlying production technology, which enhances its precision in capturing the nuances of production behavior over short periods (Rehman and Nunziante, 2023; See and Coelli, 2014). This capability is particularly valuable when analyzing productivity changes on an annual basis or when the magnitude of change is relatively small, which offers a more accurate representation than first-order methods such as the Laspeyres index (Coelli, 2002: 171).

A notable strength of the Törnqvist index is its use of dynamic weighting. In contrast to fixed-weight indices that rely solely on base-year weights, the Törnqvist method employs average cost shares as weights for the input quantity index and average revenue shares as weights for the output quantity index. This approach enables the index to effectively capture shifts in the relative importance of inputs, such as capital and labor, and thereby reflect substitution effects between these factors (Rehman and Nunziante, 2023). This flexibility is particularly advantageous in sectors characterized by labor-intensive technologies, where the role of human capital is paramount in the production process.

The method's applicability is further enhanced in contexts where comprehensive panel data are unavailable. Studies focusing on single firms or utilities have demonstrated the efficacy of the Törnqvist index in measuring productivity changes. For instance, its application in analyses of Tenaga Nasional Berhad in Malaysia (See and Coelli, 2014) and in productivity assessments of airline companies (See and Abdul Rashid, 2023) underscores its practical utility. Although the method does not facilitate the decomposition of TFP change into distinct components such as technical change and efficiency change (Rungsuriyawiboon and Coelli, 2006: 269), its superior approximation capabilities render it a favorable alternative to other index methods like the Laspeyres and Fisher indices (Marques, 2011; Bergamini et al., 2010). Empirical research over the decades has further solidified the standing of the Törnqvist index in productivity analysis.

The calculation of the Törnqvist Productivity Index is based on weighted geometric means of input and output quantity indices. The index is defined as the ratio of the Törnqvist Output Quantity Index to the Törnqvist Input Quantity Index. For a given period s (base period) and t (comparison period), the Törnqvist Input and Output Indices are calculated as in Equation 11 and Equation 12, respectively.

$$Törnqvist\ Input\ Quantity\ Index: Q_{st}^{I} = \prod_{n=1}^{N} \left[\frac{X_{nt}}{X_{ns}}\right]^{\frac{\omega_{ns}+\omega_{nt}}{2}} \quad (11)$$

where X_{nt} and X_{ns} represent the quantities of input n at times t and s. ω_{ns} and ω_{nt} are the cost shares of input n at times s and t. The exponent $\frac{\omega_{ns}+\omega_{nt}}{2}$ ensures that the index is weighted by the average cost share of each input.

$$Törnqvist\ Output\ Quantity\ Index: Q_{st}^{O} = \prod_{j=1}^{M} \left[\frac{Y_{jt}}{Y_{js}}\right]^{\frac{\gamma_{js}+\gamma_{jt}}{2}} \quad (12)$$

where Y_{jt} and Y_{js} represent the quantities of output j at times t and s. γ_{js} and γ_{jt} are the revenue shares of output j at times s and t. The exponent $\frac{\gamma_{js}+\gamma_{jt}}{2}$ ensures that the index is weighted by the average revenue share of each output. Using these indices, the Törnqvist Total Factor Productivity (TFP) Index is calculated as in Equation 13.

