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A Hybrid Multi-Criteria Decision Analysis to Explore Barriers to the Circular Economy Implementation in the Food Supply Chain

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Abstract: This research aims to identify, categorize, and prioritize the barriers hindering the implementation of the circular economy (CE) within food supply chains. To do so, a hybrid multi-criteria decision analysis method, combining a decision-making trial and evaluation laboratory (DEMATEL) and the analytical network process (ANP), is used to analyze multiple determinants extracted from the target literature and the expert panel opinions. As a result, the key barriers to implementing the CE in the food sector were identified and ranked through the hybrid multi-criteria decision analysis. The practicality and validity of the model in the case of causal relationships that have hindered the CE transition in the food sector in Iran, as a developing country, are examined. A total of 15 barriers in six dimensions were analyzed. The "technical and technological capabilities", "financial issues", and "production issues" were distinguished as the most important dimensions. Moreover, "lack of circular design and innovative packaging to reduce food waste", "high cost of CE implementation", and "insufficient use of reusable, recyclable, and recoverable materials" were identified as the key barriers in the CE transition in food supply chains. The findings of this study revealed that "government policies", "culture", and "financial issues" were the most significant "cause" dimensions, which could leverage the elimination of "effect" dimensions, including "technical and technological capabilities", "management and collaboration issues", and "production issues". The identified challenges and barriers pave the way for CE implementation and outline focal points for decision makers to mobilize their efforts in this regard. The findings can effectively contribute to the domain by providing insightful guidelines for the government and associated authorities, policymakers, and all stakeholders within the food supply chain to support the CE transition in the food sector.

Keywords: food waste; circular food supply chain; circular economy; multi-criteria decision-making; sustainable consumption

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1. Introduction

The traditional business models mainly operate based on the "take–make–dispose" model, in which virgin raw material is extracted and products are produced and sold to end customers; these products become waste at their end-of-life and are discarded by the customers [1,2]. This linear-based approach of production and consumption depletes non-renewable resources and leads to severe ecological, economic, and social impacts on the global community [3]. Hence, due to global concerns about the sustainable environment and resource efficiency, the transition from a linear economy to a circular economy (CE) has gained momentum in recent years as a solution to tackle the associated challenges by increasing resource efficiency, minimizing waste, and reducing emissions during product lifecycles [4,5].

The CE with a regenerative nature focusing on closing the supply chain loops significantly relies on effective waste management practices, from waste prevention at the top of the waste hierarchy to disposal at the bottom [6]. In this regard, implementing the CE within the various ranges of industries and sectors—such as the automobile industry [7], the construction industry [8], the textile and clothing industry [9], food supply chains [10,11], biofuel industries [12], and municipal solid waste treatment systems [13,14]—has been under intense investigation. Nevertheless, putting the CE in place faces significant challenges, and it is still unexplored due to the primary focus on the linear economy model [15].

The food industry as a global complex network of various businesses to provide people with food is one of the largest industries in the world. In this vein, food waste is significant in supply chains due to the increasing population and the need to mass produce food on an industrial scale, resulting in a wide range of adverse effects on society, the economy, and the environment. After mobility and housing, the provision of food for nutrition is the third biggest contributor to global emissions, contributing approximately 10 billion tonnes of emissions [16]. Based on the food waste index report provided by the United Nations Environment Program, around 8–10% of global greenhouse gas emissions are linked to food waste and loss [17]. For instance, the current agricultural system in Europe generates approximately 700 million tonnes of agro-food waste per year [18]. Hence, through better use of resources, the industry needs to change the way food is produced in a CE framework, especially in cities where approximately 80% of food will be consumed by 2050 [19]. There is an utmost need to reduce food waste and loss by rethinking, redesigning, and operating all practices within the food supply chain in a more sustainable and CE-based setting. In this vein, effective policies and actions are needed to support food systems in tackling food waste and loss towards achieving sustainable development goals, in particular, goals 2 (zero hunger) and 12 (sustainable consumption and production) launched by the United Nations [20].

The agri-food sector has notable potential in transitioning toward a CE as well as a low-carbon and climate-friendly economy since food waste is considered a significant contributor to global waste generation [21]. However, due to the complexity of food systems and potential conflicts among involved stakeholders within the food supply chain, creating closed loops and circularity within this industry face multiple challenges. Food waste in developed countries is mainly seen in the consumption stage, whereas due to poor handling and storage facilities in developing and emerging economies, production and post-harvest phases generate more waste [15]. Mehmood et al. [21] introduced environmental, policy and economic, and financial benefits as the most important drivers of the CE implementation in the agri-food supply chain, while institutional, financial, and technological risks appeared as the most challenging associated barriers. In an empirical survey to identify the main barriers to the implementation of sustainable food consumption and production in China, Liu et al. [22] identified that the lack of environmental regulations and education plays a key role.

However, although the contribution of the food industry to the CE transition has been investigated from different perspectives, from farm production to household consumption, the empirical research in this area is still in its infancy stage. In this vein, identifying the most critical drivers and barriers to implementing CE within the food supply chain is of great importance. Therefore, this research aims at identifying, categorizing, and prioritizing the barriers to implementing CE in food supply chains and highlighting their causal relationships in Iran, as a developing country. In this regard, the following two questions are answered in this research: (i) What are the main barriers to implementing a CE in the food sector in Iran, and (ii) how are such barriers prioritized for action? To this end, a hybrid multi-criteria decision analysis (MCDA) method, combining a decision-making trial and evaluation laboratory (DEMATEL) and the analytical network process (ANP), is used to analyze multiple determinants extracted from the literature and expert opinions. MCDA methods have been widely used to support decision-making processes by identifying the best solution among a finite set of parameters within a wide range of domains, such as risk management [23], sustainable development [24], and project management [25].

While few pieces of research differentiated between hard barriers and soft barriers [26], to the best of our knowledge, none of them has quantified the impact of hard barriers and soft barriers. This study identified the impact of these types of barriers and determined the causal relationship between them.

The majority of the research on the CE has predominantly emphasized the context of developed countries, while studies specifically focusing on developing countries remain scarce [27]. Implementing CE in Iran, as a developing country, is still unexplored. Although several contributions have been made to support the CE transition in different industries and sectors—such as the water sector [28], and the cable and wire industry [29]—these studies have mainly focused on optimization models in closed-loop supply chains. As a result, there is still a significant gap in comprehensively understanding the barriers to the CE, especially within the food supply chains. Consequently, further research is necessary to address this issue. To the best of the authors' knowledge, the current study is the first research in the literature that explores the main barriers to CE implementation in the food supply chain in Iran. Hence, the discoveries have the potential to contribute to the domain by offering valuable recommendations to policymakers, aiding the transition towards a circular economy in the food sector.

The remainder of the current research is structured as follows. Section 2 provides an overview of the MCDA applications in identifying barriers and drivers in implementing the CE within different industries. The applied method and data collection procedure are described in detail in Section 3. Section 4 delivers the analysis results and the main findings of the research, including identified barriers, the influential network relations map, and influential weights of the CE implementation barriers. A discussion of the main results is presented in Section 5, followed by concluding remarks, implications, limitations, and future research avenues for further developments in Section 6.

