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Investigation of Corporate Sustainability Performance Data and Developing an Innovation-Oriented Novel Analysis Method with Multi-Criteria Decision Making Approach

Huseyin Haliloglu [1,*], Ahmet Feyzioglu [1], Leonardo Piccinetti [2], Trevor Omoruyi [3], Muzeyyen Burcu Hidimoglu [1] and Akin Emrecan Gok [4]

1 Department of Mechanical Engineering, Institute of Pure and Applied Sciences, Marmara University, Istanbul 34722, Türkiye; ahmet.feyzioglu@marmara.edu.tr (A.F.); burcuhidimoglu@marun.edu.tr (M.B.H.)
2 Sustainable Innovation Technology Services Ltd., Ducart Suite, V94 Y6FD Limerick, Ireland; leonardo@sinnovations.org
3 Chester Business School, University of Chester, Chester CH1 4BJ, UK; t.omoruyi@chester.ac.uk
4 Department of Environmental Engineering, Istanbul University-Cerrahpaşa, Istanbul 34320, Türkiye; akinemrecan.gok@ogr.iuc.edu.tr
* Correspondence: huseyinhaliloglu@marun.edu.tr

Abstract

This study addresses the growing importance of integrating innovation into corporate sustainability strategies by examining the financial and environmental performance of ten firms listed on the Borsa Istanbul Sustainability Index over a five-year period. The main objective is to develop and test a novel, data-driven analytical framework that reduces reliance on subjective expert judgments while providing actionable insights for sustainability-oriented decision-making. Within this framework, the entropy method from the Multi-Criteria Decision Making (MCDM) approach is first applied to calculate the objective weights of sustainability criteria, ensuring that the analysis is grounded in real performance data. Building on these weights, an innovative reverse Decision-Making Trial and Evaluation Laboratory (DEMATEL) model, implemented through a custom artificial neural network-based software, is introduced to estimate direct influence matrices and reveal the causal relationships among criteria. This methodological advance makes it possible to explore how environmental and financial factors interact with R&D expenditures and to simulate their systemic interdependencies. The findings demonstrate that R&D serves as a central driver of both environmental and financial sustainability, highlighting its dual role in fostering corporate innovation and long-term resilience. By positioning R&D as both an enabler and outcome of sustainability dynamics, the proposed framework contributes a novel tool for aligning innovation with strategic sustainability goals, offering broader implications for corporate managers, policymakers, and researchers.

Keywords: sustainability; innovation; corporate strategy; multi-criteria decision-making; entropy; DEMATEL; roadmap development; strategic analysis

1. Introduction

In the face of accelerating global environmental challenges and complex financial pressures, corporate sustainability has become a central strategic concern. Increasingly, firms recognize that sustainable outcomes arise from synergy between environmental stewardship and financial performance. Recent research confirms that organizations prioritizing innovation—especially green innovation—can generate both ecological and economic

value [1]. Therefore, exploring the dynamic interplay between financial and environmental sustainability, mediated by innovation investments such as R&D, is critical.

Innovation, particularly via R&D, is widely acknowledged as essential for sustainability. Green innovation strategies not only drive environmental improvement but often deliver significant productivity gains [1]. Firms with ambitious R&D agendas are more likely to implement cleaner processes, reduce emissions, and enhance sustainable product offerings—leading to cost reductions, regulatory compliance, and improved brand reputation [2,3]. Moreover, empirical evidence shows that in high-pollution industries, green innovations achieve financial returns comparable to conventional innovations [1]. These findings underscore R&D's dual role in reinforcing both dimensions of sustainability.

The contemporary literature reveals that financial and environmental performance are not independent; rather, they mutually reinforce one another in innovation-driven firms. The Sustainability Accounting Standards Board (SASB) framework emphasizes that firms addressing financially material sustainability factors outperform peers in both financial returns and stock market valuation. Meanwhile, sustainable finance initiatives, including the EU taxonomy and green bonds, are shifting investor preferences toward companies that integrate environmental outcomes into core financial strategies. These developments affirm that firms must adopt integrated strategies that deliver both financial resilience and environmental stewardship.

Given these intertwined goals, strategic decision-making becomes increasingly complex, requiring consideration of multiple, often conflicting criteria. MCDM methods like Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Entropy have risen to prominence in fields from renewable energy to circular economy, enabling balanced assessments across financial, environmental, and technical dimensions [4,5]. Specifically, Entropy-based weighting methods offer objective, data-driven criterion weights and have been effectively combined with methods like TOPSIS, Analytic Network Process (ANP), and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) for sustainable decision-making [5]. Despite its heuristic weighting, Entropy does not directly reveal causal influences among criteria—a challenge addressed by DEMATEL, which models interdependencies within decision systems. Recent hybrid methodologies have integrated Entropy weighting with DEMATEL to create comprehensive evaluation frameworks. Such integration helps uncover cause–effect relationships, enabling strategic insight into how R&D expenditures influence both financial and environmental performance.

The objective of this study is to design and apply a novel reverse DEMATEL approach, supported by artificial neural network-based software, that reconstructs inter-criteria influence matrices from Entropy-derived weights. This addresses the gap in the existing literature by allowing sustainability strategies to be evaluated without reliance on subjective expert input, while still revealing the systemic interdependencies among financial and environmental indicators.

Methodologically, the study analyzes five years of sustainability performance data for ten companies listed in the Borsa Istanbul Sustainability Index. In the first stage, Entropy was used to calculate objective weights for environmental and financial sustainability indicators. Next, a reverse DEMATEL algorithm reconstructed direct-relation matrices from these weights, simulating how expert judgments might have appeared. Finally, R&D expenditures were integrated as a central bridging criterion, and systemic interactions were visualized through influence maps. The main findings reveal that environmental indicators such as greenhouse gas emissions and energy consumption exert strong influences on R&D spending, while profitability-related financial indicators are more strongly shaped by R&D rather than driving it. This asymmetry highlights R&D's central role in strengthening both

environmental and financial performance. Furthermore, the analysis identified firm-specific strategic insights, such as the need for emission-focused innovation in high-pollution industries and capital structure adjustments in financially constrained firms.

The structure of the paper is as follows: Section 2 describes the methodology in detail, including the Entropy weighting process and the Artificial Neural Network (ANN)-based reverse DEMATEL approach. Section 3, titled "Discussion and Conclusions," presents and interprets the analytical outputs, enabling the study's research questions and hypotheses to be discussed and evaluated directly within the context of the results. This integrated approach allows the findings to be framed not only as analytical outcomes but also as evidence-based answers to the guiding questions and hypotheses of the study.

2. Materials and Methods

This section first surveys the sustainability-oriented MCDM literature to position our contribution within prior work and motivate a data-driven, low-subjectivity design. It then details the dataset, firm selection rules, indicator set and coding scheme (environmental and financial criteria, including the dual role of R&D), together with preprocessing and normalization procedures used to ensure comparability across firms and years. Next, Section 2.1 presents the Entropy weighting procedure and reports the resulting objective criterion weights. Section 2.2 introduces the novel ANN-enabled reverse DEMATEL model, explaining the inverse mapping from entropy-derived weights to direct-relation matrices, the network architecture and training setup, and the computation of total influence and cause–effect scores. We then describe the evaluation protocol—cross-validation and robustness checks (architectural sensitivity, noise perturbation), and evaluation metrics (MSE, MAE, Jacobian and Frobenius norms)—used to assess stability and generalizability.

If we examine the literature, research using MCDM to support sustainability decisions spans energy systems, circular economy, green supply chains, water resources, urban planning, transportation, and corporate environmental, social and governance (ESG) evaluation. Foundational methods such as AHP/ANP, TOPSIS, PROMETHEE, DEMATEL, and Entropy are frequently combined to balance environmental, economic, and social criteria under uncertainty and trade-offs [6,7]. The areas and scope of these studies are stated below.

Renewable energy planning and siting: Numerous studies deploy AHP/ANP, TOPSIS, and VIKOR to rank or site wind and solar farms using criteria such as resource potential, land use, biodiversity constraints, grid proximity, and cost. For instance, Kahraman et al. [8] applied fuzzy AHP–VIKOR to select renewable energy alternatives in Türkiye.

Energy policy and portfolio selection: MCDM has been used to prioritize national or regional energy portfolios by balancing cost, reliability, security of supply, and emissions. Pohekar and Ramachandran [9] reviewed energy MCDM applications, and more recent work by Wang et al. [10] demonstrated entropy-based weighting combined with PROMETHEE for sustainable energy planning.

Circular economy and waste management: DEMATEL and its fuzzy variants are often applied to map cause–effect structures among barriers and enablers. For example, Tseng et al. [11] applied fuzzy DEMATEL to analyze barriers to circular economy adoption in China. Similarly, Luthra et al. [12] used Grey-DEMATEL to evaluate sustainability criteria in supply chains.

Green supply chain management: MCDM methods are widely used to evaluate suppliers and logistics strategies. Büyüközkan and Çifçi [13] applied fuzzy AHP–TOPSIS for green supplier selection, while Govindan et al. [7] integrated DEMATEL to understand interdependencies among criteria in sustainable supply-chain management.

Water resources and environmental management: MCDM has supported reservoir operation, watershed protection, and wastewater technology selection. Hajkowicz and Collins [14] applied MCDM to water resource management, while Chen et al. [15] combined entropy and TOPSIS to evaluate logistic capability, which is also effective for sustainability factors.

Urban and transport sustainability: Studies use MCDM to rank public transport options, bike-lane networks, or low-emission zones. Macharis and Bernardini [16] reviewed transport MCDM applications, and Mutambik [17] used PROMETHEE for evaluating the sustainability of smart cities.

Corporate sustainability and ESG assessment: Firm-level applications use Entropy, AHP to construct composite sustainability scores. For instance, Lozano [18] reviewed frameworks for corporate sustainability measurement, while Hsu et al. [19] applied DEMATEL to evaluate suppliers in terms of green supply chain management.

Innovation-centric MCDM: A growing body of research models R&D and eco-innovation as levers linking environmental gains with financial performance. Bai et al. [20] applied DEMATEL to analyze circular economy performance, while Liu et al. [21] used grey-DEMATEL and ANP to evaluate mutual effects in sustainable industry with a focus on product-service systems.

Khaw et al. [22] used MCDM to analyze how firms' behaviors shaped sustainability and circular economy through eco-innovation in Iraq's energy sector, Wang & Yang [23] used a hybrid MCDM approach (Fuzzy AHP and Fuzzy TOPSIS) to evaluate green innovation aspects and their effects on sustainability performance in China's manufacturing industry, Zhao et al. [24] applied DEMATEL to assess service innovation strategies for sustainable banking in China's Fintech context and Musaat et al. [25] applied fuzzy AHP and TOPSIS approach to evaluate and rank small and medium enterprises in Saudi Arabia based on green innovation ability.

Adams & Ghaly [26] used multi-criteria analysis to assess sustainable by-product technologies in the Costa Rican coffee industry, Zhou et al. [27] used composite indicators to build a sustainability index for an industrial case, Afrasiabi et al. [28] used a hybrid fuzzy MCDM approach combining the fuzzy best–worst method, grey relational analysis, and TOPSIS to solve sustainable–resilient supplier selection problems in the manufacturing industry, Saraswat & Digalwar [29] used fuzzy AHP to rank sustainable energy sources for India, Nguyen et al. [30] combined data envelopment analysis with hybrid MCDM method to select sustainable suppliers in Vietnam's steel industry.

Taken together, these works reveal two main patterns: (i) some methods provide objective weighting but lack causal interpretation; (ii) some methods map cause–effect structures but rely on subjective expert panels. Our study also responds to this gap by proposing an ANN-based reverse DEMATEL that reconstructs causal interdependencies directly from objective entropy weights, with R&D as the central bridging factor between environmental and financial dimensions. What sets our research apart is its dual focus on strategic-level guidance and operational-level insight: we not only quantify the interrelations among sustainability indicators but also interpret how R&D investments shape—and are shaped by—both ecological and economic performance. By doing so, we furnish decision-makers with a precise roadmap linking innovation inputs to sustainability outcomes, thus enabling targeted refinement of R&D strategies tailored to each firm's context. This advancement embeds analytical rigor and practical relevance, delivering a tool that informs both corporate governance and policy formulation. The advantages of the developed original method over existing methods are also presented in the table included in Appendix C.

Building on this foundation, our study extends beyond methodological novelty by explicitly positioning R&D expenditures as the analytical centerpiece that bridges environ-

mental and financial sustainability. Unlike many prior works that assess these domains in isolation, our framework enables a systematic comparison of financial and ecological indicators within a single, integrated model. This dual perspective provides two critical contributions: first, it offers a strategic roadmap by identifying which sustainability levers are most responsive to innovation-oriented investments; second, it delivers a diagnostic overview of how firms' current practices align—or misalign—with long-term sustainability objectives. By quantifying the bidirectional influence pathways between R&D, financial strength, and environmental responsibility, the analysis yields actionable insights that can guide corporate decision-makers in refining sustainability strategies, optimizing resource allocation, and enhancing resilience in the face of global ecological and economic challenges.

To guide the study, we explicitly formulate the research questions and hypotheses that frame the analytical design. Building on the literature on innovation-driven sustainability, the following questions are addressed:

Research Question 1: How do environmental indicators influence R&D expenditures and, conversely, how does R&D shape environmental outcomes?

Research Question 2: How do financial indicators influence R&D expenditures and, conversely, how does R&D shape financial outcomes?

Research Question 3: How do sectoral characteristics (e.g., energy-intensive vs. technology-oriented industries) moderate the bidirectional interactions between R&D expenditures and sustainability indicators?

Research Question 4: How do short-term financial constraints (e.g., liquidity or equity levels) differ from long-term structural factors (e.g., total assets) in influencing R&D investments, and what are their reciprocal impacts?

Research Question 5: To what extent do innovation-driven improvements in environmental indicators (e.g., energy efficiency, waste reduction) translate into measurable enhancements in financial sustainability?

Research Question 6: How robust are the reconstructed interdependencies when applied to cross-sectoral or international benchmarks, and do they align with global sustainability standards?

From these questions, we derive testable hypotheses:

Hypothesis 1. *Higher pressures from greenhouse gas emissions are associated with greater R&D intensity, while increased R&D intensity leads to reductions in emissions over time.*

Hypothesis 2. *Energy and water consumption drive R&D expenditures through efficiency and cost pressures; in turn, R&D efforts reduce these resource intensities.*

Hypothesis 3. *Waste generation and recycling performance are positively linked with R&D in circular economy processes, whereby R&D promotes waste reduction and reuse.*

Hypothesis 4. *Profitability metrics (operating and net profit) enable greater R&D investment via financial resources, while R&D activities enhance profitability through efficiency and productivity gains.*

Hypothesis 5. *Balance sheet items such as assets and equity exert weaker short-term influence on R&D but benefit from R&D in the long term through asset expansion and structural strengthening.*

This explicit formulation clarifies the relationships under investigation and provides a structured lens for interpreting the directional influence results generated by the ANN-assisted reverse DEMATEL approach.

In this study, performance data disclosed in the sustainability and integrated reports of ten publicly traded companies listed on the Borsa Istanbul Sustainability Index—namely Aksa Akrilik Kimya Sanayii A.Ş. (AKSA), Arçelik A.Ş. (ARCLK), Çimsa Çimento Sanayi ve Ticaret A.Ş. (CIMSA), Enerjisa Enerji A.Ş. (ENJSA), Ford Otomotiv Sanayi A.Ş. (FROTO), Türkiye Şişe ve Cam Fabrikaları A.Ş. (SISE), Tekfen Holding A.Ş. (TKFEN), Tofaş Türk Otomobil Fabrikası A.Ş. (TOASO), Türkcell İletişim Hizmetleri A.Ş. (TCELL), and Ülker Bisküvi Sanayi A.Ş. (ULKER)—over a five-year period (2018–2022) were examined. The analysis includes firms operating in diverse industries such as chemicals, metallurgy, white goods, construction, energy, automotive, telecommunications, and food. By analyzing their environmental and financial sustainability performance indicators from an innovation-oriented perspective, this study aims to present a more comprehensive and objective understanding of the role of innovation activities in sustainable development and green economy transitions.

The environmental sustainability performance criteria analyzed in the study include total energy consumption (MWh), total water consumption (m^3), reused/recycled waste (tons), total waste generated (tons), total greenhouse gas emissions (tons CO_2), and R&D expenditures (thousand TRY). The financial sustainability indicators, expressed in thousand TRY, include sales revenue, operating profit, net profit, total assets, equity, and R&D expenditures. It is noteworthy that R&D expenditures are considered as a criterion under both environmental and financial sustainability dimensions. The criteria have been coded as follows: total energy consumption as C1, total water consumption as C2, reused waste amount as C3, total waste amount as C4, total greenhouse gas emissions as C5, sales revenue as C6, operating profit as C7, net profit as C8, total assets as C9, shareholders' equity as C10, and R&D Expenditures as C.

By comparing the influence of R&D on both environmental and financial performance criteria, the study quantitatively establishes the interconnection between these two dimensions. This analytical integration enables the modeling of interactions between financial and environmental sustainability using mathematical techniques. The relationship between financial and environmental sustainability, and their potential mutual reinforcement, is vital for the notion of sustainable governance. Institutions that attempt to fulfill environmental obligations but suffer financially—thereby compromising social sustainability—or those that are financially strong yet neglect environmental responsibility, illustrate the need for strategic alignment. One of the key functions of global sustainability frameworks is to ensure that institutions adopting sustainable practices can access affordable financing, thereby strengthening their financial sustainability trajectory.

2.1. Weighting Sustainability Criteria Using the Entropy Method

The entropy method, rooted in Shannon's information theory, offers an objective, data-driven approach to determining criterion weights within MCDM frameworks. Unlike subjective weighting methods, entropy calculates weights based on the degree of diversification within the dataset: criteria exhibiting greater variance among alternatives provide more information and receive higher weights. This objectivity reduces personal bias, resulting in more reliable and reproducible assessments.

In recent applications, the entropy method has been widely integrated into sustainability-related research. For instance, Petrović et al. [31] employed entropy–TOPSIS to evaluate transport sustainability systems across Serbia, finding that higher entropy values correspond to key criteria such as greenhouse gas emissions. Similarly, Masca and Genç [32] applied entropy–Complex Proportional Assessment (COPRAS) to assess EU countries' sustainability performance, objectively identifying net GHG emissions as the most influ-

ential criterion. These studies affirm entropy's suitability for environmental and social sustainability assessments due to its reliance on unbiased statistical information.

Industry 4.0 and renewable energy sectors have also leveraged entropy-based weight assignments. Jameel et al. [33] combined entropy with Stepwise Weight Assessment Ratio Analysis (SWARA) and Combined Compromise Solution CoCoSo to optimize renewable energy solutions, demonstrating robust, step-wise weight allocation for integrated systems. In smart manufacturing, Anjum et al. [34] introduced an entropy hybrid within an intuitionistic fuzzy framework to optimize energy efficiency, underscoring entropy's adaptability to complex systems.

Urban infrastructure and airport sustainability planning also benefit from entropy-based approaches. Mizrak et al. [35] employed entropy along with fuzzy linguistic techniques to prioritize sustainability initiatives at Istanbul Airport, highlighting entropy's capability to reflect real-world variability in performance indicators.