Table 2. Descriptive statistics

Scale	*Variable*	*Mean*	*Std. Dev.*	*Min*	*Max*	*Median*
Total	Number of Employees	51,313.20	12,159.08	37,099.00	70,204.00	45,703.00
	Personnel Cost (in million Turkish Lira)	16,693.36	6,078.91	8,657. 97	27,683.14	15,176.31
	Total Purchases of Goods and Services (in million Turkish Lira)	98,352.98	31,319.80	31,700.85	137,582.77	99,380.59
	Turnover (in million Turkish Lira)	118,022.66	32,843.45	46,228.26	167,396.01	129,022.31
	Value Added at Factor Cost (in million Turkish Lira)	24,590.19	6,121.04	13,932.94	36,503.88	23,980.29
Micro	Number of Employees	3,285.02	1,771.54	768.00	6,221.00	3,082.00
	Personnel Cost (in million Turkish Lira)	543.77	264.16	162.18	965.37	543.77
	Total Purchases of Goods and Services (in million Turkish Lira)	6,440.59	2,875.97	1,974.41	11,362.94	6,319.87
	Turnover (in million Turkish Lira)	6,539.20	2,886.75	2,010.40	11,310.96	6,373.21
	Value Added at Factor Cost (in million Turkish Lira)	508.93	223.80	199.55	905.28	508.93
Small	Number of Employees	6,487.59	2,167.64	2,849.00	9,779.86	6,492.00
	Personnel Cost (in million Turkish Lira)	1,506.36	497.96	603.21	2,279.73	1,509.09
	Total Purchases of Goods and Services (in million Turkish Lira)	23,427.26	11,353.38	8,577.63	44,185.82	20,612.03
	Turnover (in million Turkish Lira)	24,487.40	11,737.81	9,475.89	47,775.47	22,767.46
	Value Added at Factor Cost (in million Turkish Lira)	2,944.93	1,099.95	843.45	4,552.95	2,855.33
Medium	Number of Employees	10,018.73	2,081.88	5,715.00	14,134.00	10,647.00
	Personnel Cost (in million Turkish Lira)	2,978.12	799.11	1,502.08	4,595.22	2,998.69
	Total Purchases of Goods and Services (in million Turkish Lira)	34,323.18	15,131.94	8,069.72	60,419.02	31,966.49
	Turnover (in million Turkish Lira)	37,788.94	15,556.01	10,170.74	62,784.62	36,057.36
	Value Added at Factor Cost (in million Turkish Lira)	5,299.75	1,597.54	2,195.70	7,669.80	5,532.41
SMEs	Number of Employees	19,935.85	5,477.82	9,332.00	27,962.77	20,964.00
	Personnel Cost (in million Turkish Lira)	4,751.27	985.19	3,270.63	6,161.78	4,750.29
	Total Purchases of Goods and Services (in million Turkish Lira)	64,520.75	26,801.15	24,106.01	101,990.23	58,898.39
	Turnover (in million Turkish Lira)	70,210.74	26,631.22	30,763.49	105,953.19	65,198.03
	Value Added at Factor Cost (in million Turkish Lira)	8,449.63	2,296.13	4,963.95	11,711.21	8,447.32
Large	Number of Employees	32,358.90	12,023.44	15,847.00	48,764.00	33,383.00
	Personnel Cost (in million Turkish Lira)	10,140.23	1,861.90	7,135.16	12,990.12	10,142.12
	Total Purchases of Goods and Services (in million Turkish Lira)	36,559.82	9,552.10	19,890.51	57,215.31	37,876.33
	Turnover (in million Turkish Lira)	54,354.91	12,792.66	32,913.90	79,828.46	54,393.94
	Value Added at Factor Cost (in million Turkish Lira)	15,438.63	2,636.24	11,585.06	19,790.88	15,227.98

$$TFP_{st} = \frac{Q_{st}^{O}}{Q_{st}^{I}} \tag{13}$$

Expanding the formula in Equation 14, we get the ratio that represents the change in productivity between periods s and t, capturing changes in output relative to input usage.

$$TFP_{st} = \frac{\Pi_{j=1}^{M}\left[\frac{Y_{jt}}{Y_{js}}\right]^{\frac{\gamma_{js}+\gamma_{jt}}{2}}}{\Pi_{n=1}^{N}\left[\frac{X_{nt}}{X_{ns}}\right]^{\frac{\omega_{ns}+\omega_{nt}}{2}}} \tag{14}$$