2. CE Barriers: An Overview

The increasing recognition of the importance of sustainability has encouraged researchers to highlight the CE potential in contributing to the achievement of sustainable development goals [30]. Sharma et al. [31] noted that waste management influences all pillars of sustainability; they concluded that CE brings long-term stability and provides economic, environmental, and social benefits. Over the last decade, the CE has attracted remarkable attention in the literature as a solution to tackle concerns about climate change, limited resources, unstable economic conditions, and exponential growth in generating waste [32].

The main body of research in the food waste domain has focused on energy production and food waste valorization through conversion processes in biorefineries [33–36] rather than food waste prevention at the consumption level. Previous studies have shown that major elements responsible for food waste and loss mainly come from stakeholder attitudes, ineffective management of perishable food items, buyer–supplier agreements, consumer behavior, and supply chain interruptions [37]. Hence, effective food waste management towards a CE requires an accurate measurement of the origin and volume of the generated waste and consumer awareness [38].

The CE proposes a new paradigm for the sustainable food industry which considers waste minimization and value mining of wastes to gain economic benefits and mitigate environmental loss [22]. Goyal [39] summarized the role of the CE in the food sector as a key player in reducing waste and hunger and enhancing social equality. However, food systems encounter many challenges due to the interdependency with political, environmental, institutional, and technological factors. Moreover, food value chains face loss and waste during various stages of the supply chain, such as agriculture, harvest, storage, process, transportation, consumption, and post-consumption [22]. Nevertheless, transitioning towards a CE is complex and faces multiple challenges and barriers. Hence, the limitation of the linear economy and the benefit of implementing CE have encouraged research communities to investigate the drivers and barriers toward the CE transition.

The CE implementation barriers have been investigated from different perspectives in different contexts. Kirchherr et al. [40] presented a detailed study on the CE barriers and distinguished four categories of barriers, including cultural, regulatory, market, and technological. They also noted that there are interaction effects among different categories. Grafström and Aasma [41] outlined four main barriers to implementing a CE in general, including technological, institutional, cultural, and market. Kumar et al. [42] highlighted the role of economic, socio-political, environmental, and legal challenges and barriers in the CE transition. Jaeger and Upadhyay [43] addressed high cost, complexity in supply chains and collaboration networks, and lack of technical skills and information as the main barriers to the CE implementation. However, due to the wide coverage of the CE within different sectors, each sector and industry might face different challenges. For instance, by conducting a systematic review, De Bernardi et al. [44] identified seven critical issues for the CE transition in food systems, namely, multistakeholder coordination, business models, consumer behavior, performance and measurement systems, transition processes, barriers, and digital technologies.

Since the CE implementation barriers are context/country-specific, the literature investigated the barriers for various industries in different countries [22]. Some studies are country-level, while others may be related to a specific region. Additionally, some of them are general while others concentrate on a specific industry and/or a specific product. In this regard, MCDA methods, as a powerful tool in decision-making processes based on multiple criteria, have been widely used in identifying and prioritizing solutions among a finite set of parameters [23]. Table 1 summarizes the research conducted on the CE drivers and barriers using various MCDA methods, highlighting the applied approach/method, the context and country, and the aims and results of the studies.

Table 1. Previous studies on prioritizing CE barriers.

Reference	Approach/Method	Context	Country	Summary of the Research	Most Significant Barrier(s)/Driver(s)
[45]	Graph theory–Matrix approach	Leather industries	Bangladesh	This study aims to assess, prioritize, and rank the drivers of sustainable manufacturing in the leather industry.	• Knowledge about the CE
[46]	Fuzzy TOPSIS	Construction and demolition (C&D) waste management	Iran	This paper introduces and prioritizes barriers to transition toward CE in C&D waste management and proposes a framework to accelerate moving toward CE.	• Using finitely recyclable construction materials • Ineffective C&D waste dismantling, sorting, and transporting
[4]	Fuzzy DEMATEL	Food industry	China	The purpose of this paper is to find the key barriers to the circular food supply chain in China.	• Lack of financial resources
[47]	Fuzzy CRITIC	Auto industry–paint industry–textile industry–generic	-	The purpose of this study is to identify and prioritize barriers to generic and industry-specific implementation of CE.	• Lack of environmental law • Insufficient financial resources • Lack of financial incentives
[1]	Fuzzy AHP	Plastic industry	India	This study integrates the philosophy of CE into supply chain management and investigates barriers to implementing circular supply chain management.	• Lack of tax relaxation policies • Poor enforcement regulations to protect the environment

Table 1. *Cont.*

Reference	Approach/Method	Context	Country	Summary of the Research	Most Significant Barrier(s)/Driver(s)
[27]	Fuzzy TOPSIS	Food industry	Pakistan	This paper aims to distinguish and prioritize the barriers to implementing the CE in the food industry in Pakistan.	• Complicated nature of CE • Poor information about shelf-life wastes • Economic viability
[48]	ISM–ANP	Agriculture supply chain	India	This study identifies Industry 4.0 (I4.0) and CE adoption barriers as well as the relationship among them in the agriculture supply chain in India.	• Lack of government support and incentives • Lack of policies and protocols
[32]	Grey–DEMATEL	Automotive sector	Pakistan	The objective of this study is to recognize the key drivers and barriers to CE and their causal effect relationships and to provide guidelines for policymakers.	• Reducing cost • Resource efficiency • Lack of expertise • The feasibility of CE implementation
[49]	Fuzzy AHP and Fuzzy TOPSIS	Dairy industry	India	This study integrates CE and triple bottom line to develop a sustainable performance assessment framework.	• Food quality • Revenue growth • Resource utilization
[22]	Fuzzy DEMATEL	Agri-food sector	China	The study addresses CE barriers from the perspectives of different stakeholders and highlights their causal relationships.	• Weak legal enforcement • Lack of investment in technologies • Behavioral barriers
[26]	Fuzzy DEMATEL	Food supply chain	India	The paper seeks to identify, categorize, and prioritize barriers to CE implementation, and provide suggestions for decision makers.	• Lack of technology • Lack of food waste estimate • Lack of supply chain design • Lack of profit
[50]	ISM–DEMATEL	Food supply chain	India	This study investigates the interrelationship and hierarchical structure of the CE adoption challenges.	• Creating government policy • Providing incentives • Enforcing environmental regulations

Moktadir et al. [45] referred to a lack of knowledge about the CE as the main barrier to the CE transition in leather industries. In research on construction and demolition waste management, Mahpour [46] found that the main barriers to the CE implementation are (i) recyclable construction materials, and (ii) ineffective waste dismantling, sorting, and transporting. Lack of financial resources was outlined as the main challenge of creating circular food supply chains in China [4]. Haleem et al. [47] identified that a lack of environmental law, insufficient financial resources, and lack of incentives play a key role in hindering the CE transition. The lack of tax relaxation policies and poor enforcement regulations to protect the environment were identified by Khandelwal and Barua [1] as the main barriers to the CE transition in the plastic industry. The complexity of the CE, poor information about shelf-life wastes, and economic viability were outlined by Ali et al. [27] as the main challenges to implementing the CE in the food industry in Pakistan. Challenges regarding government support, incentives, and policies were highlighted by Kumar et al. [48] as the main barriers in the circular agriculture supply chain in India.