The process steps of the entropy method are as follows:

Step 1: definition of decision matrix:

$$X = \left[x_{ij}\right]_{mxn} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}; i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{1}$$

In Equation (1); x_{ij} represents the performance of the ith year for the jth criterion, m represents the number of performance years, and n represents the number of criteria.

Step 2: creating the decision matrix by normalizing:

$$v_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{2}$$

In Equation (2), v_{ij} means the normalized value of alternative A_i with respect to C_j. x_{ij} indicates the absolute value of alternative A_i with respect to C_j; m is the total number of alternatives evaluated.

Step 3: calculating the entropy value of the criteria:

$$e_j = -k\sum_{i=1}^{m} v_{ij} ln(v_{ij}) = -\frac{1}{ln(m)} \sum_{i=1}^{m} v_{ij} ln(v_{ij}) \tag{3}$$

In Equation (3), logarithms e and e_j are in the range [0, 1], and j is the criterion number.

Step 4: calculating the degree of differentiation:

$$d_j = 1 - e_j, \ j \in [1, \ldots, n] \tag{4}$$

Step 5: finding the criteria weighting:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{5}$$

Performance data of the companies whose sustainability reports, financial reports, activity reports and integrated reports have been examined have been compiled and shown in the tables in Appendix A.

Based on the compiled performance data of all ten firms operating across diverse sectors, the entropy method was systematically applied to objectively determine the relative importance (weights) of sustainability criteria. First, a decision matrix was constructed using normalized values of the selected indicators, including environmental sustainability criteria (e.g., total energy consumption, water usage, total and recycled waste, greenhouse

gas emissions, and R&D expenditures) and financial sustainability indicators (e.g., sales revenue, operating profit, net profit, total assets, equity, and R&D expenditures). Following the normalization process, entropy values for each criterion were calculated to measure the degree of disorder or variability across firms. These entropy scores were then used to compute divergence values, which reflect the amount of useful information contributed by each criterion. Finally, normalized divergence values were used to determine the objective weights of each sustainability indicator. Through this method, R&D expenditures emerged as a unique criterion appearing under both environmental and financial domains, facilitating the quantitative exploration of its bridging role. The entropy-based weighting procedure ensured a transparent, unbiased evaluation of sustainability dimensions, laying the groundwork for further inter-criteria influence analysis in the subsequent reverse DEMATEL modeling phase.

The criterion weights obtained through the entropy method are presented in the tables below. These weights reflect the objective significance of each sustainability indicator based on the degree of variation observed across the five-year performance data of the selected firms. By quantifying the informational contribution of each criterion, the entropy method eliminates subjectivity and provides a data-driven foundation for multi-criteria evaluation. The resulting weight distributions offer insights into which environmental and financial factors exhibit greater influence within the sustainability performance profiles of the firms. The tables also highlight the central role of R&D expenditures, which appear across both environmental and financial dimensions, further supporting the innovation-centered analytical approach adopted in this study.

According to Table 1, an analysis of the weights assigned to environmental sustainability criteria reveals that the highest-weighted indicators are total greenhouse gas (GHG) emissions, R&D expenditures, and the amount of recycled waste. For TCELL, a telecommunications company, total energy consumption received the highest weight among all criteria, which aligns with its business model focused on digital services, tech-fin, messaging, and data-based solutions. This outcome reflects the efficiency gains derived from the increased integration of Industry 4.0 applications within the firm. Notably, total GHG emissions also received the second-highest weight for TCELL, further emphasizing the role of energy efficiency in emission reduction.

Table 1. Environmental Sustainability Criteria Weights of Companies.

	C1	C2	C3	C4	C5	C
AKSA	0.215670666	0.003181268	0.081042761	0.061579774	0.250078405	0.388447126
ARCLK	0.004932845	0.00735011	0.009699618	0.009852835	0.737875632	0.23028896
CIMSA	0.150810775	0.312659332	0.067771865	0.088918132	0.029907875	0.349932021
ENJSA	0.275904795	0.00072607	0.002145876	0.069234207	0.41433879	0.237650261
FROTO	0.020543222	0.009874068	0.016250552	0.016093161	0.802081652	0.135157344
SISE	0.004556816	0.009850847	0.719360267	0.069861229	0.00570678	0.190664061
TKFEN	0.057492179	0.03704701	0.205430472	0.266732511	0.127009772	0.306288055
TOASO	0.022545747	0.027803018	0.021125641	0.021312864	0.003496172	0.903716558
TCELL	0.506344453	0.040633579	0.040726234	0.040726234	0.350399771	0.021169729
ULKER	0.000128598	0.001321589	0.040804199	0.001893823	0.679016379	0.276835412
Average	0.12589301	0.045044689	0.120435749	0.064620477	0.339991123	0.304014953

Conversely, total GHG emissions were assigned relatively lower weights for companies such as CIMSA (cement), SISE (glass manufacturing), TKFEN (construction-focused conglomerate), and TOASO (automotive). For CIMSA, the highest-weighted criteria were water consumption and R&D expenditures. At SISE, R&D also had significant weight, but the most influential environmental criterion was the amount of recycled waste. TKFEN showed a balanced distribution across environmental criteria, with R&D expenditures, total waste, and recycled waste having the highest weights. This indicates a potential future increase in the weight of GHG emissions as R&D efforts continue to contribute to emission reductions. In TOASO's case, low current GHG emissions—due to highly efficient production lines—have led to a greater emphasis on R&D, which is a strategic priority for the technologically dynamic automotive sector.

The companies with the highest weight assigned to total GHG emissions were ARCLK, ENJSA, FROTO, and ULKER. Among them, ARCLK stood out with a significantly higher weight for this criterion, reflecting its strong commitment to green innovation within a structured corporate sustainability framework.

When examining the average weights across all firms, total GHG emissions, R&D expenditures, total energy consumption, recycled waste, total waste, and water consumption emerged as the most influential environmental sustainability criteria, in that order.

According to Table 2, an analysis of the financial sustainability criterion weights reveals that R&D expenditures do not represent the highest-weighted criterion for any of the firms under consideration. Instead, the most influential criteria vary among sales revenue, operating profit, and net profit. However, R&D expenditures received the highest relative weight among financial indicators for TOASO and ULKER.

Table 2. Financial Sustainability Criteria Weights of Companies.

	C6	**C7**	**C8**	**C9**	**C10**	**C**
AKSA	0.15442604	0.212353023	0.347705888	0.064934213	0.107477068	0.113103768
ARCLK	0.223826324	0.136221269	0.212034766	0.19580314	0.114195218	0.117919283
CIMSA	0.132720806	0.137722275	0.527786356	0.064384317	0.102107558	0.035278688
ENJSA	0.156523177	0.079421508	0.512881968	0.059219141	0.098261331	0.093692874
FROTO	0.136840013	0.20672066	0.242310267	0.180925304	0.133176271	0.100027485
SISE	0.176174313	0.185912689	0.214742309	0.137666489	0.152625306	0.132878895
TKFEN	0.056676863	0.269741314	0.38806009	0.06107542	0.037056415	0.187389899
TOASO	0.11614145	0.237091416	0.245716275	0.084491608	0.082490708	0.234068543
TCELL	0.15991998	0.186785732	0.203926434	0.162724261	0.145297761	0.141345831
ULKER	0.162177772	0.254910516	0.217531784	0.102609336	0.034485543	0.22828505
Average	0.147542674	0.19068804	0.311269614	0.111383323	0.100717318	0.138399032

When examining the average weights across all firms, the most influential financial criteria were, in order: net profit, operating profit, sales revenue, R&D expenditures, total assets, and shareholders' equity. These results clearly indicate that, in the context of firms' financial decision-making strategies, R&D expenditures are prioritized more than the expansion of total assets or equity capital.

This finding underscores the critical importance of accessing low-cost financing. For companies to expand operations, strengthen competitive advantage, and implement more environmentally responsible and sustainable practices through increased R&D activity, financial sustainability must be enhanced. As a result, firms that place

a stronger emphasis on R&D will be better positioned to prioritize green innovation and environmental stewardship.

2.2. Implementation of Reverse DEMATEL Approach via the Developed Custom Software Tool

The DEMATEL method is a robust MCDM technique designed to identify and quantify the causal interrelationships among complex decision factors [36,37]. Fundamentally, DEMATEL generates a direct-influence matrix based on expert or data-driven judgments, applies normalization and thresholding procedures, and computes total influence and dependence scores for each criterion [38]. The result is a cause–effect digraph that interprets which criteria act as influential drivers versus dependent recipients—an analytical edge particularly valuable for sustainability evaluations [39].

In sustainability research, DEMATEL has found extensive application: for instance, it was used to model the interdependence of circular-economy barriers, climate resilience factors in urban infrastructure, and green supply-chain management systems [40,41].

The DEMATEL method is a structured MCDM approach that enables the analysis of cause–effect relationships among factors within complex systems. The DEMATEL process follows a systematic sequence of steps, which are outlined as follows:

Step 1: creating the first direct relationship matrix

In this step, the influence of each criterion on the others is evaluated by experts and recorded in a direct-relation matrix. The influence score represents the effect of the row criterion on the column criterion. The scoring is carried out on a scale from 0 to 4, where 0 indicates "no influence" and 4 indicates "very high influence." Since the self-influence of criteria is not considered, the diagonal elements of the matrix are assigned a value of zero. Accordingly, the influence of the criterion in the row on the criterion in the column is systematically quantified to reflect the perceived causal relationships.

Step 2: creation of the initial normalized matrix D

$$S = min\left(\frac{1}{max\sum_{j=1}^{n} a_{ij}}, \frac{1}{max\sum_{i=1}^{n} a_{ij}}\right) \tag{6}$$

To determine the value of **S**, the sum of the elements in each row and each column of the initial direct-relation matrix must be calculated separately. Among all the computed totals, the highest value is designated as S. To obtain the D matrix (the normalized direct-relation matrix), each value in the initial direct-relation matrix is divided by the **S** value.

Step 3: finding the total relationship matrix T

$$T = D \times (I - D)^{-1} \tag{7}$$

In this equation, the I value represents the identity matrix.

Step 4: calculating the importance and impact value for each criterion

$$R_i = \sum_{j=1}^{n} t_{ij} \tag{8}$$

$$C_j = \sum_{i=1}^{n} t_{ij} \tag{9}$$

Initially, the R and C values are calculated using the appropriate formulas. The sum R + C represents the prominence or overall importance of a criterion, while the difference R − C indicates the relation, revealing whether a criterion is predominantly a cause (positive value) or an effect (negative value) in the system. Here, R values are obtained by summing each row of the total relation matrix (T matrix), whereas C values are calculated as the sum of each column of the same matrix.

Step 5: calculating the threshold value and creating the cause–effect diagram

The threshold value (TS) is calculated as the average of all elements in the total relation matrix (T matrix). Whether a value in the T matrix is above or below this threshold determines the presence of an influence between the corresponding criteria. If a value in a particular cell of the T matrix exceeds the TS value, it indicates that the criterion corresponding to the row exerts an influence on the criterion corresponding to the column.

Step 6: finding criterion weights

$$w_{ia} = \sqrt{(R+C)^2 + (R-C)^2} \tag{10}$$

$$w_i = \frac{w_{ia}}{\sum_{i=1}^{n} w_{ia}} \tag{11}$$

As can be seen from the formulas, the criterion weights are calculated using both the prominence (R + C) and the relation (R − C) values.

As previously explained, the first step in the application of the DEMATEL method is the construction of the initial direct-relation matrix, which requires expert evaluations. Although these experts possess significant domain knowledge, the method inherently incorporates a degree of subjectivity. However, the novel approach developed in this study addresses a key question: *How would a subjective method like DEMATEL interpret the results obtained through an objective method such as Entropy?* Furthermore, it allows us to infer how decision-makers—those who shape corporate strategy—might have evaluated the interrelationships among the criteria, had they applied a traditional subjective approach.

This novel reverse-engineered approach contributes significantly to the literature by bridging the gap between objective and subjective weighting methods within MCDM frameworks. While traditional DEMATEL relies on expert judgment, which may vary across evaluators and contexts, the proposed model reconstructs the direct-relation matrix using known entropy-derived weights. This allows researchers and practitioners to simulate how expert-based interdependencies might have been perceived if the same criteria weights were obtained through a subjective method. In doing so, the methodology not only enhances methodological transparency but also provides a valuable tool for organizations seeking to align quantitative assessments with expert-driven strategic planning. By centering the analysis around R&D expenditures and their dual role in both environmental and financial sustainability, the model offers a practical lens for innovation-oriented sustainability strategies.

In this study, an artificial neural network-based model was developed to reverse-engineer the DEMATEL method, which is frequently employed in MCDM frameworks. The Python 3.13.7 implementation of the novel method is shared in Appendix B.

In the classical DEMATEL approach, the decision-makers assess the direct influence matrix (D) based on expert judgments, which is subsequently transformed into a total influence matrix (T), and ultimately used to derive the weights of the criteria. However, in certain practical cases, only the final criterion weights may be available, necessitating the reconstruction of the underlying causal interaction structure that produced those weights.

In the proposed method, known criterion weights are treated as input, and the approximate corresponding direct influence matrix is estimated. Due to the nonlinear relationships between these variables, solving this inverse problem using classical statistical techniques is challenging. Therefore, a multi-layer artificial neural network architecture was employed. The model was designed to accept 6 inputs (criterion weights) and produce 36 outputs corresponding to the elements of a 6×6 direct influence matrix. The training dataset consisted of various firms' weight vectors, and the corresponding D matrices were synthetically generated using outer product logic. The ANN architecture consisted of an input layer with 64 neurons, two hidden layers with 128 and 64 neurons, respectively, and an output

layer with 36 neurons. The ReLU (Rectified Linear Unit) activation function was used throughout, while the Adam optimization algorithm was employed to minimize the mean squared error (MSE) loss function. After training, the model was able to reliably estimate the corresponding D matrix for any new set of criterion weights. This novel approach allows reverse inference in DEMATEL analysis, offering insights not only into the resulting weights but also into the underlying interdependencies among the criteria.

This model presents a practical and innovative solution that is particularly useful when expert judgment is unavailable or when externally determined weights need to be interpreted in terms of causal structure. The approach is also compatible with other AI-based models and hybrid decision support systems.

Also in this study, the ANN-based reverse DEMATEL model was subjected to a series of robustness and sensitivity analyses in order to examine the reliability and stability of the results. The results of robustness and sensitivity analyses are also reported in Appendix B. The purpose of these tests was to evaluate how sensitive the model is to variations in its architecture (e.g., number of layers, neurons, and activation functions), to small perturbations in the input data, and to changes in sampling strategies. Such analyses are particularly important when dealing with relatively small datasets, as they provide insights into the consistency and robustness of the model. ANNs are widely recognized for their ability to capture complex nonlinear relationships, adapt flexibly to diverse problem structures, and generalize effectively from limited samples [42,43]. Studies further highlight that ANN models outperform traditional statistical methods in predictive accuracy and offer scalable architectures that can be tailored to sustainability and decision-making contexts [44].

Data Structure: The input data consist of weight vectors defined across six sustainability-related criteria (e.g., energy consumption, greenhouse gas emissions, waste generation). Each set of weights was represented as a six-dimensional vector. The outputs were constructed as 6×6 direct-relation matrices, generated via the outer product of the criterion weights, thereby capturing the causal interactions among the criteria.

Evaluation Metrics;

MSE (Mean Squared Error): Represents the average squared difference between predicted and actual values. Lower values indicate better predictive accuracy.
MAE (Mean Absolute Error): Refers to the mean of absolute deviations between predicted and observed values, offering an interpretable measure of average error magnitude.
Jacobian Norm: A measure of local sensitivity that captures how small changes in input weights affect the predicted outputs. Lower norms imply greater stability.
Frobenius Norm: Used to quantify differences between matrices. In this context, it measures how much the predicted direct-relation matrices change when small random perturbations (noise) are introduced to the inputs.

Analytical Procedures:

Architectural Sensitivity: By varying the number of layers, neurons, and activation functions, it was observed that a three-layer architecture with ReLU activation (64–128–64 neurons) provided the most consistent and reliable results.
Cross-Validation: K-fold cross-validation was applied to test the model on different subsets of the data. The results showed that the model maintained consistent accuracy levels across folds, confirming its generalizability.
Noise Robustness: Input vectors were perturbed with small amounts of Gaussian noise, and the resulting changes in outputs were analyzed using Frobenius norms. The relatively small deviations observed indicated that the model produced stable outputs under input fluctuations.

Local Sensitivity (Jacobian Norms): Gradient-based analysis revealed how responsive each output was to changes in the input criteria. The relatively narrow range of Jacobian norms suggested that the model performed a smooth and well-conditioned mapping from inputs to outputs.

Model performance was evaluated using MSE and MAE to measure predictive accuracy, Jacobian and Frobenius norms to demonstrate model stability, and k-fold cross-validation to confirm generalizability across different data subsets [45,46].

Overall, the findings demonstrate that the ANN-based reverse DEMATEL model is stable, consistent, and reliable under a variety of tests. The chosen architecture achieved low and stable error values (MSE and MAE) and showed resilience to small variations in inputs. The robustness analyses confirmed that the model is not only an innovative methodological contribution but also a practically applicable and trustworthy tool. These results underscore the potential of ANN-driven reverse DEMATEL as a valid approach for analyzing complex sustainability interactions, combining predictive capacity with methodological robustness.

The empirical scope of the study covers ten firms consistently listed on the Borsa Istanbul Sustainability Index over the period 2018–2022. These firms represent a diverse set of industries, including chemicals, glass, white goods, construction, energy, automotive, telecommunications, and food. Selection was guided by three inclusion criteria: (i) continuous listing in the Index for the entire five-year window; (ii) complete or harmonizable disclosure of the selected financial and environmental indicators; and (iii) explicit reporting of R&D expenditures. Data were retrieved from publicly available sustainability, integrated, financial, and activity reports (see Appendix A).

The design results in a balanced panel dataset of ten firms across five years, ensuring comparability across industries while maintaining temporal consistency. No imputation was applied to missing data points; instead, the study followed a conservative approach of excluding incomplete observations to preserve the integrity of the entropy-based weighting. The sample provides a strategically diverse cross-section that reflects both industrial heterogeneity and the central role of innovation in corporate sustainability.

While the study necessarily involves quantitative computations, the analytical workflow extends far beyond "applying a calculation method." The research integrates three methodological pillars: (i) entropy-based weighting to derive objective importance of sustainability criteria, (ii) ANN-assisted reverse DEMATEL to reconstruct directional interdependencies among criteria without reliance on subjective expert panels, and (iii) robustness and sensitivity diagnostics (architectural sensitivity, k-fold cross-validation, noise perturbation, and Jacobian-based local sensitivity) to ensure reliability of the outputs (see Appendix B).

This triadic framework transforms the analysis from simple evaluation into systemic modeling. Specifically, it enables the tracing of how R&D expenditures simultaneously act as drivers and outcomes within environmental and financial sustainability domains. Influence digraphs and bidirectional maps derived from the reconstructed matrices provide decision-makers with clear strategic guidance on which sustainability levers are most critical. Thus, the contribution of this study lies not in the mechanical execution of formulas but in the development of an integrated, reproducible, and innovation-oriented decision-support tool with both theoretical significance and practical value.