Thus, the Törnqvist Productivity Index relies on weighted geometric means of input and output indices. In its original multiplicative form, the Törnqvist Input Quantity Index is computed as the geometric mean of input ratios weighted by the average cost shares, while the Törnqvist Output Quantity Index follows a similar approach using output revenue shares. The productivity index is then obtained as the ratio of these two indices. However, this multiplicative framework can be cumbersome in empirical applications due to numerical instability arising from potential underflow or overflow in product-based computations. To address these challenges, a logarithmic transformation is commonly applied, which converts products into sums and simplifies calculations. By taking the natural logarithm of both sides, the Törnqvist Productivity Index can be rewritten as the difference between the log-transformed output and input indices. This transformation ensures computational stability and aligns with standard economic models, where productivity growth is typically expressed as the difference between output and input growth rates. Additionally, the log-difference approach provides a direct measure of relative changes in productivity, making it more interpretable for economic analysis.

Taking the natural logarithm of both sides as in Equation 15.

$$\ln TFP_{st} = \ln Q_{st}^{O} - \ln Q_{st}^{I} \tag{15}$$

Expanding each term as in Equation 16 and Equation 17.

$$\ln Q_{st}^{O} = \sum_{j=1}^{M} \frac{\gamma_{js}+\gamma_{jt}}{2} \cdot \ln\left(\frac{Y_{jt}}{Y_{js}}\right) \tag{16}$$

$$\ln Q_{st}^{I} = \sum_{n=1}^{N} \frac{\omega_{ns}+\omega_{nt}}{2} \cdot \ln\left(\frac{X_{nt}}{X_{ns}}\right) \tag{17}$$

Thus, the log-differenced TFP index as displayed in Equation 18.

$$\ln TFP_{st} = \sum_{j=1}^{M} \frac{\gamma_{js}+\gamma_{jt}}{2} \cdot \ln\left(\frac{Y_{jt}}{Y_{js}}\right) - \sum_{n=1}^{N} \frac{\omega_{ns}+\omega_{nt}}{2} \cdot \ln\left(\frac{X_{nt}}{X_{ns}}\right) \tag{18}$$

Given the log transformation, the Törnqvist Productivity Index (TFP Change) between periods s and t is computed in Equation 19 as:

$$\Delta\ln TFP_{t} = \Delta\ln Q_{t}^{O} - \Delta\ln Q_{t}^{I} \tag{19}$$

Equation 20, Equation 21, and Equation 22 display the content of this index.

$$\Delta\ln Q_{t}^{O} = \sum_{j=1}^{M} S_{j,t} \cdot \left(\ln Y_{j,t} - \ln Y_{j,t-1}\right) \tag{20}$$

$$\Delta\ln Q_{t}^{I} = \sum_{n=1}^{N} W_{n,t} \cdot \left(\ln X_{n,t} - \ln X_{n,t-1}\right) \tag{21}$$

$$\Delta\ln TFP_{t} = \sum_{j=1}^{M} S_{j,t} \cdot \left(\ln Y_{j,t} - \ln Y_{j,t-1}\right) - \sum_{n=1}^{N} W_{n,t} \cdot \left(\ln X_{n,t} - \ln X_{n,t-1}\right) \tag{22}$$

where $S_{j,t}$ and $W_{n,t}$ are the average revenue and cost shares across two periods. Output growth minus input growth gives the TFP change.

3. RESULTS

Figure 1 presents the annual changes in Total Factor Productivity (TFP) for different firm sizes—micro, small, medium, and large—within the Turkish waste collection, treatment, disposal, and materials recovery sector (E38) over the period 2009–2023. The TFP change, which is calculated using the Törnqvist Productivity Index, captures the efficiency improvements or declines in transforming inputs into outputs over time. A positive TFP change indicates an increase in productivity, while a negative change suggests a decline in efficiency relative to the previous year. The dotted horizontal line at zero serves as a reference point, distinguishing years of positive efficiency growth from years of decline.