Khan and Paul [32] identified reducing cost, resource efficiency, lack of expertise, and the feasibility of CE implementation in practice as the main factors hindering CE implementation in the automotive sector in Pakistan. Food quality, revenue growth, and resource utilization were determined by Kumar et al. [49] as the main barriers to the CE transition in the dairy industry in India. Weak legal enforcement, lack of investment in technologies, and behavioral barriers were proposed by Liu et al. [22] as the main challenges to CE implementation in the agri-food sector in China. In two similar studies conducted on the CE transition barriers in the food supply chain in India, while lack of technology, adequate food waste estimation, effective supply chain design, and sufficient benefits were identified by Gedam et al. [26], government policy and incentives, and enforcing environmental regulations were highlighted by Kumar et al. [50] as the main challenges in adopting the CE.

3. Methodology

The literature suggests various MCDM methods to deal with such complex problems. Selecting the appropriate MCDM method is a complicated problem [51]. However, the majority of the MCDM methods, such as AHP, assume that the criteria (barriers) are independent, which is not a realistic assumption in many real-world problems. Thus, more intelligent techniques are required to overcome the modeling of criteria (barriers) dependencies. ANP is one of the most preferable MCDM methods to model barrier dependencies. Despite its popularity, ANP encounters several difficulties in practice. Traditionally, the ANP method assumed that the network structure of barriers is known a priori. However, distinguishing the network structure of barriers is not so easy, and it is substantial for the next steps of ANP. Additionally, ANP implicitly assumes that each category has the same weight [52]. However, the effect of one dimension on the other dimensions might be different in degree. Therefore, researchers employed DEMATEL-based ANP to escalate ANP capabilities and make it more practical. DANP benefits from specific features of DEMATEL such as visualization of cause-and-effect barriers and determining the most influential barriers and dimensions. DANP is a well-suited choice for the structuring network of barriers, modeling cause-and-effect relationships, and determining the importance of barriers [53]. As the impacts of distinguished barriers on implementing CE are not independent, the selected MCDM method must be practical and capable of overcoming the barriers' dependencies. Thus, DANP is preferred over existing MCDM methods.

Since DEMATEL is a well-suited choice for obtaining network relations map (NRMs) [54], the influential network relations map (INRM) generated by the DEMATEL method is used as an un-weighted super-matrix of ANP in this study. The DANP is an appropriate technique for handling causal-effect relationships among the dimensions and criteria. This method has been successfully applied to many real case studies, such as risk assessment [54], knowledge management [55], marketing strategies [52], oil supply chain [56], railway corporate sustainability [57], and waste management [58].

To address the interdependence and feedback among barriers to implementing the CE in the food industry, a hybrid MCDA framework integrating a DEMATEL and the ANP is used, which is called DANP. Unlike traditional statistic methods, only a few experts are required to respond to the DANP questionnaire [59]; for instance, Shen et al. [60] and Chiu et al. [54] gathered responses from eight experts, and Supeekit et al. [61] collected responses from nine experts.

In this research, first, a literature review on the barriers to implementing CE in the food industry in various countries and regions was conducted. Second, the list of identified barriers was presented to a group of eight experts to check for validity and inclusiveness considering the Iranian food industry, and the required amendments based on the experts' opinion was made to the list of barriers. Third, a DANP questionnaire was designed based on the pairwise comparison of the barriers, which was used to gather responses from the same experts consulted in the second stage. After gathering responses from the experts in the fourth stage, in stage 5, the DEMATEL method was used to construct an influential network relations map (INRM). Finally, key barriers were identified by employing DANP to determine the relative weights of the barriers. Figure 1 illustrates the steps taken in this research to employ DEMATEL and ANP methods.

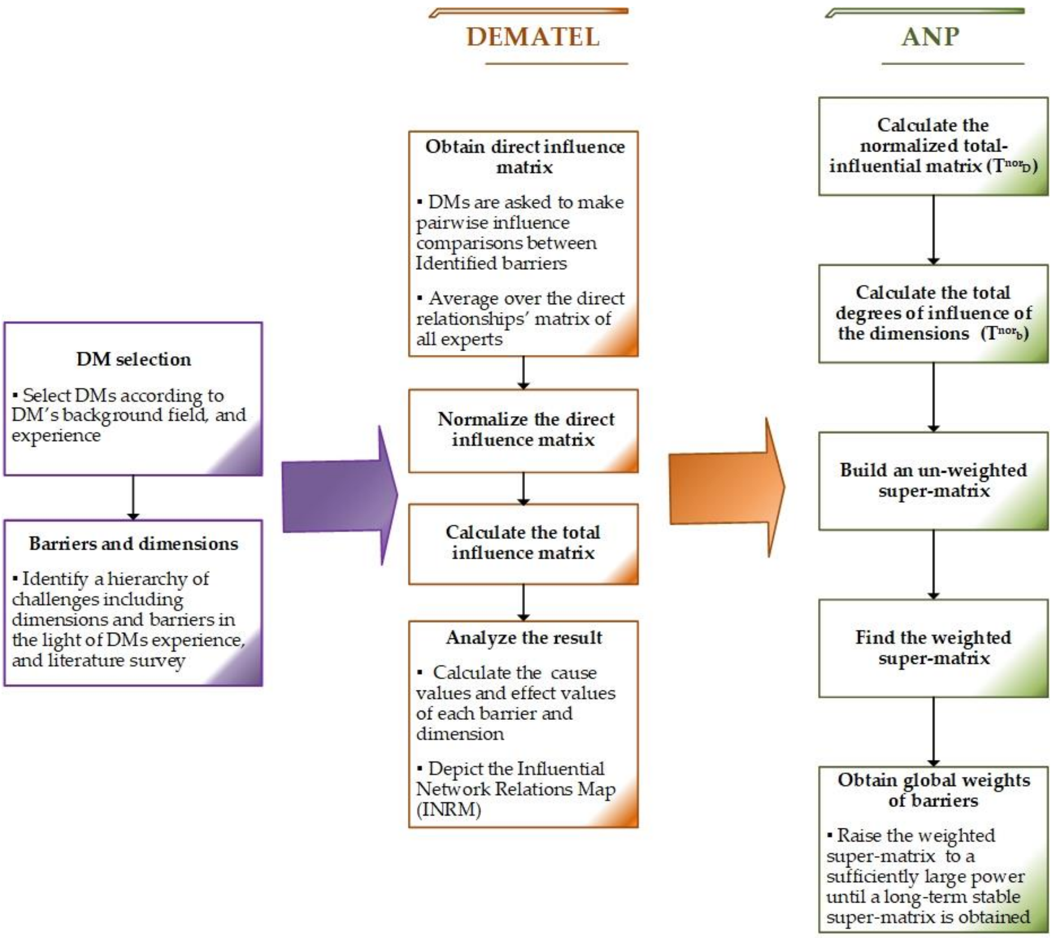

Figure 1. Steps taken in DEMATEL and ANP implementation.