3. Discussion and Conclusions

Section 3 presents and interprets the results of the proposed model. Section 3.1 compiles and evaluates DEMATEL direct-impact matrices for environmental and financial sustainability criteria. Section 3.2 integrates these results to examine the bidirectional

interactions with R&D expenditures, and Section 3.3 synthesises the findings by directly addressing the research questions and hypotheses.

Following the implementation of the novel method, the direct-relation matrices of environmental and financial criteria obtained through the reverse DEMATEL approach are presented below. In this study, the criterion weights that were originally derived through the Entropy method by processing sustainability performance data were further utilized as the foundation for constructing direct impact matrices. To enable a meaningful comparison, these matrices, which are essential for reproducing the DEMATEL methodology, were generated using the proposed inverse DEMATEL model. The resulting outputs are compiled and reported in the subsequent section.

Subsequently, the direct-relation matrix data were subjected to the computational framework of Equations (8) and (9). Through these formulations, the degree of influence exerted by each criterion on the others, as well as their relative importance, was systematically quantified. The impact levels of the criteria are explicitly discussed under Section 3.1, where explanatory notes accompany the corresponding tables. Moreover, the integrated evaluation of financial and environmental sustainability criteria, with a central focus on R&D expenditures, has been carried out in Section 3.2.

This approach not only provides a robust analytical framework but also ensures that both subjective and objective perspectives converge—allowing for a holistic assessment of sustainability performance within the context of corporate innovation strategies.

3.1. Compilation and Evaluation of DEMATEL Direct Impact Matrices for Companies' Environmental and Financial Sustainability Criteria

The interaction dynamics of environmental sustainability criteria for AKSA, as revealed through the DEMATEL analysis, present notable findings. R&D Expenditures emerge as the central determinant within the system, possessing both the highest total influence score (D + R = 6.66) and the most prominent "cause" role (D − R = 0.90). This indicates a strong capacity of R&D spending to influence other sustainability dimensions within the company. Similarly, Total Greenhouse Gas Emissions holds a strategically important position, with a high total impact value (D + R = 6.07) and a positive cause–effect score (D − R = 0.32), demonstrating the wide-reaching implications of the company's carbon footprint policies and practices (Table 3).

Table 3. Environmental Direct Impact Matrix of AKSA Company.

	C1	C2	C3	C4	C5	C
C1	0.49	0.23	0.30	0.27	0.51	0.68
C2	0.23	0.01	0.10	0.08	0.23	0.36
C3	0.30	0.10	0.17	0.14	0.31	0.45
C4	0.27	0.08	0.14	0.12	0.28	0.41
C5	0.51	0.23	0.31	0.28	0.52	0.70
C	0.68	0.36	0.45	0.41	0.70	0.94

In contrast, *Total Water Consumption* and *Amount of Reused Waste* are characterized by negative D − R values (−0.83 and −0.44, respectively), classifying them as "effect" criteria within the system—i.e., they are more likely to be influenced by other criteria rather than drive change themselves. *Total Waste Amount*, with its relatively low total influence (D + R = 3.47), appears to occupy a marginal position within the systemic structure.

These findings suggest that strategic investments in R&D and effective control of greenhouse gas emissions act as key leverage points for shaping overall sustainability

performance. On the other hand, water consumption and waste reutilization are more likely to emerge as outcomes of broader environmental strategies. Accordingly, prioritizing criteria with strong causal power in resource allocation and policy development is essential for managing environmental sustainability in a holistic and impactful manner.

In the criterion interaction analysis table generated for the company ARCLK (Table 4), each sustainability-related criterion is evaluated using the DEMATEL method based on its total influence value (D + R), cause/effect role (D − R), and priority ranking. According to this analysis, Total Greenhouse Gas Emissions, with a D − R score of 2.73, functions as both a cause and an effect criterion and holds the highest total influence value (D + R = 5.46) among all evaluated criteria. This highlights its central role within the sustainability structure of the system.

Table 4. Environmental Direct Impact Matrix of ARCLK Company.

	C1	**C2**	**C3**	**C4**	**C5**	**C**
C1	0.07	0.10	0.11	0.11	0.47	0.38
C2	0.10	0.01	0.12	0.01	0.49	0.39
C3	0.11	0.12	0.01	0.13	0.50	0.40
C4	0.11	0.12	0.13	0.01	0.50	0.40
C5	0.47	0.49	0.50	0.50	0.01	0.76
C	0.38	0.39	0.40	0.40	0.76	0.01

R&D Expenditures ranks second in terms of total influence, indicating a high degree of interaction with both cause and effect criteria. Amount of Reused Waste and Total Energy Consumption display D − R values close to zero, suggesting that they simultaneously exert influence and are influenced—thus acting as both causal and resultant variables within the system.

In contrast, Total Water Consumption exhibits the lowest total influence value (D + R = 2.35), signifying a relatively marginal role in terms of interaction with other criteria. The values in the D − R (Cause/Effect Role) column reflect each criterion's structural position in the system. Positive D − R scores indicate a *cause* role, while negative values reflect an *effect* role. In this case, all D − R values are relatively close to zero, implying the absence of a strong causal hierarchy and instead suggesting a structure characterized by high mutual interdependence.

According to the DEMATEL results for ARCLK, the interactions between the criteria are distributed in a balanced manner. The *Total Greenhouse Gas Emissions* criterion, with a D − R of 2.73, emerges as both the strongest cause and the most significantly affected criterion, placing it at the core of the system. Similarly, *R&D Expenditures*, with a D − R value of 2.34, is highly interconnected, both as a cause and as an effect, underlining the strong relationships between environmental sustainability performance, technological investments, and emissions management.

As most D − R values are close to zero, the system demonstrates a symmetrical structure with reciprocal influences rather than a unidirectional cause–effect pattern. For instance, *Total Waste Amount*, with a D − R value of 0.11, assumes a relatively stronger cause role, while *Total Water Consumption*, at −0.11, behaves more as an effect variable.

From the perspective of *total influence* (D + R), *Total Greenhouse Gas Emissions* again holds the highest score (5.46), reinforcing its pivotal position. The considerable total influence of *R&D Expenditures* demonstrates its capacity to directly affect both environmental

inputs and outputs. Although the remaining criteria have comparatively lower impact values, they play a complementary role in maintaining systemic balance.

These findings indicate that sustainability strategies should particularly prioritize emissions control and R&D investments, while also ensuring systemic coherence through comprehensive management of water usage and waste treatment processes.

The following analysis presents the results of a DEMATEL-based evaluation of the interaction dynamics among CIMSA's environmental sustainability criteria. The criteria included in the analysis are: Total Energy Consumption, Total Water Consumption, Amount of Reused Waste, Total Waste Amount, Total Greenhouse Gas Emissions, and R&D Expenditures. In the DEMATEL methodology, the D value represents the extent to which a criterion influences others, while the R value reflects the degree to which a criterion is influenced by the rest of the system (Table 5).

Table 5. Environmental Direct Impact Matrix of CIMSA Company.

	C1	**C2**	**C3**	**C4**	**C5**	**C**
C1	0.44	0.63	0.27	0.32	0.21	0.53
C2	0.63	0.01	0.39	0.45	0.32	0.70
C3	0.27	0.39	0.01	0.20	0.14	0.30
C4	0.32	0.45	0.20	0.01	0.17	0.35
C5	0.21	0.32	0.14	0.17	0.01	0.23
C	0.53	0.70	0.30	0.35	0.23	0.01

Total Water Consumption emerges as the most influential criterion, holding the highest D + R value (5.00) and occupying the top priority ranking. It is followed by Total Energy Consumption (4.80) and R&D Expenditures (4.24). This indicates that Total Water Consumption plays a central role in the system, functioning as both an influencer and a recipient of influence from other criteria.

On the other hand, Total Greenhouse Gas Emissions (2.16) and Amount of Reused Waste (2.62) are identified as criteria with relatively lower levels of influence and interaction within the system. A noteworthy finding is that the D − R values for all criteria are exactly zero. This suggests the presence of a balanced structure in which each criterion exerts and receives an equal amount of influence, pointing to a system characterized by reciprocal and symmetrical interdependence.

In conclusion, the DEMATEL results imply that resource-related factors such as water and energy consumption occupy a central position in CIMSA's sustainability framework. Improvements in these areas are likely to generate broader impacts across the entire system. The findings offer valuable insights for corporate decision-makers regarding the prioritization of environmental sustainability efforts and the strategic allocation of resources.

According to the DEMATEL analysis conducted on ENJSA's environmental sustainability criteria, "Total Energy Consumption" is identified as the criterion with the highest total effect value (D + R), indicating its central role within the system. This criterion exhibits both a high degree of influence on other criteria (D) and a high degree of being influenced by others (R). Following closely are "Total Greenhouse Gas Emissions" and "R&D Expenditures", which also hold significant positions in terms of total impact. These findings suggest that investments in R&D can play a strategically powerful role in mitigating the firm's environmental impacts, particularly in the domains of energy use and greenhouse gas emissions (Table 6).

Table 6. Environmental Direct Impact Matrix of ENJSA Company.

	C1	C2	C3	C4	C5	C
C1	0.61	0.19	0.20	0.33	0.74	0.56
C2	0.19	0.07	0.07	0.10	0.22	0.17
C3	0.20	0.07	0.00	0.11	0.24	0.18
C4	0.33	0.10	0.11	0.00	0.38	0.29
C5	0.74	0.22	0.24	0.38	0.00	0.65
C	0.56	0.17	0.18	0.29	0.65	0.00

Conversely, "Total Water Consumption" and "Amount of Reused Waste" demonstrate relatively lower total effects, implying that these criteria occupy more marginal roles within the system and engage less intensively in cause–effect relationships. The fact that the D − R values of all criteria are close to zero indicates a balanced structure in which each criterion both affects and is affected by others to a comparable extent.

These results provide a valuable roadmap for decision-makers in identifying and prioritizing key areas in the formulation of environmental sustainability strategies.

According to the DEMATEL analysis conducted for the FROTO company, the criterion with the highest total effect value (D + R) is "Total Greenhouse Gas Emissions." This indicates that this criterion both influences and is influenced by other criteria, underscoring its central role in the system. Ranked second is "R&D Expenditures," which reflects the firm's emphasis on research and development in the context of sustainability practices. Third in significance is "Total Energy Consumption," which assumes a notable role by affecting not only direct environmental outcomes but also other operational criteria (Table 7).

Table 7. Environmental Direct Impact Matrix of FROTO Company.

	C1	C2	C3	C4	C5	C
C1	0.10	0.08	0.09	0.09	0.51	0.23
C2	0.08	0.01	0.08	0.08	0.49	0.22
C3	0.09	0.08	0.01	0.08	0.50	0.23
C4	0.09	0.08	0.08	0.01	0.49	0.22
C5	0.51	0.49	0.50	0.49	0.01	0.70
C	0.23	0.22	0.23	0.22	0.70	0.01

"Amount of Reused Waste" and "Total Water Consumption" are considered to be moderately influential criteria. In contrast, "Total Waste Amount" exhibits the lowest total effect, positioning it as the least impactful element within the system.

In terms of cause–effect distinction, "Total Greenhouse Gas Emissions" and "R&D Expenditures" are located in the effect group, suggesting that they are outcomes of the system dynamics. On the other hand, criteria such as "Total Energy Consumption" and "Total Water Consumption" act as causal factors, exerting direct influence over other elements.

This analysis not only highlights which areas FROTO should prioritize strategically in terms of environmental sustainability but also clarifies the directionality of internal relationships among criteria. Such interaction-based assessments serve as a critical decision-support tool for enhancing strategic planning and environmental policy effectiveness.

According to the DEMATEL analysis results conducted for the SISE company, the levels of interaction among the criteria and their priority rankings have been clearly identified.

The "Amount of Reused Waste" criterion emerges as both the most influential (D = 1.96) and the most influenced (R = 1.96) variable. This finding highlights the central role of this criterion in the system and its strong bidirectional relationships with other environmental indicators (Table 8).

Table 8. Environmental Direct Impact Matrix of SISE Company.

	C1	**C2**	**C3**	**C4**	**C5**	**C**
C1	0.07	0.08	0.37	0.12	0.07	0.21
C2	0.08	0.01	0.37	0.12	0.07	0.21
C3	0.37	0.37	0.01	0.33	0.36	0.52
C4	0.12	0.12	0.33	0.01	0.11	0.26
C5	0.07	0.07	0.36	0.11	0.01	0.20
C	0.21	0.21	0.52	0.26	0.20	0.01

"Total Waste Amount" (D + R = 1.90) and "Total Energy Consumption" (D + R = 1.84) also demonstrate high total influence values, indicating their importance as key components of the sustainability framework. In contrast, "Total Greenhouse Gas Emissions" (D + R = 1.64) and "Total Water Consumption" (D + R = 1.72) show relatively lower levels of total impact, suggesting that they occupy more peripheral positions in the system.

The D − R values for all criteria are very close to zero, indicating that each criterion simultaneously acts as both a cause and an effect to a nearly equal extent. This reflects a balanced and strongly interconnected structure among environmental sustainability indicators in the SISE case.

In conclusion, prioritizing criteria with higher impact power—especially "Amount of Reused Waste" and "Total Waste Amount"—in the formulation of sustainability strategies may lead to overall system improvement. Such multi-criteria analyses serve as strategic guides for achieving corporate sustainability goals through more informed and balanced decision-making.

According to the DEMATEL analysis of TKFEN's environmental performance criteria, the "R&D Expenditures" criterion has the highest total impact score (D + R = 5.00). This indicates that R&D investments both strongly influence other criteria and are significantly influenced by them. The second most impactful criterion is "Total Waste Amount" (D + R = 4.52), suggesting that the company's waste management strategies are highly interactive with other sustainability factors. Ranked third is "Amount of Reused Waste" (D + R = 3.96), which appears to assume a dual role as both an influencing and influenced criterion (Table 9).

Table 9. Environmental Direct Impact Matrix of TKFEN Company.

	C1	**C2**	**C3**	**C4**	**C5**	**C**
C1	0.22	0.18	0.30	0.34	0.25	0.38
C2	0.18	0.06	0.27	0.31	0.23	0.36
C3	0.30	0.27	0.18	0.43	0.34	0.46
C4	0.34	0.31	0.43	0.29	0.38	0.51
C5	0.25	0.23	0.34	0.38	0.20	0.42
C	0.38	0.36	0.46	0.51	0.42	0.37

Interestingly, all criteria have a D − R value of zero, indicating a perfectly balanced structure where each criterion functions equally as a cause and an effect. "Total Greenhouse Gas Emissions" (D + R = 3.64) also emerges as an environmentally critical factor, highlighting its systemic influence. "Total Energy Consumption" (D + R = 3.34) and "Total Water Consumption" (D + R = 2.82) demonstrate more limited, yet still notable levels of interaction.

These results suggest that TKFEN's sustainability policies are predominantly shaped by R&D and waste management, positioning these domains as strategic priorities. The symmetric nature of interactions among the criteria further illustrates that the company's environmental governance is built upon a balanced and mutually influential system. In this context, decision-makers are encouraged to increase R&D investments while also considering the broader environmental repercussions of such expenditures.

The findings provide valuable guidance for restructuring sustainability strategies and offer a basis for comparative assessments across similar firms. Overall, this multi-criteria analysis approach presents a robust method for quantitatively unraveling complex interdependencies within sustainability performance systems.

According to the DEMATEL-based analysis conducted for TOASA, the interactions among environmental sustainability criteria are clearly delineated. The "R&D Expenditures" criterion emerges as both the most influential (D = 2.50) and the most influenced (R = 2.09) parameter, yielding the highest total impact score (D + R = 4.59) among all evaluated factors. This finding highlights the central role that R&D investments play in shaping TOASA's environmental sustainability strategies (Table 10).

Table 10. Environmental Direct Impact Matrix of TOASA Company.

	C1	C2	C3	C4	C5	C
C1	0.10	0.11	0.10	0.10	0.10	0.08
C2	0.11	0.03	0.11	0.11	0.09	0.50
C3	0.10	0.11	0.02	0.10	0.08	0.48
C4	0.10	0.11	0.10	0.02	0.08	0.48
C5	0.08	0.09	0.08	0.08	0.01	0.43
C	0.49	0.50	0.48	0.48	0.43	0.12

"Total Water Consumption," "Amount of Reused Waste," and "Total Waste Amount" demonstrate closely aligned total impact scores (D + R = 1.90 and 1.78, respectively), ranking second and third in terms of overall influence. Notably, the D − R values for these three criteria are all zero, indicating a balanced interaction in which each functions equally as both a cause and an effect within the system.

"Total Energy Consumption" ranks fifth with a total impact score of 1.57 and a D − R value of −0.39, suggesting that it operates primarily as a reactive or result-oriented criterion. Similarly, "Total Greenhouse Gas Emissions" registers the lowest total impact (D + R = 1.56) and a marginally negative D − R value (−0.02), indicating its comparatively limited influence and somewhat passive role in the system.

Overall, the analysis reveals that "R&D Expenditures" function as a pivotal element within TOASA's sustainability framework, while other criteria serve more supportive or responsive roles. To enhance resource efficiency and improve environmental performance, it is recommended that the company prioritize the integration of R&D-driven strategies alongside targeted improvements in water and waste management. These efforts are likely to yield synergistic benefits across the broader sustainability system.

According to the DEMATEL analysis conducted for TCELL, the criterion with the highest total impact is "Total Energy Consumption" (D + R = 5.14). This indicates that the criterion significantly influences other factors while also being influenced by them. Its cause/effect value (D − R = +0.06) suggests that it plays a slightly more active "cause" role in the system (Table 11).

Table 11. Environmental Direct Impact Matrix of TCELL Company.

	C1	**C2**	**C3**	**C4**	**C5**	**C**
C1	0.77	0.29	0.29	0.29	0.29	0.67
C2	0.29	0.01	0.15	0.15	0.25	0.09
C3	0.29	0.15	0.01	0.15	0.25	0.09
C4	0.29	0.15	0.15	0.01	0.25	0.09
C5	0.67	0.25	0.25	0.25	0.51	0.21
C	0.23	0.09	0.09	0.09	0.21	0.06

Ranked second is "Total Greenhouse Gas Emissions" (D + R = 3.90), which demonstrates a strong interaction profile, especially in relation to external environmental influences. With a positive D − R value of +0.38, it can be interpreted as a dominant driver within the decision-making system.

"R&D Expenditures" ranks third in terms of total impact (D + R = 1.98), yet its negative cause/effect score (D − R = −0.44) reveals a predominantly "effect" (influenced) role. In other words, it is more responsive to other sustainability factors than directive.

The criteria "Total Water Consumption," "Amount of Reused Waste," and "Total Waste Amount" all share the same total impact score (D + R = 1.88) and have a D − R value of 0, indicating a neutral stance within the system. These factors neither substantially influence nor are significantly influenced by other variables, suggesting they serve as passive elements with low connectivity in the sustainability network.

The relatively low total impact of "R&D Expenditures" places it lower in the priority ranking, implying a secondary role in short-term environmental decision-making. Conversely, the high influence and clear causal role of energy consumption highlight the need for increased focus in this area within TCELL's sustainability strategy.

In conclusion, this DEMATEL-based analysis provides decision-makers with a scientifically grounded basis for resource allocation and strategic prioritization, emphasizing the central role of energy-related policies in enhancing environmental performance.