Over the observed period, all firm types exhibit fluctuations in TFP growth, which reflects periods of efficiency gains and downturns. The most volatile trends are observed for micro firms, which experience frequent and sharp deviations from the zero line. Thus, smaller firms are more sensitive to external shocks, regulatory changes, or shifts in market conditions. Large and medium-sized firms, while also experiencing fluctuations, tend to exhibit more stabilized patterns over time, with relatively smaller deviations from the mean compared to micro firms. Small firms demonstrate a mix of volatility and occasional stability, aligning closer to medium-sized firms in certain periods.

A notable trend is the occurrence of sharp declines in TFP change across all firm types around economic downturns (e.g., post-2009 financial crisis, the mid-2010s, and the pandemic period around 2020). The early 2010s and 2020s appear to be particularly challenging for firm productivity, likely due to macroeconomic instability, rising costs, and disruptions in waste management and recycling activities. However, periods of recovery are also visible, as seen in post-recession rebounds, particularly in later years.

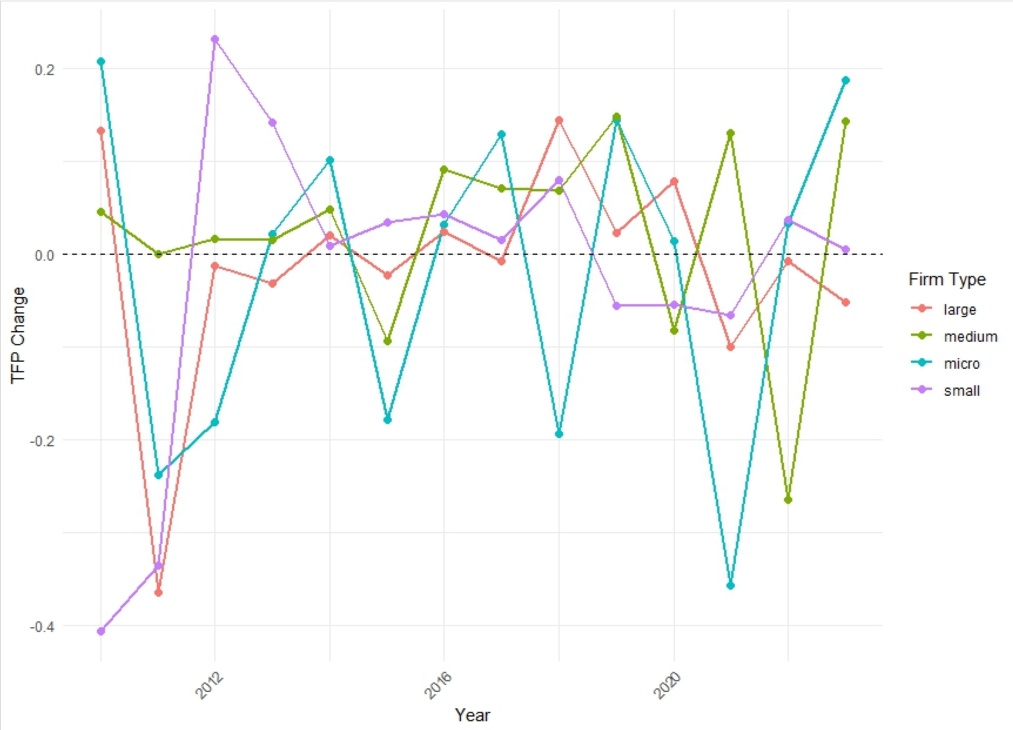

Figure 1. Tornqvist Productivity Index changes over time

Table 3 presents the average TFP change, calculated using the Törnqvist Productivity Index, for different firm sizes in the Turkish waste collection, treatment, disposal, and materials recovery sector (E38) over the period 2009–2023. The results highlight a notable divergence in productivity performance across different firm sizes. Medium-sized firms demonstrate the highest average TFP change (0.0242), which indicates consistent efficiency improvements over the observed period. This suggests that these firms may have benefited from a balance of economies of scale and flexibility, which allows them to adapt to industry changes more efficiently than their counterparts. In contrast, large, micro, and small firms all exhibit negative average TFP change, which implies a decline in efficiency over the years. Among these, large firms (-0.0123) experience a relatively moderate decline. Micro (-0.0197) and small firms (-0.0228) show the most significant declines in TFP change, which indicates that these enterprises faced persistent productivity challenges throughout 2009–2023. These results are also visualized in Figure 2.