Steps to construct an INRM using the DEMATEL method (steps 1–4) and the relative weights determined by DANP to determine key barriers (steps 5–9) are introduced in the following.

3.1. DEMATEL Technique to Acquire an INRM

Step 1: Calculating the direct influence matrix using a linguistic scale. Knowledge-based experts use a five-point scale to make pairwise influence comparisons between barriers ranging from 0 "absolutely no influence" to 4 "very high influence". Each expert indicates the extent to which barrier i affects barrier j, showing this by g_k^{ij}. Thus, the matrix $G_k = \left[g_k^{ij}\right]$, as shown in Equation (1), represents the direct relationships among barriers from the perspective of the k-th expert. All elements of the diagonal are zero.

$$G_k = \begin{bmatrix} g_k^{11} \cdots g_k^{1j} \cdots g_k^{1n} \\ \vdots \quad\quad \vdots \quad\quad \vdots \\ g_k^{i1} \cdots g_k^{ij} \cdots g_k^{in} \\ \vdots \quad\quad \vdots \quad\quad \vdots \\ g_k^{n1} \cdots g_k^{nj} \cdots g_k^{nn} \end{bmatrix} \quad (1)$$

Then, by averaging over the direct relationships' matrix of all experts, the elements of the direct influence matrix Z are calculated as in Equation (2):

$$z^{ij} = \frac{\sum_{k=1}^{K} \omega_k g_k^{ij}}{\sum_{k=1}^{K} \omega_k} \tag{2}$$

where K is the total number of experts, and ω_k is the weight of the k-th expert. This research considers equal weights for all experts.

Step 2: Normalizing the direct influence matrix Z. The normalized direct influence matrix X is produced by using Equation (3). The maximum sum of rows or columns is one.

$$\begin{aligned} & X = \mu.Z \\ & \text{where} \\ & \mu = \min_{i.j}\left\{\frac{1}{\max\limits_{i} \sum_{j=1}^{n} z^{ij}}, \frac{1}{\max\limits_{j} \sum_{i=1}^{n} z^{ij}}\right\}, i, j \in \{1, 2, .., n\} \end{aligned} \tag{3}$$

Step 3: Calculating the total influence matrix T_b. Following Equation (4), the total influential matrix T_b (Equation (5)) is obtained, in which I and O denote the identity and zero matrix, respectively.

$$\begin{aligned} & T_b = X + X^2 + X^3 + \cdots + X^{\xi} \\ & = X(1 + X + X^2 + \cdots + X^{\xi-1})(I - X)(I - X)^{-1} \\ & = X(1 - X^{\xi})(I - X)^{-1} = X(I - X)^{-1}, \text{when} \lim_{\xi \to \infty} X^{\xi} = O \end{aligned} \tag{4}$$

$$T_b = \begin{array}{cc} & \begin{array}{ccccc} D_1 & \cdots & D_j & \cdots & D_m \\ b_{11} \cdots b_{1n_1} & \cdots & b_{j1} \cdots b_{jn_j} & \cdots & b_{m1} \cdots b_{mn_m} \end{array} \\ \begin{array}{cc} D_1 & \begin{array}{c} b_{11} \\ b_{12} \\ \vdots \\ b_{1n_1} \end{array} \\ \vdots & \vdots \\ D_i & \begin{array}{c} b_{i1} \\ b_{i2} \\ \vdots \\ b_{in_i} \end{array} \\ \vdots & \vdots \\ D_m & \begin{array}{c} b_{m1} \\ b_{m2} \\ \vdots \\ b_{mn_m} \end{array} \end{array} & \begin{bmatrix} t_b^{11} & \cdots & t_b^{1j} & \cdots & t_b^{1m} \\ \vdots & & \vdots & & \vdots \\ t_b^{i1} & \cdots & t_b^{ij} & \cdots & t_b^{im} \\ \vdots & & \vdots & & \vdots \\ t_b^{m1} & \cdots & t_b^{mj} & \cdots & t_b^{mm} \end{bmatrix} \end{array} \tag{5}$$

Step 4: Analyzing the results. At this stage, using Equations (6) and (7), each row of matrix T_b is summed to obtain the value of r, and each column is summed to obtain the value of s. By adding r_i to s_i for each barrier, the vector $(r_i + s_i)$ is generated to indicate the importance of each barrier. Similarly, by subtracting s_i from r_i for each barrier, the vector $(r_i - s_i)$ is generated, which indicates the overall influence of the barrier (net effect). Generally, if the value of $(r_i - s_i)$ is positive, barrier i is of causal cluster (i.e., barrier i affects the other barriers), and if $(r_i - s_i)$ is negative, barrier i is of the affected cluster (i.e., barrier i is influenced by other barriers). Finally, an INRM is acquired. The horizontal and vertical axes of a causal graph map the set of $(r_i + s_i)$ and $(r_i - s_i)$ values, respectively. INRM is depicted considering significant relationships above the threshold value. For instance, if the value of t_b^{ij} is higher than the threshold, this significant influence can be shown using an arrow from the $i-$th barrier to the $j-$th barrier in the INRM. In this study, the threshold value is calculated following the Fu et al. [62] threshold calculation formula, as one standard deviation plus the mean of the total influence matrix T_b.

$$T_b = [t_b^{ij}]_{n\times n}, i,j \in \{1,2,\ldots,n\}.$$

$$r = \left[\sum_{j=1}^{n} t_b^{ij}\right]_{n\times 1} = \left[t_b^{i}\right]_{n\times 1} = (r_1,\ldots,r_i,\ldots,r_n)' \tag{6}$$

$$s = \left[\sum_{i=1}^{n} t_b^{ij}\right]'_{1\times n} = \left[t_b^{j}\right]_{n\times 1} = (s_1,\ldots,s_j,\ldots,s_n)' \tag{7}$$

3.2. DANP Steps to Find the Influential Weights of Barriers

Step 5: Finding the normalized total influential matrix. The total influential matrix T_D should be normalized by dividing each row i by t_D^i, following Equations (8) and (9).