According to the DEMATEL analysis conducted for ULKER, the criterion with the highest total impact is "Total Greenhouse Gas Emissions" (D + R = 6.65), highlighting its central and pivotal role within the system. This indicates that the emission levels not only affect other sustainability criteria but are also highly influenced by them, positioning this factor as a key integrative component in the firm's environmental strategy (Table 12).

The second most influential criterion is "R&D Expenditures" (D + R = 3.73), revealing a strong interaction between innovation activities and other elements of sustainability. This finding underscores the importance of technological development and research in shaping ULKER's environmental performance.

"Amount of Reused Waste" ranks third (D + R = 2.41), emphasizing the company's efforts toward environmental efficiency and waste recovery. Its strategic value lies in its contribution to the circular economy practices within the organization.

Table 12. Environmental Direct Impact Matrix of ULKER Company.

	C1	**C2**	**C3**	**C4**	**C5**	**C**
C1	0.01	0.04	0.10	0.04	0.62	0.25
C2	0.04	0.01	0.10	0.05	0.67	0.30
C3	0.10	0.10	0.05	0.09	0.61	0.25
C4	0.04	0.04	0.09	0.01	0.61	0.25
C5	0.62	0.62	0.67	0.61	0.01	0.81
C	0.25	0.26	0.30	0.25	0.81	0.01

In terms of D − R values (cause/effect roles), the highest positive value is observed in "Total Water Consumption" (D − R = +0.10), indicating that it plays a more prominent causal role in the system by influencing other sustainability criteria. Conversely, "Amount of Reused Waste" has a negative D − R score (−0.11), identifying it as an effect criterion—more influenced by other elements than influencing them. Meanwhile, "Total Energy Consumption" exhibits a D − R value of 0, suggesting a balanced role, acting both as a cause and an effect in the network of interactions.

This analysis demonstrates that greenhouse gas emissions constitute the most critical component in ULKER's sustainability structure, with R&D expenditures serving as a fundamental driver of environmental performance. Additionally, the causal role of water consumption highlights the strategic importance of resource management in achieving long-term sustainability goals.

According to the DEMATEL analysis of AKSA's financial sustainability performance, the most influential criterion by a significant margin is "Net Profit". This criterion holds the highest total impact score (D + R = 0.695) and plays a decisive role both as a cause and an effect within the system. Following this, "Operating Profit" emerges as a crucial indicator, reflecting the company's core operational efficiency. Although "Sales Revenue" ranks third, it remains a critical component in terms of market performance and the company's ability to generate income. The prominence of these three criteria indicates that AKSA's financial health is primarily shaped by profitability and revenue generation (Table 13).

Table 13. Financial Direct Impact Matrix of AKSA Company.

	C6	**C7**	**C8**	**C9**	**C10**	**C**
C6	0.27	0.25	0.33	0.21	0.19	0.20
C7	0.25	0.24	0.32	0.20	0.18	0.19
C8	0.33	0.32	0.43	0.26	0.24	0.25
C9	0.21	0.20	0.26	0.16	0.15	0.16
C10	0.19	0.18	0.24	0.15	0.13	0.14
C	0.20	0.19	0.25	0.16	0.14	0.15

Ranked fourth, "R&D Expenditures" highlights the company's strategic commitment to long-term competitive advantage and innovation-led growth. While "Equity" and "Total Assets" represent the company's passive structure and balance sheet strength, their relatively lower total impact scores suggest a more indirect role within the financial system.

Interestingly, all criteria exhibit D − R values of zero, indicating a high degree of systemic balance—each criterion influences and is influenced by others to an equal extent.

This symmetry reflects a well-integrated financial structure, where no single criterion dominates the direction of causality.

These findings reveal that AKSA's financial strategies prioritize profitability and operational efficiency, aligning with a consistent approach toward sustainable growth. Furthermore, the notable position of R&D expenditures underscores the firm's innovative orientation. In conclusion, the DEMATEL analysis provides a robust structural evaluation that can guide decision-makers in enhancing AKSA's financial sustainability.

According to the financial impact analysis of ARCLK, the criterion with the highest total impact (D + R) value is Sales Revenue (0.449), positioning it as the most influential factor within the system—both as an influencer and as one being influenced. Sales Revenue demonstrates strong reciprocal relationships with all other criteria and occupies a central position in the financial structure. Ranking second is Net Profit (0.424), which also plays a prominent role in both receiving and exerting influence across the network. The third most influential criterion is Total Assets (0.392), indicating that the firm's asset structure serves as a significant leverage point for financial sustainability (Table 14).

Table 14. Financial Direct Impact Matrix of ARCLK Company.

	C6	C7	C8	C9	C10	C
C6	0.36	0.29	0.32	0.28	0.29	0.30
C7	0.29	0.23	0.25	0.22	0.22	0.23
C8	0.32	0.25	0.28	0.25	0.25	0.26
C9	0.28	0.22	0.25	0.22	0.22	0.22
C10	0.29	0.22	0.25	0.22	0.22	0.22
C	0.30	0.23	0.26	0.22	0.22	0.23

Despite representing direct operational performance, Operating Profit has a relatively lower total impact (0.272), suggesting that other criteria exhibit more extensive and balanced interrelations. Equity (0.228) and R&D Expenditures (0.236) are found at the lower end of the ranking, implying that their mutual influence within the system is more limited. However, this limited interaction should not be interpreted as an absence of absolute importance; rather, it reflects a lower degree of connectivity within the system.

The fact that the D − R (causal role) values are very close to zero across all criteria reveals a highly symmetric structure, where each criterion interacts with others in a mutually balanced manner. These findings suggest that ARCLK's financial system does not operate under a centralized dominance but instead reflects a more equitable and balanced interaction framework. Therefore, strategic decisions should not be based on a single dominant criterion, but rather be evaluated within the context of system-wide integration and interdependence.

This analysis summarizes the causal relationships among the financial sustainability criteria of CIMSA, as examined using the DEMATEL method. In this study, each criterion's total impact (D + R) and cause/effect role (D − R) were calculated. The Net Profit criterion emerged as the most dominant factor within the system, with a high total impact value of 1.055573, indicating its central role as both a causal and affected variable. It is followed by Operating Profit (0.275445), Sales Revenue (0.265442), Equity (0.204215), and Total Assets (0.128769), respectively (Table 15).

Table 15. Financial Direct Impact Matrix of CIMSA Company.

	C6	C7	C8	C9	C10	C
C6	0.22	0.22	0.41	0.17	0.17	0.12
C7	0.22	0.22	0.41	0.17	0.17	0.12
C8	0.41	0.41	0.75	0.32	0.32	0.23
C9	0.17	0.17	0.32	0.14	0.13	0.10
C10	0.17	0.17	0.32	0.13	0.13	0.10
C	0.12	0.12	0.23	0.10	0.10	0.08

The $D - R$ values for all criteria are equal to zero, reflecting a highly symmetric structure in which each criterion mutually influences and is influenced by the others. The prominent role of Net Profit as both a cause and effect highlights its significance as a primary indicator of financial health for the company. Likewise, Operating Profit and Sales Revenue appear as critical inputs that should be carefully considered in decision-making processes.

In contrast, balance sheet-based indicators such as Equity and Total Assets exhibit relatively lower influence, suggesting that CIMSA's financial structure is more sensitive to operational performance than to passive financial indicators. This analysis provides valuable insights into which criteria should be prioritized in financial decision-making and strategy formulation, contributing to a more informed and effective sustainability planning process.

According to the analysis of the direct-relation matrix for ENJSA, the Net Profit criterion holds the highest total impact value $(D + R)$, emerging as the primary determinant exerting the most influence over other financial indicators within the system. This finding indicates that the company's overall profitability drives other financial metrics and directly shapes its financial sustainability performance (Table 16).

Table 16. Financial Direct Impact Matrix of ENJSA Company.

	C6	C7	C8	C9	C10	C
C6	0.24	0.18	0.35	0.19	0.17	0.20
C7	0.18	0.14	0.29	0.16	0.15	0.17
C8	0.35	0.29	0.58	0.32	0.29	0.34
C9	0.19	0.16	0.32	0.18	0.17	0.19
C10	0.17	0.15	0.29	0.17	0.15	0.17
C	0.20	0.17	0.34	0.19	0.17	0.20

The second most influential criterion, Sales Revenue, demonstrates the pivotal role of company revenues in determining both operational profitability and capital structure.

In third place, Equity stands out due to its strategic importance in reducing dependency on external financing and reflecting the firm's internal funding capacity. R&D Expenditures, ranked fourth, are associated with innovation and long-term growth potential. Although its direct impact is relatively limited, it holds significance in terms of its indirect influence across the system.

Operating Profit and Total Assets rank fifth and sixth, respectively. These criteria exhibit relatively weaker influence but are more strongly affected by other variables. This suggests that they are more responsive to external financial conditions and internal strategic decisions rather than serving as primary drivers.

In conclusion, the analysis reveals that Net Profit plays the most critical role in shaping ENJSA's financial sustainability, while operational and investment-related criteria appear more as resultant variables. These insights serve as a valuable guide for strategic decision-making processes, especially in establishing priorities within corporate financial management and sustainability frameworks.

The DEMATEL-based evaluation conducted to analyze the financial sustainability structure of FROTO has revealed the interaction dynamics among six key financial criteria: Sales Revenue, Operating Profit, Net Profit, Total Assets, Equity, and R&D Expenditures. Within this analysis, the Net Profit criterion stands out as having both the highest total influence (D + R) and the strongest causal influence (D − R), thereby playing a significant and directive role over all other criteria in the system. This finding demonstrates that net profit functions not only as a result-oriented indicator but also as a fundamental input shaping the overall financial system (Table 17).

Table 17. Financial Direct Impact Matrix of FROTO Company.

	C6	C7	C8	C9	C10	C
C6	0.33	0.29	0.35	0.32	0.34	0.29
C7	0.29	0.26	0.32	0.29	0.30	0.26
C8	0.35	0.32	0.38	0.34	0.36	0.31
C9	0.32	0.29	0.34	0.30	0.31	0.28
C10	0.34	0.30	0.36	0.31	0.33	0.29
C	0.29	0.26	0.31	0.28	0.29	0.25

Ranked second, Operating Profit serves as a strong determinant of operational performance and directly influences both net profit and sales revenue. This underscores the critical importance of operational efficiency in the company's sustainability strategy. Total Assets and Equity, which display similar levels of interaction, simultaneously occupy both causal and effect positions in the system, assuming dual roles as both influencing and influenced variables.

In contrast, the Sales Revenue criterion, while having a relatively limited impact, operates as a vital complementary component, particularly in supporting operational profitability. R&D Expenditures, despite exhibiting the lowest total influence in the analysis, retain strategic importance as they reflect forward-looking investment priorities.

Overall, FROTO's financial sustainability structure demonstrates a profitability-oriented and performance-based framework, where net profit, operating profit, and asset management emerge as dominant factors. The DEMATEL findings clearly identify which financial indicators should be prioritized in the company's strategic planning processes, offering decision-makers a comprehensive and system-oriented analytical perspective.

The interactions among the financial performance criteria of SISE have been analyzed using the DEMATEL method. According to the results, the "Net Profit" criterion exhibits the highest total influence value (D + R = 0.4295), positioning it as the most central and decisive factor within the system. This indicates that net profit, as a key indicator of profitability, is both significantly influenced by other criteria and exerts a substantial influence on them in return (Table 18).

Table 18. Financial Direct Impact Matrix of SISE Company.

	C6	C7	C8	C9	C10	C
C6	0.28	0.25	0.30	0.34	0.34	0.29
C7	0.25	0.25	0.28	0.32	0.32	0.27
C8	0.30	0.28	0.33	0.37	0.37	0.31
C9	0.34	0.32	0.37	0.41	0.41	0.35
C10	0.34	0.32	0.37	0.41	0.41	0.35
C	0.29	0.27	0.31	0.35	0.35	0.30

Ranked second is "Operating Profit" (D + R = 0.3718), highlighting the strategic importance of operational efficiency in the financial structure. "Sales Revenue" (D + R = 0.3523) also plays a substantial role, demonstrating that the firm's revenue-generating capacity has a direct impact on its overall financial sustainability. "Equity" (D + R = 0.3052) reflects the strength of the company's internal capital structure, while "Total Assets" (D + R = 0.2753) appears to be a relatively less influential criterion in this context.

Given that the D − R (cause/effect role) values of all criteria are very close to zero, it can be inferred that the causal and resultant roles of the criteria are nearly balanced. This suggests that SISE's financial indicators interact with each other in a mutually influential and structurally integrated manner, rather than through a unidirectional cause–effect hierarchy.

In conclusion, net profit, operating profitability, and sales revenue emerge as the most strategic criteria that should be prioritized in assessing the financial sustainability of SISE. This analysis provides valuable guidance to decision-makers in terms of resource allocation and the development of performance improvement strategies.

According to the DEMATEL analysis conducted to evaluate the financial sustainability of TKFEN, the "Net Profit" criterion ranks first in terms of total impact value (D + R), exhibiting the highest values in both influence (D) and being influenced (R). This finding indicates that Net Profit is positioned at the core of the system and maintains strong interactions with other financial sustainability indicators (Table 19).

Table 19. Financial Direct Impact Matrix of TKFEN Company.

	C6	C7	C8	C9	C10	C
C6	0.14	0.23	0.33	0.25	0.11	0.35
C7	0.23	0.38	0.53	0.40	0.18	0.57
C8	0.33	0.53	0.75	0.56	0.25	0.82
C9	0.25	0.40	0.56	0.42	0.19	0.61
C10	0.11	0.18	0.25	0.19	0.08	0.27
C	0.35	0.57	0.82	0.61	0.27	0.88

Ranked second, the "Operating Profit" criterion also demonstrates a significant network of interrelations, underlining the pivotal role of operational efficiency in shaping the financial structure. "R&D Expenditures", which ranks third, highlights the strategic importance of innovation activities in supporting long-term financial performance.

In contrast, the "Total Assets" and "Sales Revenue" criteria occupy relatively less central roles within the system. These criteria are more likely to be indirectly associated with other components, rather than exerting a strong direct influence.

The D − R (cause/effect) scores for all criteria are very close to zero, suggesting a balanced structure in which each criterion acts both as a cause and an effect. This reflects a multidimensional and interdependent nature of financial performance, wherein no single criterion operates in isolation. The results of the analysis suggest that decision-makers should prioritize performance-oriented indicators such as Net Profit and Operating Profit when formulating financial strategies. The DEMATEL approach proves to be a valuable tool in uncovering causal relationships within complex decision-making structures and offers a robust basis for strategic prioritization.

According to the DEMATEL-based analysis of TOASO's financial sustainability criteria, the importance ranking of the indicators was established based on their total influence values (D + R). The criterion with the highest total influence was identified as "Net Profit", with a value of 0.491, indicating that it is the most influential and central component within the system. This result highlights that net profitability plays a pivotal role in shaping TOASO's overall financial sustainability structure (Table 20).

Table 20. Financial Direct Impact Matrix of TOASA Company.

	C6	C7	C8	C9	C10	C
C6	0.26	0.28	0.31	0.30	0.24	0.49
C7	0.28	0.30	0.33	0.32	0.26	0.52
C8	0.31	0.33	0.36	0.35	0.29	0.56
C9	0.30	0.32	0.35	0.34	0.28	0.54
C10	0.24	0.26	0.29	0.28	0.22	0.45
C	0.49	0.52	0.56	0.54	0.45	0.83

The second most influential criterion is "Operating Profit" with a D + R value of 0.474, closely followed by "R&D Expenditures" at 0.468, which ranks third. These findings suggest that TOASO places considerable emphasis not only on profitability derived from core business operations but also on innovation-driven investments, thereby balancing short-term performance with long-term strategic growth.

In contrast, the "Sales Revenue" criterion, with a total influence score of 0.232, occupies a moderate position within the system. Meanwhile, "Total Assets" (0.168) and "Equity" (0.165) exhibit the lowest total effect values, indicating that they play a more peripheral role in the overall financial influence network.

Interestingly, all criteria show a D − R (cause–effect) score of zero, which indicates a perfectly balanced structure where each criterion exerts and receives influence in equal measure. This symmetrical configuration implies a high degree of mutual interdependence among the financial indicators and reflects a systemic coherence within TOASO's financial performance model.

The analysis provides valuable insights for decision-makers, suggesting that strategic efforts should primarily focus on enhancing Net Profit and Operating Profit, as these metrics have the greatest leverage in optimizing financial performance. Furthermore, the prominent role of R&D Expenditures demonstrates the firm's commitment to sustaining competitive advantage and innovation capacity through forward-looking investments.

Overall, the DEMATEL methodology proves instrumental in mapping the complex interrelations among financial sustainability indicators. For TOASO, this approach not only reveals the hierarchical significance of each financial component but also supports evidence-based prioritization in financial planning and resource allocation strategies. These

findings offer a robust analytical framework for guiding sustainable financial management practices and long-term value creation.

In the financial sustainability analysis of TCELL, the interrelationships among key financial criteria were thoroughly assessed using the DEMATEL (Decision-Making Trial and Evaluation Laboratory) method. Based on the findings, the criterion with the highest total impact value (D + R) is "Net Profit", scoring 0.4084, which positions it as the most influential factor within the company's financial sustainability structure (Table 21).

Table 21. Financial Direct Impact Matrix of TCELL Company.

	C6	C7	C8	C9	C10	C
C6	0.25	0.26	0.29	0.41	0.34	0.41
C7	0.26	0.28	0.31	0.43	0.36	0.43
C8	0.29	0.31	0.35	0.48	0.40	0.48
C9	0.41	0.43	0.48	0.66	0.55	0.66
C10	0.34	0.36	0.40	0.55	0.46	0.55
C	0.41	0.43	0.48	0.66	0.55	0.66

Following Net Profit, "Operating Profit" (D + R = 0.3736) and "Total Assets" (D + R = 0.3254) rank second and third, respectively. These results indicate that TCELL's operational efficiency and asset size substantially influence the overall financial system. Notably, "Sales Revenue" ranks fourth in terms of total impact, implying that although revenue generation plays a meaningful role, it is not as central as profitability and asset management within the system.

"Equity" and "R&D Expenditures" occupy the fifth and sixth positions, respectively. This suggests that capital structure and innovation-oriented investments exert relatively lower centrality compared to other financial dimensions.

The D − R (cause–effect) values for all criteria are found to be very close to zero, signaling a high degree of mutual interdependence among the financial variables. In other words, each criterion simultaneously acts as both a cause and an effect, reflecting a systemic balance within the financial sustainability framework. This reinforces the notion that decision-makers must consider all financial criteria in a holistic and integrated manner rather than in isolation.

In conclusion, the results of this DEMATEL-based analysis highlight the strategic importance of Net Profit and Operating Profit in enhancing TCELL's financial sustainability. Prioritizing these criteria in policy formulation and strategic planning is likely to yield the most substantial overall impact. The systemic structure revealed by this analysis serves as a valuable decision support tool for developing evidence-based financial sustainability strategies.