Table 3. Average total factor productivity changes over 2009-2023

Sector	*Average Total Factor Productivity Change over 2009-2023*
Medium	0.0242
Large	-0.0123
Micro	-0.0197
Small	-0.0228

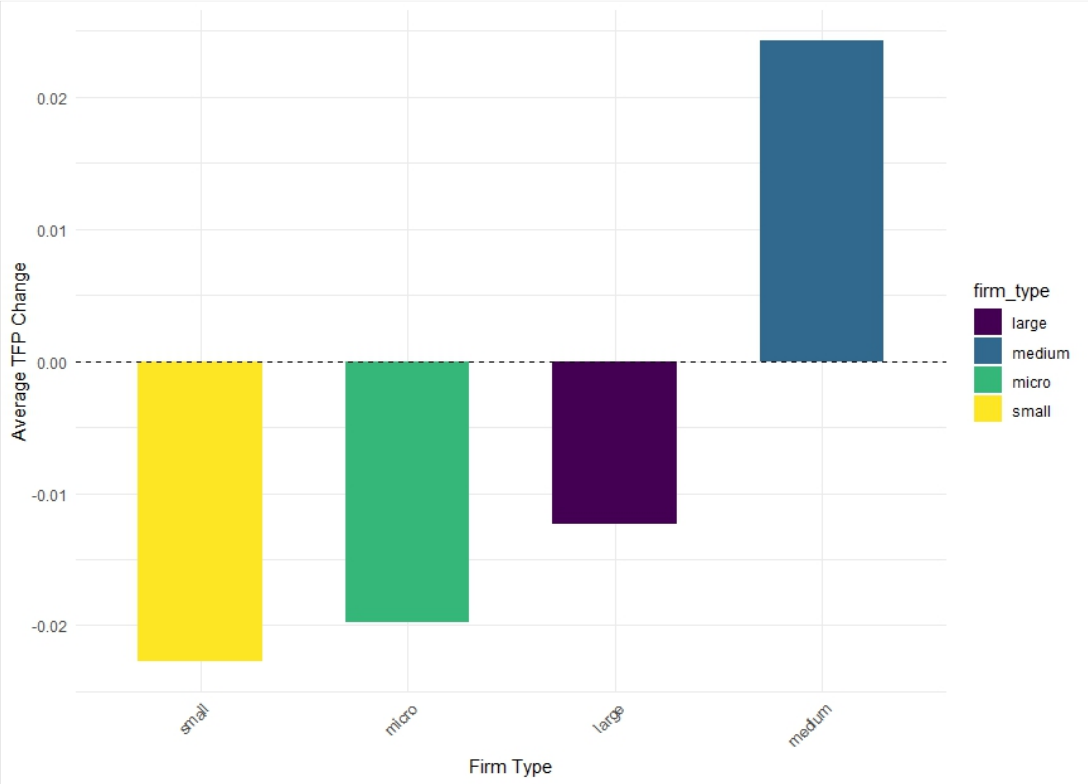

Figure 2. Average Tornqvist Productivity Index change by firm type

4. DISCUSSION and CONCLUSION

This study contributes to the literature by presenting the first comprehensive efficiency analysis of Türkiye's Waste Management and Resource Recovery sector at an industry-wide level. To the best of our knowledge, no prior research has evaluated this sector's efficiency in Türkiye, despite its crucial role in the country's sustainable development and environmental management. By examining an emerging-economy context at a national scale, our analysis fills an important gap in the literature and offers new insights into the performance of Türkiye's waste management sector.