$$t_D^i = \sum_{j=1}^{m} t_D^{ij}$$

$$T_D = \begin{bmatrix} t_D^{11} & \cdots & t_D^{1j} & \cdots & t_D^{1m} \\ \vdots & & \vdots & & \vdots \\ t_D^{i1} & \cdots & t_D^{ij} & \cdots & t_D^{im} \\ \vdots & & \vdots & & \vdots \\ t_D^{m1} & \cdots & t_D^{mj} & \cdots & t_D^{mm} \end{bmatrix} \begin{matrix} \to \sum_{j=1}^{m} t_D^{1j} = t_D^1 \\ \\ \to \sum_{j=1}^{m} t_D^{ij} = t_D^i \\ \\ \to \sum_{j=1}^{m} t_D^{mj} = t_D^m \end{matrix} \tag{8}$$

$$T_D^{nor} = \begin{bmatrix} t_D^{11}/t_D^1 & \cdots & t_D^{1j}/t_D^1 & \cdots & t_D^{1m}/t_D^1 \\ \vdots & & \vdots & & \vdots \\ t_D^{i1}/t_D^i & \cdots & t_D^{ij}/t_D^i & \cdots & t_D^{im}/t_D^i \\ \vdots & & \vdots & & \vdots \\ t_D^{m1}/t_D^m & \cdots & t_D^{mj}/t_D^m & \cdots & t_D^{mm}/t_D^m \end{bmatrix} = \begin{bmatrix} t_D^{nor_{11}} & \cdots & t_D^{nor_{1j}} & \cdots & t_D^{nor_{1m}} \\ \vdots & & \vdots & & \vdots \\ t_D^{nor_{i1}} & \cdots & t_D^{nor_{ij}} & \cdots & t_D^{nor_{im}} \\ \vdots & & \vdots & & \vdots \\ t_D^{nor_{m1}} & \cdots & t_D^{nor_{mj}} & \cdots & t_D^{nor_{mm}} \end{bmatrix} \tag{9}$$

Step 6: Finding the T_b^{nor} matrix. The total influence matrix T_b should be normalized based on the total degrees of influence of the dimensions to obtain T_b^{nor}, as shown in Equation (10).

$$T_b^{nor} = \begin{matrix} & & \begin{matrix} D_1 & & \cdots & & D_j & & \cdots & & D_m \\ b_{11} & \cdots & b_{1n_1} & \cdots b_{j1} & \cdots & b_{jn_j} & \cdots b_{m1} & \cdots & b_{mn_m} \end{matrix} \\ \begin{matrix} D_1 \\ \vdots \\ D_i \\ \vdots \\ D_m \end{matrix} & \begin{matrix} b_{11} \\ b_{12} \\ \vdots \\ b_{1n_1} \\ \vdots \\ b_{i1} \\ b_{i2} \\ \vdots \\ b_{in_i} \\ \vdots \\ b_{m1} \\ b_{m2} \\ \vdots \\ b_{mn_m} \end{matrix} & \begin{bmatrix} t_b^{nor_{11}} & \cdots & t_b^{nor_{1j}} & \cdots & t_b^{nor_{1m}} \\ \vdots & & \vdots & & \vdots \\ t_b^{nor_{i1}} & \cdots & t_b^{nor_{ij}} & \cdots & t_b^{nor_{im}} \\ \vdots & & \vdots & & \vdots \\ t_b^{nor_{m1}} & \cdots & t_b^{nor_{mj}} & \cdots & t_b^{nor_{mm}} \end{bmatrix} \end{matrix} \tag{10}$$

Step 7: Building an un-weighted super-matrix W_b. The un-weighted super-matrix W_b can be obtained by transposing the normalized total influential matrix T_b^{nor}, that is, $W_b = (T_b^{nor})'$ (Equation (11)). If an array of the matrix is zero, its corresponding barriers are independent.

$$W_b = (T_b^{nor})' = \begin{array}{c} \\ \\ D_1 \begin{array}{c} b_{11} \\ b_{12} \\ \vdots \\ b_{1n_1} \end{array} \\ \vdots \quad \vdots \\ D_i \begin{array}{c} b_{i1} \\ b_{i2} \\ \vdots \\ b_{in_i} \end{array} \\ \vdots \quad \vdots \\ D_m \begin{array}{c} b_{m1} \\ b_{m2} \\ \vdots \\ b_{mn_m} \end{array} \end{array} \overset{\begin{array}{ccccccc} D_1 & & \cdots & & D_j & \cdots & D_m \\ b_{11} \cdots b_{1n_1} & \cdots & b_{j1} & \cdots & b_{jn_j} & \cdots b_{m1} & \cdots b_{mn_m} \end{array}}{\begin{bmatrix} w_b^{11} & \cdots & w_b^{i1} & \cdots & w_b^{m1} \\ \vdots & & \vdots & & \vdots \\ w_b^{1j} & \cdots & w_b^{ij} & \cdots & w_b^{mj} \\ \vdots & & \vdots & & \vdots \\ w_b^{1m} & \cdots & w_b^{im} & \cdots & w_b^{mm} \end{bmatrix}} \tag{11}$$

Step 8: Finding the weighted super-matrix W_b^* of the DANP. The weighted super-matrix W_b^* (which simplifies the traditional ANP by assuming equal weights to make the method applicable for real world problems) can be calculated by multiplying T_D^{nor} and W_b, as shown in Equation (12).

$$W_b^* = T_D^{nor} W_b = \begin{bmatrix} t_D^{nor_{11}} \times w_b^{11} & \cdots & t_D^{nor_{i1}} \times w_b^{i1} & \cdots & t_D^{nor_{m1}} \times w_b^{m1} \\ \vdots & & \vdots & & \vdots \\ t_D^{nor_{1j}} \times w_b^{1j} & \cdots & t_D^{nor_{ij}} \times w_b^{ij} & \cdots & t_D^{nor_{mj}} \times w_b^{mj} \\ \vdots & & \vdots & & \vdots \\ t_D^{nor_{1m}} \times w_b^{1m} & \cdots & t_D^{nor_{im}} \times w_b^{im} & \cdots & t_D^{nor_{mm}} \times w_b^{mm} \end{bmatrix} \tag{12}$$

Step 9: Obtaining global weights of barriers. Finally, the weighted super-matrix should be raised to a sufficiently large power M until a long-term stable super-matrix is obtained. The converged weighted super-matrix W_b^* should be limited ($\lim_{M\to\infty}(W_b^*)^M$) to reach the overall influential weights of barriers $W = (w_1, \ldots, w_i, \ldots, w_n)$.

3.3. Data Collection

The designed web-based questionnaire was used to gather responses from our panel of eight experts from seven food-related areas, including food production, customer relationship, top management, environment, agriculture, food science, and logistics. Using the questionnaire, the experts were asked to determine the direct effects of each *i*-th barrier on each other *j*-th barrier. The influence of the identified barriers was estimated on a five-point scale ranging from zero "absolutely no influence" to four "very high influence". For each expert *k*, the answers were aggregated in the *k*-th direct influence matrix.

4. Result

Here, the identified variables used to design the questionnaire, the built INRM, and the CE implementation barriers' weights are presented in Section 4.1, Section 4.2, and Section 4.3, respectively.