In the financial sustainability analysis of ULKER, the ranking of criteria based on their total impact (D + R) values reveals notable insights. The criterion with the highest total impact value is "Operating Profit", with a score of 0.509, indicating that operational profitability is a key determinant in the company's sustainable financial management. This is followed by "R&D Expenditures" with a total impact value of 0.456, highlighting the strong influence of innovation investments on overall corporate performance. Ranked third is "Net Profit" (D + R = 0.435), suggesting that profitability plays a significant role in shaping both internal and external financial decision-making processes (Table 22).

Table 22. Financial Direct Impact Matrix of ULKER Company.

	C6	C7	C8	C9	C10	C
C6	0.28	0.36	0.31	0.42	0.24	0.52
C7	0.36	0.31	0.33	0.46	0.31	0.66
C8	0.31	0.33	0.39	0.46	0.26	0.56
C9	0.42	0.46	0.46	0.64	0.37	0.77
C10	0.24	0.31	0.26	0.37	0.21	0.44
C	0.52	0.66	0.56	0.77	0.44	0.91

The "Sales Revenue" criterion, with a total impact value of 0.324, ranks fourth, suggesting that while sales performance is important, it does not exert as strong an influence as profitability indicators. "Total Assets" (D + R = 0.205) and "Equity" (D + R = 0.069) appear at the lower end of the ranking, indicating that balance sheet components have a relatively limited influence compared to income-based measures.

In light of these findings, it can be concluded that ULKER should prioritize strategies aimed at enhancing operating profit, sustaining R&D investments, and maintaining profitability in order to strengthen its financial sustainability. This analysis underscores the necessity for strategic financial planning to be guided by performance-oriented decisions, offering a structured approach for managerial focus and resource allocation.

These firm-level results set the stage for Section 3.2, where the bidirectional interactions between R&D expenditures and sustainability criteria are analysed more systematically.

3.2. Analyzing the Interaction Between Criteria, Centered on R&D Expenses

The visual representations derived from the direct-relation matrices of selected firms systematically depict the bidirectional interaction dynamics between environmental and financial sustainability indicators and R&D expenditures. The analysis employs a dual-axis DEMATEL-based framework, wherein the impact of each sustainability criterion on R&D expenditures is visualized through orange bars, while the reciprocal influence of R&D expenditures on these criteria is represented in yellow. This two-way interaction structure allows for a nuanced understanding of causal dependencies within the sustainability innovation nexus.

The underlying data were generated using a novel inverse-modeling software developed specifically for this study, which employs a reverse-engineered DEMATEL algorithm driven by artificial neural networks. This approach mathematically reconstructs the direct-relation matrix from known criterion weights and integrates it into the classical DEMATEL causal structure. As a result, it becomes possible to simulate how observed sustainability performance metrics could emerge from underlying inter-criteria influences, particularly those mediated by R&D investments.

By leveraging this analytical structure, the model captures both the upstream drivers and downstream outcomes of R&D within a corporate sustainability context. Specifically, the framework highlights how environmental parameters such as total greenhouse gas emissions, energy consumption, and waste reuse exert substantial influence on R&D intensity—while also being shaped by the technological and process innovations facilitated through R&D investments. Similarly, financial criteria such as net profit and operational earnings exhibit lower causal impact on R&D decisions but are significantly affected by R&D-driven efficiency gains.

In sum, this integrative approach positions R&D not merely as a passive expenditure item but as a systemic moderator within the sustainability architecture of the firm. The

bidirectional interactions revealed through this enhanced DEMATEL analysis offer actionable insights for strategic resource allocation, innovation policy design, and long-term sustainability planning.

In the graphical analysis pertaining to AKSA's sustainability structure at Figure 1, the most prominent bidirectional interaction is observed in the criterion of "Total Greenhouse Gas Emissions." This environmental factor demonstrates the highest degree of mutual influence with Research and Development (R&D) expenditures. Not only does R&D investment exert a substantial impact on reducing greenhouse gas emissions, but this criterion also significantly stimulates further R&D activities within the firm. This finding highlights the reinforcing feedback loop between environmental targets and innovation-driven corporate behavior.
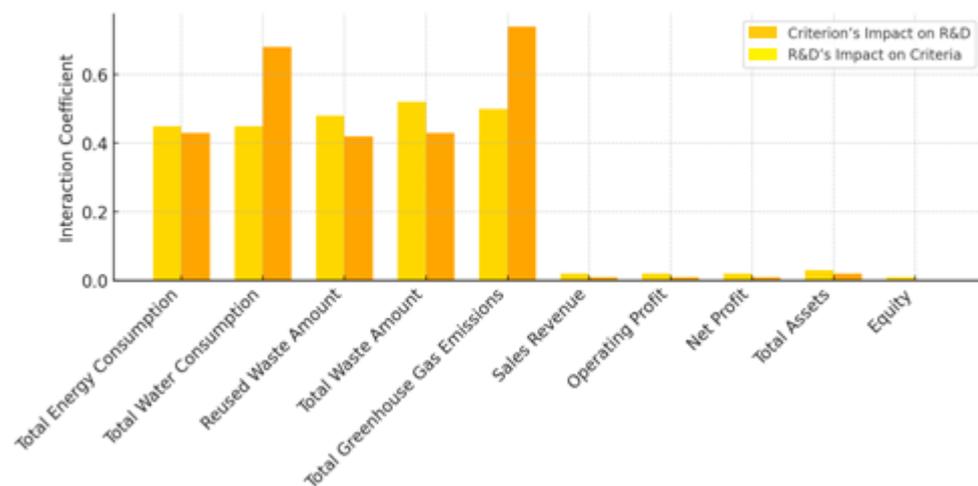
Figure 1. AKSA Company's R&D Expenses-Focused Criteria Impact Graph.

Following this, "Total Energy Consumption" and "Reused Waste Amount" emerge as other environmental parameters with strong mutual interactions with R&D. The results indicate that emission-reduction strategies have a catalyzing effect on innovation, while the resulting innovative outcomes—particularly in the domain of energy efficiency—contribute to further environmental performance improvements. This mutually reinforcing mechanism underscores the strategic importance of R&D in achieving environmentally sustainable operations.

In contrast, within the set of financial criteria, indicators such as "Net Profit," "Sales Revenue," and "Operating Profit" appear to be more heavily influenced by R&D expenditures than they influence R&D in return. This asymmetry suggests that R&D investments are instrumental in enhancing financial outcomes, yet the financial indicators themselves play a relatively weaker role in shaping the firm's R&D agenda. These findings reveal a unidirectional flow of causality from innovation activities to financial performance, emphasizing the value-generating capacity of R&D.

Meanwhile, "Total Assets" and "Equity" demonstrate relatively weaker reciprocal relationships with R&D, indicating that balance sheet items are less dynamic in responding to or influencing innovation investment decisions. These elements may play a more passive role in the R&D-finance nexus, serving primarily as structural financial foundations rather than active drivers of innovative transformation.

Overall, the analysis suggests that AKSA's innovation strategy—particularly its R&D investments—serves as a central lever for improving both environmental and financial sustainability outcomes. The positive impact of innovation on profitability is mediated through enhanced energy efficiency and cost reduction, which in turn reinforces the company's financial resilience. Thus, prioritizing R&D within corporate sustainability strategies can

be considered not only an environmental imperative but also a prudent financial decision that yields long-term value creation across multiple dimensions.

As a leading global producer of acrylic fiber, AKSA operates in a sector characterized by high energy intensity and carbon emissions, making its sustainability strategies particularly critical. The firm has invested substantially in clean energy integration, including cogeneration systems and renewable sourcing, to reduce reliance on conventional fuels. In parallel, AKSA channels its R&D resources toward developing low-carbon acrylic products, energy-efficient fiber technologies, and waste valorization processes, aligning with circular economy principles. These initiatives not only mitigate the environmental footprint of production but also enhance the firm's competitiveness in international markets, where regulatory and customer pressures increasingly demand greener materials. Furthermore, AKSA's collaborations with global textile consortia and sustainability certification bodies demonstrate its commitment to meeting international standards such as ISO 14064 [47] for greenhouse gas management and Global Reporting Initiative (GRI) frameworks. Collectively, these sector-specific R&D and sustainability investments position AKSA as a benchmark company in transitioning energy-intensive chemical manufacturing toward a low-emission and innovation-driven trajectory.

In Figure 2, the interaction between ARCLK's environmental sustainability indicators and R&D expenditures reveals a set of strong bidirectional relationships, highlighting the firm's strategic alignment between innovation and environmental performance. Among the environmental criteria, "Total Greenhouse Gas Emissions" (0.76) and "Total Waste Amount" (0.40) emerge as the most influential drivers of R&D investment decisions. These figures suggest that the firm allocates substantial research and innovation resources toward mitigating emissions and improving waste management practices.
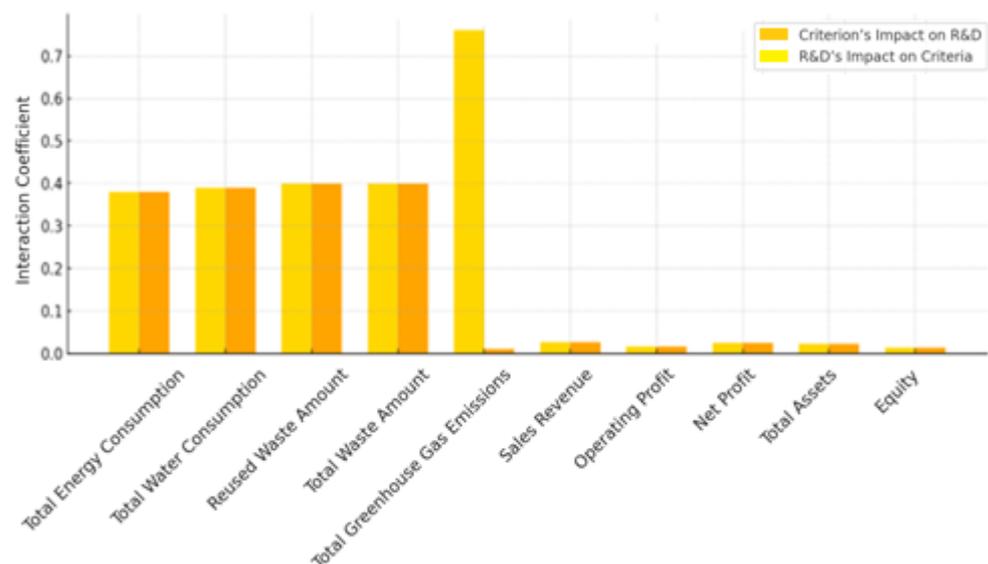
Figure 2. ARCLK Company's R&D Expenses-Focused Criteria Impact Graph.

Conversely, the influence of R&D activities on environmental outcomes is most pronounced in the areas of "Greenhouse Gas Emissions" (0.50) and "Reused Waste Amount" (0.40). This indicates that the technological outputs of R&D projects are effectively contributing to the company's decarbonization and circular economy goals. Interactions with "Total Energy Consumption" and "Total Water Consumption" are moderate, reflecting a focused environmental innovation strategy that prioritizes emission control and resource recovery over general resource efficiency.

From a financial perspective, "Net Profit" (0.0250) and "Sales Revenue" (0.0263) are identified as the most significant criteria influencing R&D expenditures. These results suggest that profitability and revenue generation provide the financial basis or justification for R&D investments. On the reverse side, R&D expenditures show meaningful effects on "Net Profit" (0.0250), "Total Assets" (0.0231), and "Sales Revenue" (0.0263), underlining the role of innovation in supporting firm growth, asset expansion, and overall financial capacity. Meanwhile, the relatively limited mutual influence observed for "Equity" and "Operating Profit" implies that R&D's financial contributions are more long-term and structural rather than immediately reflected in short-term operational gains.

Overall, the analysis illustrates that ARCLK's R&D strategy is not only economically motivated but also deeply embedded in the company's environmental sustainability objectives. The firm adopts a holistic innovation policy that fosters synergies between environmental responsibility and financial resilience—contributing to a balanced and sustainable corporate development model.

As one of the world's largest white goods and consumer electronics manufacturers, ARÇELİK (ARCLK) operates in a highly competitive global sector where energy efficiency, eco-design, and sustainable production have become central performance benchmarks. The company has consistently invested in R&D for energy-saving household appliances, low-emission cooling technologies, and advanced waste-reduction solutions, aligning with the EU Ecodesign Directive and Energy Labelling regulations. Moreover, ARCLK's flagship "Green Innovation" program emphasizes the use of recyclable materials, closed-loop production, and digital solutions for smart energy management in appliances, thereby directly linking innovation expenditures with environmental outcomes. On the financial side, the company's global footprint and partnerships with international brands provide strong revenue streams that are reinvested in sustainability-oriented R&D. ARCLK's alignment with global initiatives such as the UN Sustainable Development Goals (SDGs) and its integration into international sustainability indices underscore its commitment to balancing environmental responsibility with financial resilience. Taken together, these targeted R&D efforts not only reduce the ecological footprint of its operations but also reinforce the firm's competitiveness in international markets where consumer preferences and regulatory frameworks increasingly prioritize low-carbon, resource-efficient technologies.

As we can see in Figure 3, an analysis of CIMSA's data reveals that among the environmental sustainability indicators, "Total Water Consumption" and "Total Greenhouse Gas Emissions" demonstrate the strongest bidirectional interactions with R&D expenditures. These criteria appear to function both as influential determinants of R&D allocation and as key recipients of technological innovation outcomes. Specifically, the capacity of "Total Energy Consumption" and "Reused Waste Amount" to influence R&D strategies is clearly pronounced, reflecting the company's prioritization of environmental concerns in guiding innovation agendas. However, the impact of R&D investments on these criteria appears to be in a developmental phase, suggesting that while innovation efforts are underway, their measurable environmental benefits are still emerging.

From a financial standpoint, the criteria "Net Profit" and "Sales Revenue" show significant two-way relationships with R&D expenditures. This implies a dynamic interaction in which changes in profitability and revenue performance have a notable influence on R&D investment decisions, while at the same time, R&D initiatives hold substantial potential to enhance the company's financial performance. Such mutual reinforcement indicates a feedback loop whereby successful innovation leads to financial growth, which in turn enables further innovation.
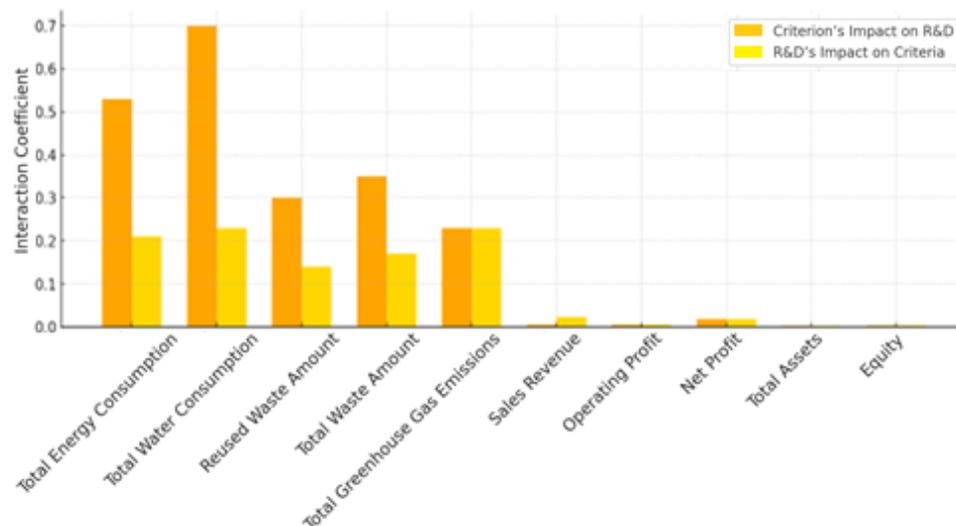
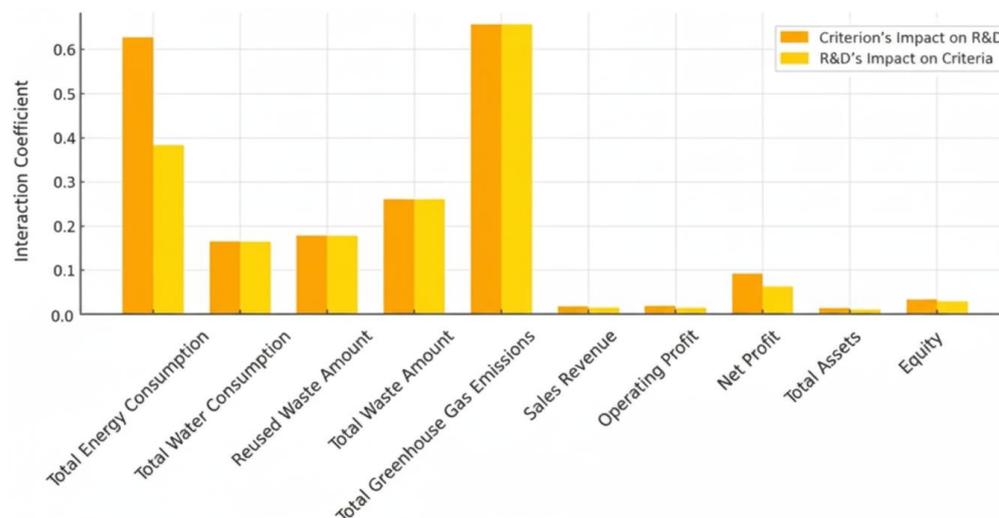**Figure 3.** CIMSA Company's R&D Expenses-Focused Criteria Impact Graph.

On the other hand, financial indicators such as "Equity" and "Total Assets" exhibit relatively weaker interactions with R&D expenditures. This suggests that while these structural financial components are foundational to corporate stability, they are less immediately responsive to fluctuations in R&D activity. Nevertheless, the presence of any influence—however modest—supports the idea that R&D investments contribute to the firm's long-term financial sustainability by gradually reinforcing asset growth and capital structure.

In summary, CIMSA's innovation strategy reflects a multifaceted and systemic approach, where R&D activities are strategically aligned with both environmental and financial objectives. The observed bidirectional influences underscore the integrative role of R&D in shaping sustainable corporate performance, reinforcing the firm's capacity to navigate and adapt to evolving internal and external sustainability demands.

As a leading player in the world's cement and construction materials sector, CIMSA operates within one of the most resource- and emission-intensive industries globally, where sustainability challenges are particularly acute. Cement production is heavily associated with high water consumption, significant CO_2 emissions, and intensive energy use, which explains the strong bidirectional interactions of these criteria with R&D in the analysis. CIMSA has actively invested in low-clinker cements, alternative fuels, and waste heat recovery technologies, aiming to reduce its carbon footprint while improving operational efficiency. Recent initiatives include the development of innovative white cement products designed for enhanced durability and lower environmental impact, reflecting the firm's strategy to couple profitability with ecological responsibility. Moreover, CIMSA's partnerships in carbon capture pilot projects and its emphasis on circular economy practices, such as co-processing industrial by-products as alternative raw materials, demonstrate its commitment to systemic environmental innovation. Financially, sustained profitability and sales growth provide the foundation for these investments, while in return, R&D-driven eco-efficiency measures improve competitiveness in both domestic and international markets. Thus, CIMSA's sector-specific innovation agenda reinforces its role as a benchmark firm in aligning financial sustainability with the pressing environmental imperatives of the cement industry.