Our analysis of total factor productivity changes in Türkiye's E38 sector for the period 2009–2023 reveals marked disparities in efficiency trends across different firm sizes. Medium-sized firms consistently emerge as the most productive segment. These firms appear to benefit from an optimal balance between scale economies and managerial flexibility, which enables them to adapt more efficiently to market conditions and regulatory changes. In contrast, large, micro, and small firms have experienced productivity declines. Large firms may face bureaucratic inertia and complex operational structures that hinder rapid adjustments, while micro and small firms often encounter resource constraints and limited access to advanced technologies, which restricts their ability to achieve scale and realize efficiency improvements.

Our size-specific results confirm earlier evidence on productivity in waste management and recycling activities. The persistent underperformance of micro and small enterprises mirrors the efficiency gaps documented for emerging-economy recyclers by Bui et al. (2022), and it echoes the broader cross-country pattern in which the labor productivity of smaller firms is typically one-half that of their larger peers (McKinsey Global Institute, 2024). What sets Türkiye apart is the markedly positive TFP growth of medium-sized enterprises—a size class that, in many OECD industries, tends to lag behind large firms (OECD, 2024: 51). In short, our findings extend the literature by showing that the productivity leader in an emerging circular-economy sector need not be the largest corporation but rather the firm size that balances technological capability with adaptable governance structures.

The heterogeneity observed in productivity dynamics within the sector has important policy implications. First, targeted support for micro and small firms is essential. In the short term, improving their access to financing through low-interest loans or grants could alleviate immediate resource constraints. Additionally, capacity-building initiatives, such as specialized training programs and technical assistance, could empower these smaller operators to adopt modern technologies and best practices. For example, experience from several European countries suggests that tailored financial support and technical training for small waste management enterprises have led to measurable improvements in operational efficiency and productivity (OECD, 2016: 241; Cialani and Mortazavi, 2020).

Large firms, on the other hand, could benefit from efficiency-driven strategies such as process optimization and digital transformation. Short-term interventions might include the implementation of digital management systems and advanced analytics to streamline operations. In the longer term, policies should encourage these firms to invest in automation, Internet of Things (IoT) technologies, and other forms of digital infrastructure that can reduce operational inefficiencies and enhance decision-making (e.g., Cheah et al., 2022; Muirova et al., 2022).

Ensuring the continued growth of medium-sized firms—the sector's most efficient segment—should remain a strategic priority. These firms not only drive overall sector productivity but also serve as models of best practices. In the long term, a robust framework that promotes the scaling of best practices can reinforce the role of medium-sized enterprises as the backbone of the sector.

In summary, this study not only highlights significant productivity disparities across different firm sizes in Türkiye's Waste Management and Resource Recovery sector but also underscores the need for targeted policy interventions. By supporting micro and small firms with enhanced financing and capacity-building measures, encouraging large firms to embrace digital transformation and process optimization, and promoting the sustained growth of medium-sized enterprises, policymakers can foster an environment in which the entire sector becomes more efficient, competitive, and aligned with national and global sustainability objectives.

Building on these insights, several avenues merit exploration. First, firm-level or panel micro-data would allow the decomposition of TFP change into technical progress, scale effects, and pure efficiency, thereby revealing whether medium-sized firms improve primarily through innovation, learning-by-doing, or resource reallocation. Second, future studies should test causal links between digital-process adoption (e.g., IoT-enabled fleet routing, AI-based sorting) and productivity, given recent evidence of efficiency gains from such technologies in waste services (Cheah et al., 2022). Third, integrating environmental outputs (avoided CO_2-eq., recycled tonnage) into a joint productivity/eco-efficiency framework would clarify whether economic gains coincide with environmental gains. Finally, cross-country comparisons covering other upper-middle-income economies would test the generalizability of the "medium-firm advantage."

Conflict of Interest
No potential conflict of interest was declared by the authors.

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Compliance with Ethical Standards
It was declared by the author that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement
It was declared by the author that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

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