4.1. Identified Barriers to the Implementation of CE in Food Supply Chains

Based on the literature, a list of barriers to adopting CE in food supply chains was presented to the expert panel, who were asked to mark the validity of each barrier for the case of Iran's food industry and check if any significant barrier is missing. Based on the feedback received, 15 barriers were identified as the ones affecting the implementation of CE in the Iranian food industry, which were then classified into six main dimensions, including (i) production issues, (ii) management and collaboration issues, (iii) technical and technological capabilities, (iv) financial issues, (v) government policies, and (vi) culture. A description of the classified barriers is presented in Table 2. In this table, the type of barriers, in terms of being hard or soft, is also specified. In practical terms, the obstacles to the transition towards a CE can be categorized into two types: hard barriers, such as technological and financial challenges, and soft barriers, which encompass regulatory and cultural issues. These barriers collectively impede the progress towards achieving a circular economy [63]. This classification is based on the work of Nye [64], which differentiated between soft power, implying the ability to bring changes through values and institutional practices, and hard power, implying the ability to make changes through technological or economic tools. This study follows the classification of barriers into soft and hard categories, as proposed by de Jesusa and Mendonça [63].

Table 2. Identified CE implementation barriers.

Dimensions	Barriers	Type of Barriers	Descriptions	Supporting Literature
Production issues	Lack of circular design and innovative packaging to reduce food waste	Hard	This barrier considers a lack of circular design regarding redesigning, remanufacturing, reducing, reusing, recycling, and recovering materials, as well as energy inefficiency due to the inability to rethink the design phase, challenges of green materials, complexity in product architecture and functionality, and inadequate environmentally friendly technology. In developing economies, a major part of food waste results from improper packaging, and unsuitable handling and transportation facilities and methods.	[32,40,45–48,50,65]
	Insufficient use of reusable, recyclable, and recoverable materials	Hard	Since recycling is an important element of CE, using recyclable and eco-friendly materials is recommended. The unavailability of high-quality circular materials and their high price are among CE challenges.	
Management and collaboration issues	Limited top managers' engagement in CE practices	Soft	Top managers design policies and strategies for new initiatives in businesses; hence, weak support and commitment of top managers to reduce, reuse, recycle, and recover policies are barriers to achieving CE.	[1,4,26,32,47,50,66,67]
	Insufficient/ineffective collaboration among supply chain players	Soft	The involvement and support of both the supply and demand sides of the market are crucial to the successful implementation of CE strategies. Willingness to supply, design, purchase, and use circular products allows a shift from a linear economy to a CE, while cost or quality issues reduce the attractiveness of the shift toward CE.	

Table 2. *Cont.*

Dimensions	Barriers	Type of Barriers	Descriptions	Supporting Literature
Technical and technological capabilities	Poor logistics and reverse logistics networks	Hard	Optimization of logistics and reverse logistics networks can lead to a reduction in negative environmental impacts and economic costs and allow transitioning from a linear economy to CE.	[1,4,21,26,27,32,47,48,50,66,67]
	Limited technical expertise	Soft	Implementation of the CE, as an emerging concept, requires a skilled workforce equipped with a wide range of knowledge and technical know-how expertise, such as strategy development, material sciences, product and packaging design, system analysis, and logistics. Inadequate expertise negatively affects the implementation of CE.	
	Absence of an information exchange system among supply chain partners	Hard	The lack of appropriate information technology infrastructure hinders tracking information on material flow among supply chain partners.	
	Insufficient food waste to energy recovery technologies/ practices	Hard	A high percentage of food waste is generated during the production stage, leading to economic and environmental costs. These costs can be reduced by using innovative technologies such as bio-refinery, industrial symbiosis, etc. Innovative technological solutions to avoid waste or reuse it for other value-added applications (food waste valorization) are prerequisites for CE transition	
Financial issues	High cost of CE implementation	Hard	Besides the low profit margin of food recycling, the high cost of green design, eco-friendly materials, green technology, sustainable packaging, waste collection, segregation, and transportation acts as a deterrent to switching to CE. Additionally, due to the absence of successful circular business models, organizations may encounter extra costs for CE implementation.	[1,4,21,22,26,27,32,47,66,67]
	Insufficient financial resources for the CE implementation	Hard	To adopt CE for the food industry, further processing/ transformation is required, which is cost-intensive (e.g., R&D and extra infrastructure investment). Thus, extra financial resources are required to adopt CE.	
	Low economic benefits in the short term	Hard	CE is an emerging business strategy, and there are few successfully established CE models. Therefore, it is challenging to correctly adopt it to gain economic benefits.	
Government policies	Lack of effective regulations and environmental enforcement	Soft	This theme refers to ineffective punitive policies such as tax policy, legislative enforcement regarding recycling products, environmental standards, and regulations supporting CE. The lack of these policies hinders responsible production and consumption.	[22,32,45,46,66,67]
	Lack of government support and incentives	Soft	Inadequate supportive policies such as government incentives, financial subsidies, and public training programs are some other barriers to adopting CE.	

Table 2. *Cont.*

Dimensions	Barriers	Type of Barriers	Descriptions	Supporting Literature
Culture	Inadequate public awareness and knowledge about values and adopting CE	Soft	In emerging economies, customers produce a large portion of food waste. Lack of knowledge about environmental impacts and long-term economic values, maintaining products during the consumption period, recycling materials, and returning used products are barriers to transition from linear economy to CE.	[1,26,27,32,47,50,66,67]
	Lack of market enthusiasm/pressure for circular technologies and products	Soft	In addition to poor demand for environmentally superior products, limited consumer willingness for accepting circular products plays a key role in transitioning towards CE. Circular product characteristics and limitations—such as price, material, beauty, design, and packaging that fail to fulfill consumers' cultural, social, and psychological needs—appear as a barrier to adopting CE. Additionally, in developing countries, customers have few/no responsibilities for using recycled and refurbished products.	

Barriers mentioned in Table 2 were used to design a web-based questionnaire asking the experts to make a pairwise comparison between them. The expert panel's consensus of significant confidence in the questionnaires was 95.23%.

4.2. The Built INRM

Using a five-point scale, the experts were asked to determine the influential relationships among each pair of barriers in the designed questionnaire. The DEMATEL method was used to find the relationships among dimensions and barriers to CE implementation.

By averaging over the direct relationships' matrix of all knowledge-based experts, the initial direct influence matrix Z, as shown in Table 3, was obtained. Following the equations presented in Section 3, the total influence matrix T_b and the cause-effect of dimensions and barriers were calculated as reported in Tables 4 and 5, respectively.

Table 3. Direct influence matrix Z.