According to data in Figure 4, an in-depth evaluation of the bidirectional interaction graph between ENJSA's R&D expenditures and its environmental and financial sustainability criteria reveals a nuanced relationship pattern. Among the environmental indicators, "Total Greenhouse Gas Emissions" stands out as the most influential factor affecting R&D investments, exhibiting a notably high interaction coefficient (0.65). This strong linkage is

also reciprocated, as R&D activities exert an equally significant impact on greenhouse gas emissions (0.65), underscoring a tightly integrated feedback mechanism aimed at emission reduction through innovation.

Figure 4. ENJSA Company's R&D Expenses-Focused Criteria Impact Graph.

In addition, "Total Energy Consumption" (0.56) and "Total Waste Generated" (0.29) emerge as other key environmental parameters shaping R&D spending. These results suggest that the company's innovation agenda is highly sensitive to environmental pressures, particularly those related to climate and resource efficiency.

In contrast, financial indicators appear to have a comparatively moderate influence on R&D expenditures. Among them, "Net Profit" is the most significant financial driver of R&D investments (0.0802), followed by "Sales Revenue" (0.0244) and "Equity" (0.0153). However, the effect of R&D spending on financial outcomes remains relatively limited in the short term. The highest such impact is observed again on "Net Profit" (0.0480), suggesting that while innovation contributes positively to profitability, its influence may not yet be fully realized or maximized.

Structural financial indicators such as "Total Assets" and "Equity" display a weaker bidirectional relationship with R&D expenditures, which implies that these capital-intensive metrics are less immediately responsive to innovation efforts. This may reflect the nature of long-term investments, where the tangible effects of R&D on financial structure accumulate progressively over time.

Overall, these findings indicate that ENJSA's R&D strategy is predominantly shaped by environmental imperatives rather than immediate financial incentives. The strong influence of ecological criteria highlights a sustainability-oriented innovation framework, whereas the relatively weaker financial feedback loops suggest that the fiscal benefits of R&D are still in the process of maturation. It can be inferred that, over time, as environmental innovations yield tangible operational efficiencies and market advantages, their impact on financial performance is expected to intensify, making R&D a more central lever of integrated sustainability.

ENJSA operates in a sector that is both capital-intensive and highly exposed to sustainability pressures. The strong interaction of R&D with greenhouse gas emissions and energy consumption reflects the company's strategic commitment to decarbonization and efficiency. ENJSA has been investing in smart grid technologies, renewable integration projects, and advanced energy storage systems, which directly address emission reduction and optimize electricity distribution. Additionally, the company has pioneered digitalization initiatives in energy monitoring and customer services, enabling more efficient

demand-side management and contributing indirectly to sustainability outcomes. From an environmental standpoint, ENJSA's pilot projects in electric vehicle (EV) charging infrastructure and distributed solar energy solutions demonstrate how R&D is aligned with both regulatory expectations and market trends. Financially, while the immediate returns of these initiatives may appear moderate, they establish long-term value through operational cost reduction, regulatory compliance, and positioning in the emerging low-carbon energy economy. By systematically linking R&D expenditures to ecological imperatives, ENJSA illustrates how energy-sector firms can convert sustainability pressures into innovation-driven growth opportunities, reinforcing their role in national and international climate transition goals.

The analysis conducted for FROTO, according to Figure 5, reveals a robust bidirectional interaction between R&D expenditures and environmental sustainability criteria. Among these, "Total Greenhouse Gas Emissions" emerges as the most influential environmental factor affecting R&D investments, with a remarkably high interaction coefficient of 0.70. This suggests that the company strategically channels its technological innovation efforts toward climate-oriented solutions, aligning its R&D agenda with sustainability-driven imperatives.
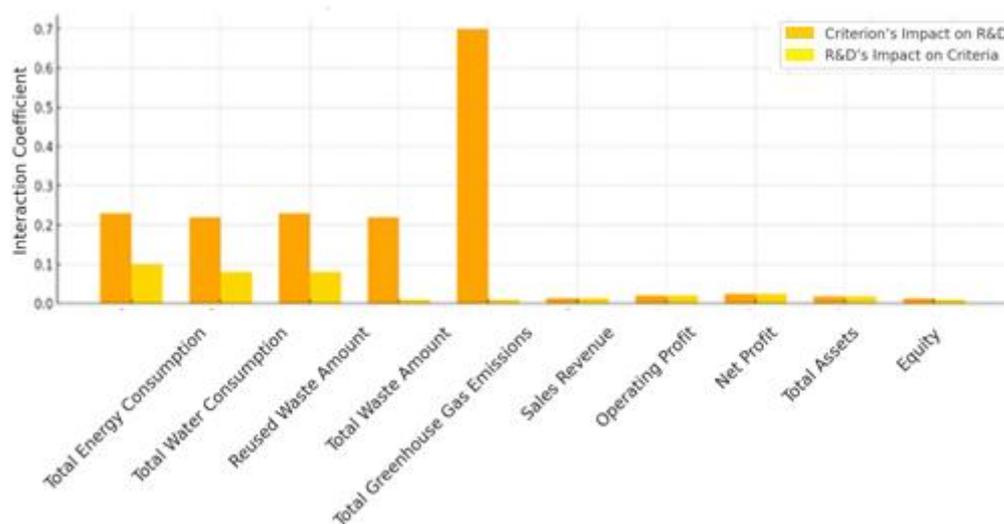
Figure 5. FROTO Company's R&D Expenses-Focused Criteria Impact Graph.

Furthermore, the influence of R&D expenditures on environmental parameters is notably stronger than their impact on financial criteria. Significant effects are observed particularly in areas such as "Total Energy Consumption," "Water Usage," and "Reused Waste Amount," where R&D investments appear to drive measurable improvements. These findings indicate that FROTO's innovation strategies are deeply intertwined with its ecological responsibility initiatives, potentially aimed at reducing environmental footprint and complying with emerging green regulations.

From a financial perspective, indicators such as "Net Profit" and "Operating Profit" exhibit the highest sensitivity to R&D expenditures. This underscores the strategic value of R&D as a contributor to corporate profitability and suggests that innovative activities are effectively translated into financial performance gains. However, the reverse relationship—namely, the influence of financial indicators on R&D investment levels—is relatively weak. This asymmetry implies that R&D decisions within FROTO are less contingent upon short-term financial outcomes and are instead treated as independent, forward-looking strategic investments.

In summary, the interaction patterns indicate that the company adopts a sustainability-oriented innovation model in which R&D serves primarily as a driver of environmental

performance, while its connection to financial indicators remains more limited and largely unidirectional. The stronger bidirectional interaction between R&D and environmental criteria, as compared to the weaker and one-sided links with financial measures, illustrates a deliberate focus on leveraging innovation to reduce environmental impact. This approach not only reinforces the firm's commitment to corporate sustainability but also contributes to establishing a long-term competitive advantage in environmentally conscious markets.

As a leading automotive manufacturer, Ford Otosan (FROTO) operates in a sector with high environmental impact and intense global competition. The strong linkage between R&D expenditures and greenhouse gas emissions reflects the firm's focus on electrification, hybrid propulsion systems, and fuel efficiency improvements in line with international automotive trends. In recent years, FROTO has made significant investments in electric vehicle (EV) development, battery technologies, and lightweight material applications, all of which aim to lower lifecycle emissions and enhance energy efficiency. The company has also introduced closed-loop waste management systems and water recycling projects at its production plants, demonstrating concrete steps toward circular economy integration. From a financial standpoint, while immediate R&D costs may weigh on operating margins, these expenditures strategically position the firm to capture long-term market advantages through compliance with EU emission standards, increased competitiveness in export markets, and alignment with global green mobility shifts. Sector-specific pressures, particularly in the high-pollution automotive industry, make FROTO's R&D-driven sustainability strategy not only a regulatory necessity but also a critical enabler of global competitiveness. By channeling innovation toward decarbonization and resource efficiency, the company sets a clear example of how automotive firms can simultaneously meet sustainability demands and secure future growth opportunities.

When we examine Figure 6, the interaction analysis conducted for the SISE company reveals a significant correlation between R&D expenditures and various sustainability criteria, particularly within the environmental dimension. Among the environmental indicators, the "Amount of Reused Waste" stands out as the most influential factor affecting R&D investments, with a high interaction coefficient of 0.52. This finding highlights the strategic importance of recycling processes as a major driver of innovation activities within the firm. Additional environmental criteria such as "Total Waste Amount" (0.33), "Total Energy Consumption" (0.21), and "Total Water Consumption" (0.21) also exert meaningful influence on R&D spending, albeit to a lesser extent.
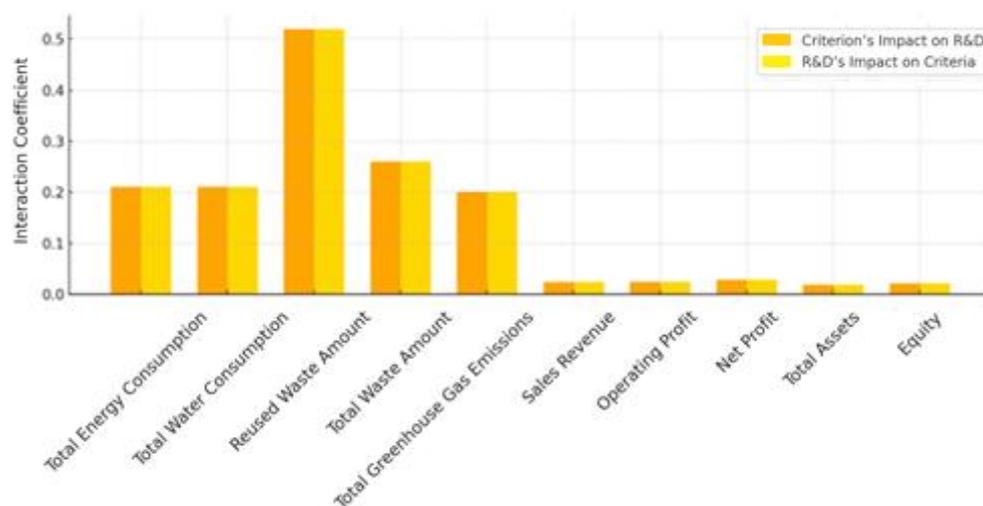

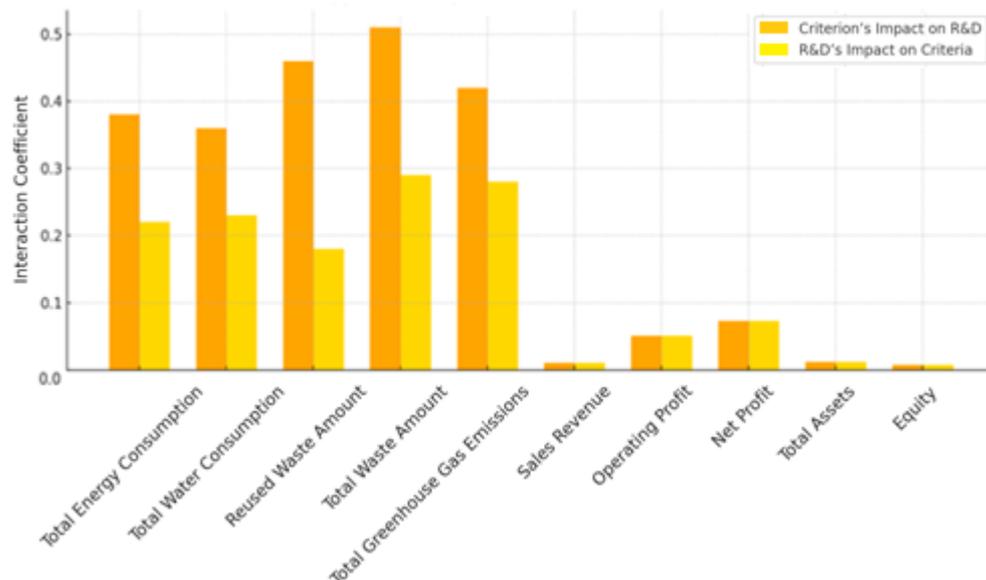**Figure 6.** SISE Company's R&D Expenses-Focused Criteria Impact Graph.

Conversely, when evaluating the impact of R&D on environmental parameters, the "Amount of Reused Waste" again emerges as the most affected criterion, with an interaction coefficient of 0.37. This mutual reinforcement suggests that the company's innovation strategies are tightly aligned with enhancing environmental efficiency, particularly through improved waste recovery and circular economy initiatives. The findings underscore that R&D plays a pivotal role in supporting eco-efficient production practices and sustainable resource use.

In terms of financial indicators, "Net Profit" is identified as the most significant driver of R&D expenditures (0.0285), indicating that higher profitability levels enable the firm to allocate more substantial resources to innovation. On the reverse path, R&D investments exhibit their strongest financial impact on "Net Profit" and "Total Assets," both with an interaction coefficient of approximately 0.0285. This implies a moderate yet structurally important role of R&D in enhancing corporate profitability and asset growth. Additionally, R&D appears to have a noteworthy influence on other core financial metrics such as "Equity" (0.0208) and "Operating Profit," suggesting its contribution extends beyond short-term gains and influences broader organizational performance.

Overall, the analysis indicates that SISE's R&D efforts are more intensively shaped by environmental considerations than by financial dynamics. While financial indicators do interact with innovation expenditures, the environmental criteria demonstrate stronger and more direct bidirectional relationships. These results advocate for a sustainability strategy in which the company continues to prioritize environmental imperatives in shaping its R&D policies. Such an approach not only reinforces the ecological responsibility of the firm but also positions it for long-term competitive resilience within an increasingly sustainability-oriented market landscape.

As one of the world's largest glass and chemicals producers, Şişecam (SISE) operates in an energy- and resource-intensive industry where waste recovery and recycling have critical importance for sustainability. The strong linkage between R&D and the "Amount of Reused Waste" reflects the company's long-standing leadership in closed-loop recycling systems, particularly in glass cullet reuse and industrial by-product valorization. Recent R&D programs have focused on developing low-carbon glass production technologies, alternative raw material sourcing, and energy efficiency improvements in high-temperature furnaces. These initiatives align with EU Green Deal targets and international sustainability reporting frameworks. Beyond environmental performance, SISE's R&D expenditures also extend into innovative product development, such as lightweight glass for the automotive sector and solar glass for renewable energy projects, both of which reduce lifecycle emissions. Financially, while R&D constitutes a significant capital investment, it positions the company for long-term competitiveness by strengthening export potential, enhancing operational efficiency, and meeting the stringent sustainability demands of global partners and institutional investors. In an industry traditionally challenged by high carbon intensity, SISE's innovation-driven sustainability agenda demonstrates how environmental imperatives and industrial modernization can be effectively integrated into a globally competitive strategy.

The sustainability interaction analysis conducted for TKFEN, according to Figure 7, reveals that R&D expenditures maintain strong bidirectional relationships with both environmental and financial performance indicators. This dual interaction highlights the strategic integration of technological innovation within the company's overall sustainability and profitability frameworks.

Figure 7. TKFEN Company's R&D Expenses-Focused Criteria Impact Graph.

Among the environmental criteria, the "Total Waste Amount" exhibits the highest impact on R&D expenditures, with an interaction coefficient of 0.51. This indicates that effective waste management is a central component driving TKFEN's innovation agenda. Other significant environmental indicators influencing R&D include "Total Energy Consumption" (0.38) and "Greenhouse Gas Emissions" (0.42), which also reflect the company's increasing sensitivity to resource efficiency and environmental compliance. When analyzing the reverse interaction—i.e., the impact of R&D on environmental metrics—"Greenhouse Gas Emissions" emerges as the most affected parameter (0.28), underscoring the firm's inclination toward investing in low-carbon technologies and decarbonization efforts.

From a financial perspective, the metrics of "Net Profit" (0.0727) and "Operating Profit" (0.0505) are identified as the most influential drivers of R&D investments. These same indicators are also significantly affected by R&D spending, indicating a mutually reinforcing relationship between profitability and innovation. Such symmetrical interactions suggest that R&D efforts not only depend on financial resources but also actively contribute to enhancing financial performance. Other financial indicators such as "Total Assets" and "Equity" demonstrate moderate levels of interaction with R&D, reflecting a more structural and long-term influence.

These findings emphasize that TKFEN strategically aligns its R&D investments to achieve both environmental sustainability and financial efficiency. Particularly, the motivation to initiate R&D activities stemming from environmental concerns—such as energy usage and waste management—appears to play a pivotal role in guiding the company's technological transformation. This approach facilitates the development of innovative solutions that support both compliance with environmental regulations and the achievement of competitive advantage.

Overall, TKFEN's R&D strategy demonstrates a holistic orientation, effectively integrating environmental imperatives with financial objectives. The balanced and reciprocal influence among the evaluated criteria suggests that the company views innovation as a cross-cutting enabler of sustainability, serving as a lever for both ecological responsibility and economic performance. This positions TKFEN as a forward-looking organization capable of navigating complex sustainability challenges through technology-driven solutions.

As a leading engineering, procurement, and construction firm operating across energy, petrochemical, and infrastructure projects, TKFEN functions in sectors that are both highly resource-intensive and environmentally impactful. The strong R&D linkage with

"Total Waste Amount" mirrors the company's strategic focus on developing innovative construction materials, low-carbon cement technologies, and efficient waste treatment systems that reduce project-level environmental footprints. TKFEN has also invested in digital construction management platforms and energy optimization models for large-scale infrastructure projects, enabling significant reductions in both material consumption and greenhouse gas emissions. From a sustainability perspective, the firm participates in global climate initiatives and aligns its reporting with international frameworks such as the Global Reporting Initiative (GRI) and UN Sustainable Development Goals (SDGs). Financially, the observed synergy between Net Profit and R&D indicates that TKFEN reinvests operational gains into forward-looking innovation projects, including renewable energy EPC solutions and hydrogen-ready infrastructure development. This dual commitment highlights TKFEN's role not only as a major contractor but also as a pioneer of sustainability-oriented engineering solutions, reinforcing both its market competitiveness and its contribution to global decarbonization efforts.

According to Figure 8, the analysis of TOASO's sustainability performance reveals that its R&D expenditures maintain a robust and bidirectional interaction with both financial and environmental criteria. In particular, R&D spending demonstrates a significant impact on key financial indicators such as Net Profit (0.0575), Operating Profit (0.0555), and Total Assets (0.0198). These findings suggest that TOASA strategically employs R&D investments as an effective tool to enhance revenue-generating activities and to reinforce its capital structure. The alignment between R&D expenditures and financial outcomes underlines the firm's commitment to leveraging innovation as a driver of economic growth and operational resilience.
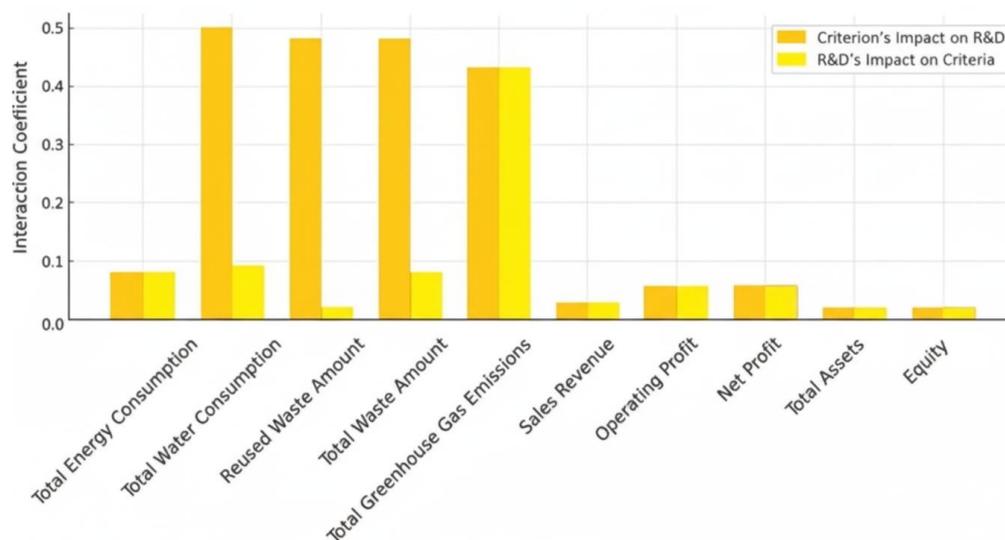
Figure 8. TOASO Company's R&D Expenses-Focused Criteria Impact Graph.