	A1	A2	B1	B2	C1	C2	C3	C4	D1	D2	D3	E1	E2	F1	F2
A1	0.000	4.000	1.000	2.000	1.500	1.000	1.750	1.500	4.000	1.000	4.000	2.000	1.500	1.000	1.875
A2	4.000	0.000	1.000	2.000	0.000	1.875	2.000	2.250	4.000	2.250	4.000	1.875	0.000	2.000	2.000
B1	3.750	2.500	0.000	3.875	3.000	3.750	3.250	3.250	1.000	1.500	1.500	2.500	2.250	0.000	0.000
B2	1.500	1.500	1.000	0.000	3.000	2.000	4.000	2.000	2.250	1.000	1.000	0.000	1.000	0.000	0.000
C1	1.250	1.500	2.000	4.000	0.000	1.000	3.000	2.000	4.000	1.000	1.250	0.000	0.000	0.000	0.000
C2	4.000	2.625	1.000	3.000	2.000	0.000	2.000	4.000	2.250	0.000	1.625	0.000	0.000	1.000	1.000
C3	0.000	0.000	1.625	4.000	0.625	4.000	0.000	1.375	3.000	0.375	0.500	0.000	0.000	0.000	0.125
C4	4.000	2.625	2.000	0.625	1.000	0.125	1.000	0.000	4.000	1.000	3.000	1.375	0.125	0.625	1.375
D1	3.000	2.875	4.000	2.500	1.000	1.750	1.875	2.000	0.000	1.000	3.500	3.625	1.000	1.000	4.000
D2	4.000	1.000	3.875	2.000	2.000	1.000	2.000	3.000	1.000	0.000	0.000	0.125	0.000	1.000	1.000
D3	3.500	2.750	4.000	2.750	1.500	1.875	2.000	2.500	1.000	1.000	0.000	1.250	0.000	1.500	4.000
E1	4.000	4.000	3.625	1.500	1.375	1.000	1.375	2.625	0.000	1.000	0.000	0.000	3.625	2.625	3.000
E2	3.000	2.625	3.000	1.625	1.375	1.000	1.375	1.625	2.375	4.000	3.000	2.375	0.000	1.625	2.000
F1	2.000	1.000	3.000	0.125	1.000	0.250	0.125	1.000	1.625	0.125	2.000	4.000	3.000	0.000	4.000
F2	4.000	3.000	3.375	1.625	0.625	1.000	1.000	3.000	1.000	1.000	1.000	4.000	4.000	2.625	0.000

Table 4. Total influence matrix T_b.

	A1	A2	B1	B2	C1	C2	C3	C4	D1	D2	D3	E1	E2	F1	F2
A1	0.1256	0.1899	0.1248	0.1420	0.0930	0.0931	0.1233	0.1298	0.1871	0.0736	0.1780	0.1184	0.0820	0.0707	0.1218
A2	0.2177	0.1048	0.1275	0.1424	0.0631	0.1127	0.1290	0.1489	0.1882	0.0983	0.1792	0.1180	0.0519	0.0933	0.1274
B1	0.2117	0.1613	0.0975	0.1930	0.1350	0.1594	0.1663	0.1749	0.1358	0.0863	0.1259	0.1205	0.0951	0.0446	0.0715
B2	0.1111	0.0962	0.0855	0.0710	0.1085	0.0959	0.1486	0.1086	0.1235	0.0543	0.0806	0.0407	0.0468	0.0253	0.0441
C1	0.1113	0.1009	0.1120	0.1628	0.0455	0.0779	0.1325	0.1125	0.1628	0.0557	0.0898	0.0458	0.0285	0.0264	0.0482
C2	0.1895	0.1425	0.1002	0.1480	0.0956	0.0573	0.1166	0.1671	0.1419	0.0397	0.1150	0.0581	0.0366	0.0576	0.0830
C3	0.0650	0.0519	0.0848	0.1447	0.0517	0.1303	0.0497	0.0850	0.1208	0.0314	0.0561	0.0320	0.0211	0.0191	0.0371
C4	0.1946	0.1467	0.1297	0.0964	0.0728	0.0623	0.0929	0.0793	0.1724	0.0643	0.1447	0.0953	0.0450	0.0538	0.0986
D1	0.2159	0.1851	0.2045	0.1695	0.0956	0.1227	0.1408	0.1597	0.1113	0.0810	0.1769	0.1664	0.0863	0.0786	0.1751
D2	0.1791	0.0971	0.1549	0.1205	0.0940	0.0774	0.1111	0.1386	0.1026	0.0349	0.0669	0.0542	0.0355	0.0514	0.0706
D3	0.2062	0.1651	0.1863	0.1618	0.0982	0.1156	0.1326	0.1562	0.1260	0.0721	0.0880	0.1028	0.0545	0.0800	0.1602
E1	0.2210	0.1954	0.1809	0.1319	0.0946	0.0940	0.1168	0.1580	0.1081	0.0798	0.0958	0.0793	0.1382	0.1088	0.1423
E2	0.2049	0.1677	0.1772	0.1416	0.0990	0.0982	0.1224	0.1422	0.1575	0.1447	0.1591	0.1311	0.0539	0.0870	0.1259
F1	0.1592	0.1174	0.1590	0.0852	0.0759	0.0645	0.0732	0.1078	0.1161	0.0509	0.1194	0.1612	0.1230	0.0455	0.1586
F2	0.2305	0.1829	0.1849	0.1390	0.0827	0.0972	0.1130	0.1722	0.1324	0.0830	0.1222	0.1736	0.1514	0.1130	0.0839

Table 5. Sum of the influences given and received on dimensions and barriers.

Dimensions	Barriers	r_i	s_i	$(r_i - s_i)$	$(r_i + s_i)$
A. Production issues		3.756	4.748	−0.993	8.504
	A1 Lack of circular design and innovative packaging to reduce food waste	1.853	2.643	−0.790	4.497
	A2 Insufficient use of reusable, recyclable, and recoverable materials	1.902	2.105	−0.202	4.007
B. Management and collaboration issues		3.219	4.159	−0.940	7.378
	B1 Limited top managers' engagement in CE practices	1.979	2.109	−0.131	4.088
	B2 Insufficient/ ineffective collaboration among supply chain players	1.241	2.050	−0.809	3.290
C. Technical and technological capabilities		5.391	6.573	−1.183	11.964
	C1 Poor logistics and reverse logistics networks	1.313	1.305	0.007	2.618
	C2 Limited technical expertise	1.549	1.459	0.090	3.007
	C3 Absence of an information exchange system among supply chain partners	0.981	1.769	−0.788	2.749
	C4 Insufficient food waste to energy recovery	1.549	2.041	−0.492	3.590
D. Financial issues		5.464	4.934	0.530	10.398
	D1 High cost of CE implementation	2.169	2.086	0.083	4.256
	D2 Insufficient financial resources for the CE implementation	1.389	1.050	0.339	2.439
	D3 Low economic benefits in the short term	1.906	1.798	0.108	3.703
E. Government policies		3.957	2.547	1.410	6.504
	E1 Lack of effective regulations and environmental enforcement	1.945	1.497	0.448	3.442
	E2 Lack of government support and incentives	2.012	1.050	0.963	3.062
F. Culture		3.678	2.503	1.175	6.182
	F1 Inadequate public awareness and knowledge about values and adopting CE	1.617	0.955	0.661	2.572
	F2 Lack of market enthusiasm/pressure for circular technologies and products	2.062	1.548	0.514	3.610

The significant causal relationship diagrams for barriers are plotted in Figure 2. To plot the INRM, the relationships above the calculated threshold value (one standard deviation plus the mean of the total influence matrix) were considered significant and are illustrated in the figure. The $(r+s)$ values denote cause values, whereas $(r-s)$ values denote the effect values of each barrier. One-way and two-way arrows represent one-way and two-way relationships between corresponding barriers, respectively.