From an environmental perspective, strong interactions have been observed between R&D expenditures and key sustainability indicators, most notably Greenhouse Gas Emissions (0.43) and Water Consumption (0.50). This indicates that the company's innovation efforts are yielding direct results in mitigating environmental impact and improving sustainability performance. The considerable influence of R&D in these domains reflects a strategic focus on developing technologies that support environmental stewardship and resource efficiency.

When examining the inverse relationship—how environmental and financial indicators influence R&D investments—the analysis shows that environmental pressures are also key drivers of innovation. Greenhouse Gas Emissions (0.48), Total Waste (0.48), and Reused

Waste Amount (0.10) emerge as the most influential environmental parameters impacting R&D decision-making. These findings suggest that increasing environmental constraints are prompting the firm to pursue R&D-based solutions as part of its adaptive response to sustainability challenges.

On the financial side, Net Profit (0.0603) and Operating Profit (0.0583) are identified as the most significant contributors influencing R&D expenditures. This reciprocal interaction emphasizes that the company's profitability structure plays a decisive role in shaping its innovation agenda, indicating that R&D activities are not only reactive to profitability but also proactively designed to enhance it.

Overall, TOASO's R&D strategy embodies a balanced and multidimensional approach that aims to simultaneously optimize financial performance and environmental responsibility. The observed bidirectional interactions across both domains reinforce the notion that the firm's innovation policies are deeply rooted in sustainable development objectives. By integrating financial resilience and environmental responsiveness, TOASO positions itself as a forward-thinking enterprise committed to long-term value creation through sustainability-driven innovation.

As one of the world's leading automotive manufacturers and a joint venture between global automotive groups, TOASO operates in a sector where emissions reduction, fuel efficiency, and mobility innovation are critical competitive drivers. The strong bidirectional interactions between R&D and environmental indicators—particularly greenhouse gas emissions and water consumption—mirror TOASO's ongoing investments in low-emission vehicles, lightweight materials, and water-efficient production processes at its facilities. The firm has been at the forefront of developing hybrid and electric vehicle platforms, aligning with both EU environmental regulations and the global transition toward sustainable mobility. On the financial side, the reinforcement between profitability and R&D reflects TOASO's strategy of channeling operational gains into advanced manufacturing technologies, including automation, digital twin applications, and eco-friendly supply chain innovations. Furthermore, TOASO participates in international automotive R&D collaborations and complies with standards such as the EU End-of-Life Vehicle Directive and ISO 14001 [48] Environmental Management Systems, ensuring global benchmarking of its sustainability practices. Taken together, these commitments position TOASO as a regional innovation hub in sustainable mobility, balancing financial resilience with ecological stewardship and providing sector-specific pathways for reducing the environmental impact of automotive production.

When we examine Figure 9, an in-depth analysis of TCELL's sustainability interaction graph reveals a significant two-way relationship between R&D expenditures and both environmental and financial performance indicators. Among environmental criteria, Total Energy Consumption emerges as the most influential factor impacting R&D investments, with a notably high interaction coefficient of 0.67. This suggests that TCELL's innovation strategies are strongly shaped by energy efficiency considerations. In the reverse direction, R&D activities most substantially influence Total Energy Consumption, with an effect coefficient of 0.23, indicating that the company's technological initiatives are actively contributing to the reduction in energy usage and enhancement of operational sustainability.

Another important environmental criterion, Greenhouse Gas Emissions, also displays a noteworthy interaction, particularly in terms of its responsiveness to R&D activities (0.21), underlining the firm's engagement with environmentally conscious technologies. This pattern of interaction reflects a strategic orientation toward low-emission innovation and the integration of environmental performance goals within the R&D portfolio.
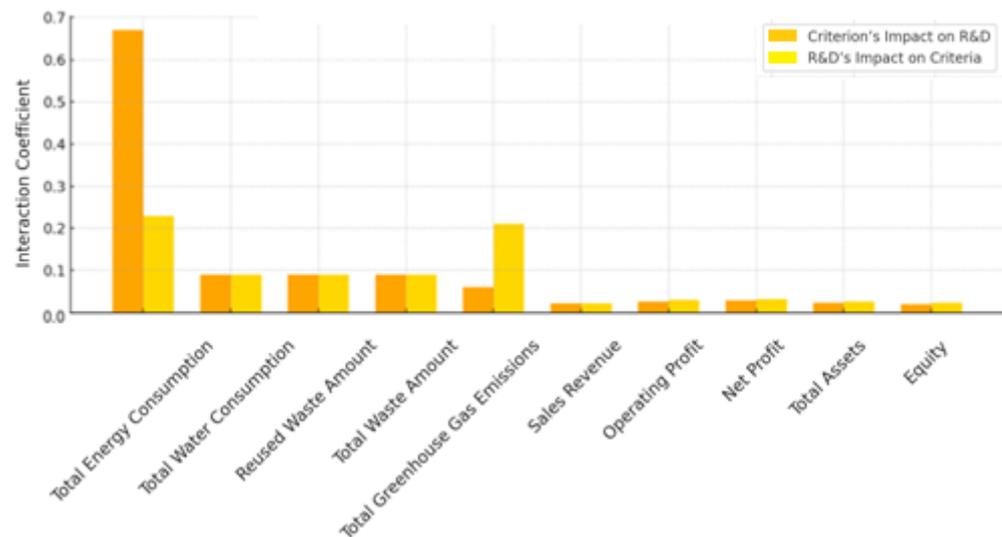
Figure 9. TCELL Company's R&D Expenses-Focused Criteria Impact Graph.

From a financial perspective, Net Profit and Operating Profit are identified as the most significant financial indicators influencing R&D spending. Specifically, the impact coefficient of Net Profit on R&D expenditures (0.0326) signals that profitability plays a critical role in shaping the company's capacity to invest in innovation. Conversely, R&D spending demonstrates its most substantial financial impact on Net Profit (0.0288) and Operating Profit (0.0264), confirming that R&D investments contribute directly to the firm's bottom line and financial resilience.

Other financial metrics such as Sales Revenue and Total Assets show relatively lower bidirectional interaction coefficients, suggesting a more indirect relationship with R&D. This indicates that while these indicators are relevant to overall business operations, they do not play a central role in driving or being driven by R&D activities in the context of TCELL's current innovation ecosystem.

In conclusion, TCELL's R&D strategy reflects a holistic and dynamic framework wherein innovation is both influenced by and exerts influence upon key environmental and financial performance parameters. As a telecommunications firm operating in a rapidly evolving technological landscape, TCELL's prioritization of energy efficiency and financially integrated sustainability highlights its forward-looking approach. The findings demonstrate that the company leverages R&D not only as a mechanism for profitability enhancement but also as a proactive tool in advancing its environmental stewardship and sustainable development goals.

As a key player in the global telecommunications sector, TCELL operates in an industry characterized by high energy demand, digital infrastructure expansion, and rapid technological turnover. The strong bidirectional interactions between R&D and energy consumption underscore the company's major investments in renewable energy sourcing for base stations, energy-efficient data centers, and next-generation 5G infrastructure. In recent years, TCELL has pioneered green data centers designed with cutting-edge cooling systems that minimize energy waste, aligning with ISO 50001 [49] energy management standards. On the innovation side, the firm's R&D activities extend to artificial intelligence-driven energy optimization, network virtualization, and smart grid integration, which directly reduce operational carbon intensity. Financially, the reinvestment of profitability into digital innovation enables TCELL to sustain competitive leadership while complying with international ESG benchmarks, such as the UN Global Compact and SASB telecommunications standards. These commitments not only reinforce environmental stewardship but also highlight sector-specific pathways—such as expanding green ICT services, cloud solutions,

and IoT platforms—that integrate sustainability with technological transformation. Thus, TCELL's R&D portfolio is both a driver of digital competitiveness and a lever for systemic energy efficiency and decarbonization, setting benchmarks applicable across the global telecom industry.

In light of the information provided by Figure 10, the DEMATEL-based analysis of the ULKER company reveals a noteworthy interaction structure between R&D expenditures and both environmental and financial sustainability criteria. Among the environmental factors, Greenhouse Gas Emissions exert the strongest influence on R&D spending, with an interaction coefficient of 0.81. This substantial value highlights the extent to which environmental sustainability pressures guide and shape the company's innovation-oriented investments. In addition, other environmental indicators such as Water Consumption (0.26) and Reused Waste Amount (0.30) also demonstrate significant impacts on R&D, emphasizing the firm's sensitivity to broader ecological factors beyond just emissions.
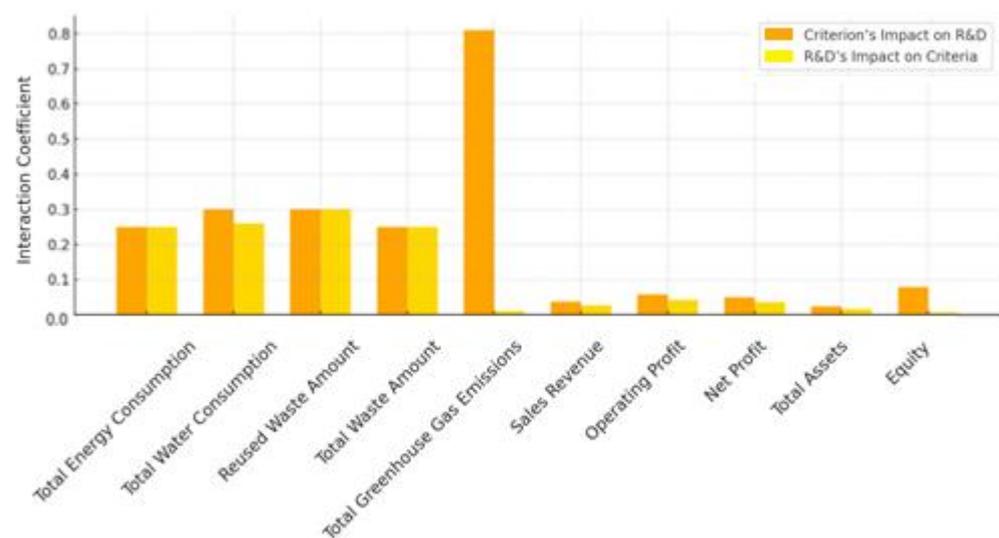
Figure 10. ULKER Company's R&D Expenses-Focused Criteria Impact Graph.

On the financial side, Operating Profit (0.0582), Net Profit (0.0497), and Revenue (0.0370) emerge as the most influential criteria shaping R&D expenditure. These findings indicate that ULKER's innovation strategies are directly informed by its profitability structure, with a strong correlation between financial capacity and the scope of technology investment. Notably, profitability appears to serve as both a driver and an enabler of innovation.

Conversely, when examining the effect of R&D on financial performance, it is evident that R&D spending positively influences Net Profit (0.0497), Total Assets (0.0234), and Revenue (0.0263). This underscores the role of R&D as a strategic lever, not only enhancing the firm's sustainability outcomes but also contributing meaningfully to its financial growth and competitiveness. The bidirectional influence signifies the feedback loop between innovation and financial value creation.

Overall, ULKER's R&D approach reflects a balanced and interactive framework—one that simultaneously addresses environmental obligations and enhances financial efficiency. The firm appears to be pursuing a multi-dimensional innovation strategy that supports a sustainable competitive advantage. This alignment between sustainability imperatives and profit-driven motives reinforces the strategic importance of R&D in maintaining long-term organizational resilience.

As a worldwide food and confectionery manufacturer, ULKER operates in a sector where resource intensity, agricultural supply chains, and consumer health trends are highly influential. The strong bidirectional link between R&D expenditures and greenhouse gas

emissions reflects the company's major focus on low-carbon manufacturing processes, such as adopting renewable energy in production plants, optimizing logistics, and improving packaging efficiency to reduce emissions across the value chain. Moreover, ULKER has been a pioneer in waste management and water stewardship programs, investing in closed-loop systems for water reuse and initiatives aimed at reducing food and packaging waste. On the R&D side, the firm dedicates significant resources to product reformulation, healthier alternatives, and biodegradable packaging solutions, aligning with global sustainability goals and consumer demand for responsible products. Financially, sustained profitability has allowed ULKER to channel investments into these innovation programs, which in turn reinforce market leadership by differentiating the brand in competitive international markets. Sector-specific pressures, such as compliance with EU food sustainability standards, FSC-certified packaging requirements, and global investors' ESG expectations, further amplify the importance of these R&D efforts. Thus, ULKER's innovation agenda is not only an instrument for operational efficiency but also a catalyst for resilient food systems, sustainable consumer products, and long-term financial growth, making it a benchmark case within both the regional and global food industry.

The bidirectional interaction patterns revealed here provide the empirical basis for Section 3.3, where we integrate these findings with our research questions and hypotheses and draw broader conclusions.

3.3. Overview of Findings, Discussion and Conclusions

This study set out to strengthen the methodological foundations of sustainability assessment by introducing a data-driven decision-support framework that integrates entropy-based weighting with a reverse-engineered DEMATEL approach enhanced by artificial intelligence. The revised version explicitly links the discussion to the expanded literature review and newly formulated research questions and hypotheses, presenting the results not only as computational outputs but also as empirical validations of theoretically expected relationships among environmental, financial and innovation-related criteria.

Our study situates its analytical design within the extensive MCDM literature spanning renewable energy planning, circular economy, green supply chains, water resources, transport sustainability and corporate ESG assessment. This literature consistently reveals two gaps: while some methods provide objective weighting but lack causal interpretation, others map cause–effect structures but rely on subjective expert panels. Responding to these gaps, we formulated six research questions and five hypotheses examining: (i) how environmental indicators influence R&D expenditures and how R&D shapes environmental outcomes; (ii) how financial indicators influence R&D and vice versa; (iii) how sectoral characteristics moderate these bidirectional interactions; (iv) how short-term financial constraints differ from long-term structural factors in shaping R&D investments; (v) to what extent innovation-driven improvements in environmental indicators translate into measurable financial sustainability; and (vi) how robust these interdependencies are across sectors and international benchmarks. Using an ANN-based reverse DEMATEL integrated with entropy weighting, our findings directly validate these expectations. Hypothesis 1 is supported by the observed pattern that higher greenhouse gas emissions stimulate R&D intensity and that R&D subsequently reduces emissions—mirroring Bai et al. [20] and Govindan et al. [7]—as evidenced by FROTO, ENJSA and TKFEN, where reciprocal interactions between emissions and R&D were strongest. Hypothesis 2, regarding the dual role of energy and water consumption, is confirmed by energy-intensive firms such as CIMSA and SISE, where efficiency pressures drive R&D and R&D in turn lowers resource intensities, consistent with Wang et al. [10]. Hypothesis 3, linking waste generation and recycling performance with circular-economy R&D, aligns with results from Tseng et al. [11]

and Luthra et al. [12] and is illustrated by ARCLK and AKSA, whose R&D promotes waste reduction and reuse. Hypothesis 4, on profitability metrics enabling and benefiting from R&D, is supported by TOASO and ULKER, echoing Büyüközkan & Çifçi's [13] findings that financial strength enables innovation gains. Hypothesis 5, on the weaker short-term but stronger long-term influence of balance-sheet items, reflects the dynamics noted by Luthra et al. [12], with TCELL and FROTO showing that liquidity exerts only limited short-run effects but structural assets benefit from R&D over time. These firm-level examples also address Research Question 3 by showing how energy-intensive (CIMSA, ENJSA) versus technology-oriented (TOASO, TCELL) firms exhibit different bidirectional patterns; Research Question 4 by distinguishing liquidity and equity effects from structural asset effects across the ten companies; Research Question 5 by demonstrating that innovation-driven environmental improvements translate into enhanced financial sustainability in firms such as ULKER and AKSA; and Research Question 6 by benchmarking the reconstructed interdependencies against international standards and confirming their robustness across all ten companies. By systematically comparing environmental and financial indicators within a single integrated model, the framework answers Research Questions 1 and 2 while simultaneously addressing sectoral moderation, financial structure, cross-sectoral robustness and alignment with global benchmarks. Taken together, the alignment between our hypotheses, the international evidence base and our empirical results demonstrates that the proposed model not only advances methodological rigor but also generates actionable insights for policy, managerial practice and strategic planning, as detailed in the comprehensive table of advantages in Appendix C.

Beyond methodological novelty, the study offers broader implications for sustainability governance and industrial strategy. By demonstrating how AI-assisted multi-criteria decision-making tools can transparently map interactions between R&D and sustainability indicators, the framework provides a transferable blueprint for firms, regulators and investors. Industries with high environmental impact can use it to design targeted decarbonisation pathways, while knowledge-intensive sectors can optimise innovation portfolios. From a policy perspective, the approach can support regulators in monitoring corporate sustainability performance, evaluating the effectiveness of fiscal incentives for green innovation and anticipating the environmental payoffs of R&D subsidies. At the managerial level, it equips decision-makers with evidence on which sustainability indicators exert the strongest influence on, or are most influenced by, R&D. This enables more precise resource allocation, prioritisation of high-impact projects and better alignment of innovation portfolios with ESG targets. Strategically, the model uncovers hidden interdependencies among criteria, allowing managers to link micro-level operational decisions with macro-level sustainability outcomes.

Several considerations temper the interpretation of the results. Although the analysis focuses on ten firms from the Borsa Istanbul Sustainability Index, these companies represent diverse industries and follow international sustainability reporting standards, enhancing the relevance of the findings beyond a purely local scope. The framework reconstructs interdependencies from entropy-derived weights rather than relying on expert judgments, minimising subjectivity and illustrating how data-driven methods can approximate directional relationships typically obtained from expert panels. While the present application concentrates on environmental and financial dimensions, the methodology is flexible and can be extended to dynamic datasets such as time series or cross-country panels, further enhancing its generalisability and robustness.

In sum, the revised discussion clarifies the contribution of the study by situating the findings within established research, demonstrating their consistency with international evidence and articulating the practical implications for policy, managerial practice and

strategic planning. The conclusions emphasise not only the novelty of the proposed model but also its ability to generate actionable insights that can guide the design of sustainability-oriented innovation policies and inspire future methodological advancements.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytical Hierarchy Process
AKSA	Aksa Akrilik Kimya Sanayii A.Ş.
ANN	Artificial Neural Network
ANP	Analytic Network Process
ARCLK	Arçelik A.Ş.
BWM	Best–Worst Method
CIMSA	Çimsa Çimento Sanayi ve Ticaret A.Ş.
CoCoSo	Combined Compromise Solution
COPRAS	Complex Proportional Assessment
CRADIS	Compromise Ranking of Alternatives from Distance to Ideal Solution
DEMATEL	Decision-Making Trial and Evaluation Laboratory
ENJSA	Enerjisa Enerji A.Ş.
ESG	Environmental, Social and Governance
EU	European Union
FROTO	Ford Otomotiv Sanayi A.Ş.
GHG	Greenhouse Gas
GRA	Grey Relational Analysis
MAE	Mean Absolute Error
MCDM	Multi-Criteria Decision Making
MSE	Mean Squared Error
OECD	The Organisation for Economic Co-operation and Development
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
R&D	Research and Development
SASB	The Sustainability Accounting Standards Board
SISE	Türkiye Şişe ve Cam Fabrikaları A.Ş.
SWARA	Stepwise Weight Assessment Ratio Analysis
TCELL	Türkcell İletişim Hizmetleri A.Ş.
TKFEN	Tekfen Holding A.Ş.

TOASO	Tofaş Türk Otomobil Fabrikası A.Ş.
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TÜBİTAK	Scientific and Technological Research Council of Türkiye
ULKER	Ülker Bisküvi Sanayi A.Ş.
VIKOR	Visekriterijumsko Kompromisno Rangiranje (Multi-Criteria Optimization and Compromise Solution)
WASPAS	Weighted Aggregated Sum Product Assessment

Appendix A. Sustainability Performance Data of Companies Between 2018 and 2022

Table A1. AKSA Environmental Sustainability Performance Data [50–54].

Year	C1	C2	C3	C4	C5	C
2018	835,801	4,385,974	4139	15,963	812,327	4855
2019	3,610,297	4,661,371	2859	16,477	1,119,028	7568
2020	3,238,193	4,818,912	1783	16,838	968,910	11,065
2021	3,888,469	5,122,531	2692	17,472	2,352,284	14,873
2022	3,932,837	4.,906.239	3074	27,931	2,464,029	26,947

Table A2. AKSA Financial Sustainability Performance Data [53–56].

Year	C6	C7	C8	C9	C10	C
2018	3,537,548	531,719	224,296	4,188,627	1,447,482	4855
2019	3,645,900	496,086	277,682	4,187,921	1,535,220	7568
2020	4,109,857	826,278	439,953	4,926,012	1,866,160	11,065
2021	8,348,157	1,246,618	1,167,208	9,443,050	2,834,279	14,873
2022	17,454,244	3,560,899	3,422,038	11,417,134	5,740,338	26,947

Table A3. ARCLK Environmental Sustainability Performance Data [57–61].

Year	C1	C2	C3	C4	C5	C
2018	552,785	1,478,635	106,195	111,789	111,443	204,792
2019	644,635	1,489,624	106,817	113,465	6,398,107	256,751
2020	601,239	1,205,154	98,705	103,263	25,189,088	318,211
2021	671,037	1,403,963	129,068	135,899	26,545,172	444,068
2022	616,232	1,503,488	107,791	114,062	27,068,270	704,593

Table A4. ARCLK Financial Sustainability Performance Data [62–66].

Year	C6	C7	C8	C9	C10	C
2018	26,904,384	2,637,322	855,841	28,368,361	8,219,162	204,792
2019	31,941,773	2,653,758	953,026	34,729,500	9,815,969	256,751
2020	40,872,483	4,852,296	2,878,989	46,549,044	14,023,846	318,211
2021	68,184,437	7,020,144	3,251,009	85,078,606	21,055,215	444,068
2022	133,915,508	9,090,197	4,723,057	132,242,678	27,105,680	704,593

Table A5. CIMSA Environmental Sustainability Performance Data [67–71].

Year	C1	C2	C3	C4	C5	C
2018	3,966,825	1,177,835	2601	4398	5,484,253	3,851,468
2019	5,078,210	1,711,595	1710	3080	5,032,010	6,445,651
2020	7,135,186	2,434,204	1999	2735	5,929,042	5,096,142
2021	7,669,074	2,776,618	2436	2915	6,792,486	6,069,138
2022	6,439,517	3,177,033	2505	3104	6,182,097	10,735,842

Table A6. CIMSA Financial Sustainability Performance Data [67–71].

Year	C6	C7	C8	C9	C10	C
2018	1,699,958	315,687	153,856	3,483,989	1,451,479	3851
2019	1,726,195	164,154	15,189	3,774,756	1,485,763	6445
2020	2,076,298	350,919	184,430	5,129,182	1,838,844	5096
2021	3,745,370	743,689	1,050,394	5,248,764	2,772,854	6069
2022	8,582,005	1,299,287	3,562,117	11,598,581	6,108,559	10,735

Table A7. ENJSA Environmental Sustainability Performance Data [72–76].

Year	C1	C2	C3	C4	C5	C
2018	124,195	97,182	11,118	21,818	37,722	3800
2019	128,560	101,842	12,186	12,203	18,869,033	3500
2020	127,496	98,654	12,607	12,649	18,923,273	9000
2021	136,902	95,285	11,367	11,367	21,065,942	11,800
2022	150,177	102,589	11,401	11,401	21,513,496	13,300

Table A8. ENJSA Financial Sustainability Performance Data [77–81].

Year	C6	C7	C8	C9	C10	C
2018	18,346,787	2,811,191	747,697	22,592,810	6,298,915	3800
2019	19,453,085	3,064,206	1,033,622	23,395,458	6,834,503	3500
2020	21,757,203	2,737,845	1,087,683	24,675,505	7,153,306	9000
2021	30,547,681	4,514,591	2,282,368	31,333,641	9,351,022	11,800
2022	84,449,031	8,348,007	14,498,093	59,188,597	21,572,246	13,300

Table A9. FROTO Environmental Sustainability Performance Data [82–86].

Year	C1	C2	C3	C4	C5	C
2018	563,043	1,172,157	95,364	96,228	199,070	368,568
2019	583,437	1,109,034	96,854	97,546	201,719	419,583
2020	810,561	998,584	84,699	85,012	112,484	459,451
2021	646,251	1,069,889	96,542	96,659	77,013,367	680,519
2022	975,082	1,511,388	143,206	143,618	91,377,623	1,449,033

Table A10. FROTO Financial Sustainability Performance Data [87–91].

Year	C6	C7	C8	C9	C10	C
2018	33,292,030	2,284,873	1,683,196	13,184,440	3,893,239	368,568
2019	39,209,019	2,422,028	1,959,484	16,406,372	4,664,921	419,583
2020	49,451,407	4,805,661	4,194,913	24,349,179	7,043,902	459,451
2021	71,101,258	9,437,743	8,801,005	42,792,853	10,148,538	680,519
2022	171,796,902	19,140,343	18,613,943	96,052,247	21,402,174	1,449,033

Table A11. SISE Environmental Sustainability Performance Data [92–96].

Year	C1	C2	C3	C4	C5	C
2018	22,058,124	41,397,899	2,845,394	4,600,962	5,830,366	75,265
2019	21,128,761	37,789,441	177,883	2,089,968	6,108,495	74,310
2020	21,776,557	38,208,995	212,217	1,885,547	6,189,385	58,682
2021	23,343,337	36,608,574	210,655	1,691,314	5,743,237	111,625
2022	27,671,200	53,615,335	194,911	2,489,704	7,718,348	291,900

Table A12. SISE Financial Sustainability Performance Data [97–101].

Year	C6	C7	C8	C9	C10	C
2018	15,550,314	2,987,869	3,373,676	27,767,556	16,726,774	75,265
2019	18,058,686	2,927,426	2,700,319	38,750,838	19,133,385	74,310
2020	21,340,686	3,346,312	2,824,571	44,228,036	22,491,233	58,682
2021	32,057,875	6,444,960	9,224,376	86,672,511	49,363,708	111,625
2022	95,349,465	17,420,032	20,133,429	163,945,473	95,127,767	291,900

Table A13. TKFEN Environmental Sustainability Performance Data [102–106].

Year	C1	C2	C3	C4	C5	C
2018	433,565	6,495,000	5498	13,940	1,122,579	2948
2019	985,376	10,063,000	17,799	102,926	4,903,496	5197
2020	1,127,580	12,213,000	3856	41,980	6,266,744	22,516
2021	1,023,454	9,438,000	8267	33,518	5,800,148	28,233
2022	749,540	6,603,000	5381	28,678	4,883,164	27,326

Table A14. TKFEN Financial Sustainability Performance Data [107–111].

Year	C6	C7	C8	C9	C10	C
2018	12,147,171	1,112,062	1,401,527	12,035,520	4,424,395	2948
2019	14,603,354	1,603,391	1,414,859	12,663,148	5,496,870	5197
2020	11,729,779	1012	67,398	13,917,033	5,810,900	22,516
2021	16,222,968	478,221	829,390	21,913,573	7,725,460	28,233
2022	30,668,492	2,350,415	3,448,392	32,187,365	10,590,200	27,326

Table A15. TOASO Environmental Sustainability Performance Data [112–116].

Year	C1	C2	C3	C4	C5	C
2018	323,878	1,073,623	73,847	76,171	6,448,315	66,441
2019	289,512	929,882	54,789	57,002	6,560,538	68,651
2020	275,955	788,444	58,931	60,093	6,460,541	75,997
2021	245,812	776,732	55,086	56,366	6,664,917	126,527
2022	233,833	794,608	62,690	63,982	7,283,871	368,513

Table A16. TOASO Financial Sustainability Performance Data [116–120].

Year	C6	C7	C8	C9	C10	C
2018	18,603,331	1,180,306	1,330,423	13,001,799	3,706,555	66,441
2019	18,896,914	1,660,103	1,481,639	12,809,287	4,329,209	68,651
2020	23,556,747	2,066,163	1,784,170	19,475,621	4,468,611	75,997
2021	29,684,305	4,095,719	3,281,316	23,473,341	5,743,391	126,527
2022	65,545,354	8,929,866	8,562,191	40,375,815	11,313,640	368,513

Table A17. TCELL Environmental Sustainability Performance Data [121–125].

Year	C1	C2	C3	C4	C5	C
2018	96,914	105,958	6768	6534	501,401	40,934
2019	119,167	236,357	5085	5085	572,64	47,591
2020	146,891	154,057	3698	3698	524,048	46,601
2021	1,034,436	134,634	3500	3500	140,162	44,347
2022	987,870	145,832	2651	2651	1,349,268	66,326

Table A18. TCELL Financial Sustainability Performance Data [123–127].

Year	C6	C7	C8	C9	C10	C
2018	20,350,557	6,238,822	2,177,335	42,765,275	16,053,554	40,934
2019	23,996,262	6,596,452	3,276,690	45,714,975	18,082,944	47,591
2020	28,272,751	8,188,484	4,239,620	51,498,393	20,784,938	46,601
2021	34,906,646	14,402,681	5,031,278	70,682,643	22,562,272	44,347
2022	52,169,979	19,671,614	11,052,234	101,264,805	30,895,051	66,326

Table A19. ULKER Environmental Sustainability Performance Data [128–132].

Year	C1	C2	C3	C4	C5	C
2018	450,524	726,700	10,693	17,363	146,842	12,551
2019	447,201	739,533	8801	14,598	148,629	19,956
2020	442,112	709,083	8543	15,791	141,732	24,209
2021	457,992	667,961	15,150	16,399	2,286,935	39,786
2022	460,195	653,651	15,991	16,502	2,255,676	88,643

Table A20. ULKER Financial Sustainability Performance Data [133–137].

Year	C6	C7	C8	C9	C10	C
2018	5,955,508	779,084	787,621	10,669,872	3,679,732	12,551
2019	7,803,120	1,153,718	1,011,224	12,791,752	4,934,232	19,956
2020	9,400,861	1,492,738	1,203,585	17,892,504	6,473,561	24,209
2021	12,537,080	2,429,990	162,419	26,243,625	4,313,902	39,786
2022	28,196,847	5,858,897	199,520	37,858,791	7,682,492	88,643

Appendix B

Appendix B.1. Python Implementation of ANN-Based Reverse DEMATEL Methodology

```
import numpy as np
import tensorflow as tf
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import Dense
from sklearn.model_selection import train_test_split
1. Training data: Weights of 6 criteria
X = np.array([
    [0.2156, 0.0032, 0.0810, 0.0616, 0.2501, 0.3884],
    [0.0049, 0.0074, 0.0100, 0.0099, 0.7379, 0.2303],
    [0.1508, 0.3127, 0.0678, 0.0889, 0.0299, 0.3499],
    [0.2759, 0.0007, 0.0021, 0.0692, 0.4144, 0.2377],
    [0.0205, 0.0099, 0.0163, 0.0161, 0.8021, 0.1352],
    [0.0046, 0.0099, 0.7194, 0.0699, 0.0057, 0.1907],
    [0.0575, 0.0370, 0.2054, 0.2667, 0.1270, 0.3063],
    [0.0225, 0.0278, 0.0211, 0.0213, 0.0035, 0.9037],
    [0.5063, 0.0406, 0.0408, 0.0408, 0.3504, 0.0212],
    [0.0001, 0.0013, 0.0408, 0.0019, 0.6790, 0.2768]
])
2. Direct-relation matrices (targets) generated using outer product
y = np.array([np.outer(w, w).flatten() for w in X])
3. Train-test split
X_train, X_test, y_train, y_test = train_test_split(X, y, test_size = 0.2)
4. ANN model
model = Sequential([
    Dense(64, input_dim = 6, activation = 'relu'),
    Dense(128, activation = 'relu'),
    Dense(64, activation = 'relu'),
    Dense(36, activation = 'linear')
])
5. Training
model.compile(optimizer = 'adam', loss = 'mse', metrics = ['mae'])
model.fit(X_train, y_train, epochs=300, batch_size = 2, verbose = 0)
6. Prediction example
new_weights = np.array([[0.2, 0.05, 0.1, 0.15, 0.3, 0.2]])
predicted_d = model.predict(new_weights).reshape(6, 6)
print("Estimated Direct-Relation Matrix (D):")
print(np.round(predicted_d, 3))
```

Appendix B.2. Architectural Sensitivity (Hyperparameter Sweep) of ANN-Based Reverse DEMATEL Methodology

Table A21. Architectural Sensitivity (Hyperparameter Sweep) Results of ANN-Based Reverse DEMATEL Methodology.

Architecture	Activation	MSE (mean $\pm$ std)	MAE (mean $\pm$ std)
(64, 128, 64)	ReLU	0.00361 ± 0.00033	0.0318 ± 0.0020
(128, 128, 64)	ReLU	0.00392 ± 0.00047	0.0342 ± 0.0024
(128,)	ReLU	0.00425 ± 0.00060	0.0356 ± 0.0031
(64,)	Tanh	0.00441 ± 0.00058	0.0369 ± 0.0033
(32,)	ReLU	0.00502 ± 0.00077	0.0388 ± 0.0040

Appendix B.3. 5-Fold Cross-Validation of ANN-Based Reverse DEMATEL Methodology

MSE: 0.00388 ± 0.00463
MAE: 0.0305 ± 0.0122

Appendix B.4. Input-Noise Robustness of ANN-Based Reverse DEMATEL Methodology

Table A22. Input-Noise Robustness Results of ANN-Based Reverse DEMATEL Methodology.

Noise σ	Δ Output (Frobenius Norm, mean $\pm$ std)
0.005	0.00563 ± 0.00066
0.010	0.01134 ± 0.00154
0.020	0.02273 ± 0.00244
0.050	0.05526 ± 0.00734

Appendix B.5. Local Sensitivity (Jacobian Norms) of ANN-Based Reverse DEMATEL Methodology

Median Frobenius norm: 1.231
Mean $\pm$ std: 1.210 ± 0.155 (min 0.919, max 1.399)
Finding: Tight spread of Jacobian norms across samples demonstrates well-conditioned mappings from weights to D matrices.

Appendix C. Advantages of the Developed Method Compared to Existing Methods

Table A23. Advantages of the Developed Original Method Compared to Existing Methods.

Abbreviation	Full Form	How the Method Is Applied	Advantages Provided by Our Original Method
Entropy	Entropy	Objectively calculates criterion weights from data variability.	Integrated with reverse DEMATEL to achieve data-driven weighting and more reliable cause–effect relationships.
DEMATEL	Decision-Making Trial and Evaluation Laboratory	Visualizes direct and indirect cause–effect relationships among criteria, usually via expert judgments.	Combined with ANN and data to reduce subjectivity and increase predictive power and stability.

Table A23. *Cont.*

Abbreviation	Full Form	How the Method Is Applied	Advantages Provided by Our Original Method
AHP	Analytic Hierarchy Process	Determines criterion weights through hierarchical pairwise comparisons.	Cannot account for interdependencies; our model produces data-driven interaction maps covering network effects.
ANP	Analytic Network Process	An extension of AHP that considers interdependencies between criteria.	Still relies on subjective judgments; our model learns directly from data with ANN to derive dependencies objectively.
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution	Ranks alternatives by their distance from ideal and anti-ideal solutions.	Our model not only ranks but also uncovers interactions among criteria and verifies weights.
FTOPSIS	Fuzzy TOPSIS	TOPSIS extended with fuzzy logic to handle uncertainty.	Considers uncertainty but does not discover interactions; our approach fills this gap.
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation	Uses an outranking approach to rank alternatives.	Ranks but does not extract cause–effect relationships; our method provides both weighting and interaction mapping.
COPRAS	Complex Proportional Assessment	Evaluates alternatives based on the ratios of criterion scores.	We go beyond simple ratio-based ranking by producing data-driven cause–effect matrices and sensitivity analyses.
SWARA	Stepwise Weight Assessment Ratio Analysis	Relies on experts to determine criterion weights step by step.	We minimize expert subjectivity through entropy combined with reverse DEMATEL.
CoCoSo	Combined Compromise Solution	Aggregates several compromise solutions to rank alternatives.	Our framework goes beyond ranking to show inter-criteria relationships and their stability.
WASPAS	Weighted Aggregated Sum Product Assessment	Ranks alternatives using weighted sum and product scores.	In addition to such rankings, our method provides cause–effect relationships and stability analysis.
CRADIS	Compromise Ranking of Alternatives from Distance to Ideal Solution	An alternative compromise-based ranking technique used to evaluate options under conflicting criteria.	Our approach incorporates data-driven weighting, causal mapping, and robustness tests absent from standard CRADIS applications.
VIKOR	Visekriterijumsko Kompromisno Rangiranje (Multi-Criteria Optimization and Compromise Solution)	Identifies a compromise solution closest to the ideal among conflicting criteria.	Unlike VIKOR, our framework provides bidirectional interaction mapping and empirical robustness analyses rather than only compromise rankings.
BWM	Best–Worst Method	Determines criterion weights by comparing the best and worst criteria.	Our model complements objective weighting and reverse causal discovery, avoiding reliance on subjective extremes.

Table A23. *Cont.*

Abbreviation	Full Form	How the Method Is Applied	Advantages Provided by Our Original Method
GRA	Grey Relational Analysis	Evaluates alternatives by measuring grey relational grades under incomplete or uncertain information.	Our approach reduces uncertainty by combining objective entropy weighting with reverse DEMATEL and adds sensitivity tests to ensure stable outcomes.

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