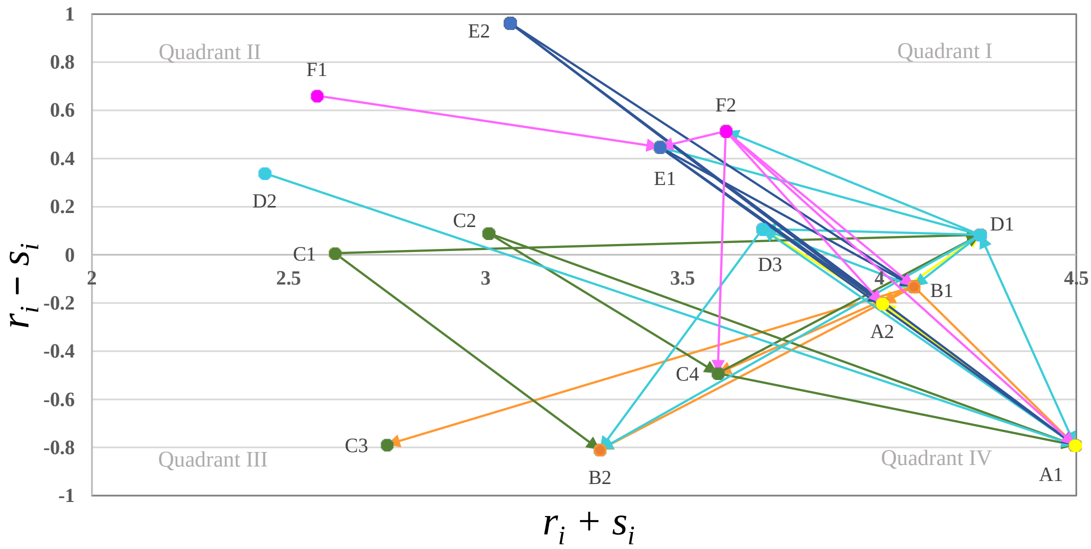

Figure 2. Influential network relations map (INRM).

4.3. Influential Weights of CE Implementation Barriers

After determining the relationship structure of the barriers, the DANP method was applied to derive their influential weights. The un-weighted super-matrix W_b is presented in Table 6, and the overall influential weights of the barriers are reported in the second column of Table 7. In addition, Table 7 provides the DANP ranking, DEMATEL ranking, the sum of rankings, and the overall ranking of the barriers. According to Hu et al. [68], the Borda count is applied to integrate DANP and DEMATEL results.

Table 6. Un-weighted super-matrix W_b.

	A1	**A2**	**B1**	**B2**	**C1**	**C2**	**C3**	**C4**	**D1**	**D2**	**D3**	**E1**	**E2**	**F1**	**F2**
A1	0.3981	0.6751	0.5676	0.5360	0.5246	0.5708	0.5562	0.5703	0.5385	0.6484	0.5553	0.5307	0.5498	0.5756	0.5576
A2	0.6019	0.3249	0.4324	0.4640	0.4754	0.4292	0.4438	0.4297	0.4615	0.3516	0.4447	0.4693	0.4502	0.4244	0.4424
B1	0.4678	0.4725	0.3355	0.5463	0.4076	0.4036	0.3696	0.5736	0.5468	0.5623	0.5352	0.5782	0.5559	0.6512	0.5707
B2	0.5322	0.5275	0.6645	0.4537	0.5924	0.5964	0.6304	0.4264	0.4532	0.4377	0.4648	0.4218	0.4441	0.3488	0.4293
C1	0.2117	0.1391	0.2124	0.2350	0.1234	0.2190	0.1632	0.2369	0.1842	0.2233	0.1953	0.2041	0.2144	0.2361	0.1779
C2	0.2120	0.2484	0.2508	0.2079	0.2116	0.1313	0.4115	0.2028	0.2365	0.1838	0.2301	0.2028	0.2127	0.2008	0.2090
C3	0.2807	0.2843	0.2616	0.3220	0.3597	0.2671	0.1568	0.3023	0.2714	0.2637	0.2638	0.2521	0.2650	0.2277	0.2429
C4	0.2956	0.3282	0.2752	0.2352	0.3052	0.3826	0.2685	0.2580	0.3079	0.3292	0.3107	0.3410	0.3079	0.3355	0.3702
D1	0.4265	0.4042	0.3902	0.4779	0.5279	0.4785	0.5800	0.4520	0.3015	0.5018	0.4403	0.3809	0.3414	0.4054	0.3922
D2	0.1679	0.2111	0.2481	0.2100	0.1807	0.1338	0.1505	0.1686	0.2194	0.1709	0.2520	0.2813	0.3137	0.1776	0.2459
D3	0.4056	0.3847	0.3618	0.3121	0.2914	0.3877	0.2695	0.3794	0.4791	0.3274	0.3077	0.3378	0.3449	0.4170	0.3619
E1	0.5909	0.6945	0.5589	0.4650	0.6163	0.6136	0.6025	0.6794	0.6585	0.6042	0.6535	0.3646	0.7087	0.5671	0.5342
E2	0.4091	0.3055	0.4411	0.5350	0.3837	0.3864	0.3975	0.3206	0.3415	0.3958	0.3465	0.6354	0.2913	0.4329	0.4658
F1	0.3675	0.4227	0.3840	0.3650	0.3535	0.4097	0.3405	0.3532	0.3099	0.4216	0.3330	0.4332	0.4087	0.2230	0.5740
F2	0.6325	0.5773	0.6160	0.6350	0.6465	0.5903	0.6595	0.6468	0.6901	0.5784	0.6670	0.5668	0.5913	0.7770	0.4260

Table 7. Ranking of the barriers.

Barriers	DANP Influential Weights	DANP Ranking	DEMATEL Ranking	Sum of Rankings	Overall Ranking
A1 Lack of circular design and innovative packaging to reduce food waste	0.10180	1	1	2	1
A2 Insufficient use of reusable, recyclable, and recoverable materials	0.08286	3	4	7	3
B1 Limited top managers' engagement in CE practices	0.08099	5	3	8	4
B2 Insufficient/ineffective collaboration among supply chain players	0.08201	4	9	13	6
C1 Poor logistics and reverse logistics networks	0.05258	12	13	25	13
C2 Limited technical expertise	0.06039	9	11	20	10
C3 Absence of an information exchange system among supply chain partners	0.07179	8	12	20	10
C4 Insufficient food waste to energy recovery	0.07962	6	7	13	6
D1 High cost of CE implementation	0.08675	2	2	4	2
D2 Insufficient financial resources for CE implementation	0.04032	13	15	28	14
D3 Low economic benefits in the short term	0.07182	7	5	12	5
E1 Lack of effective regulations and environmental enforcement	0.05583	11	8	19	9
E2 Lack of governmental support and incentives	0.03894	14	10	24	12
F1 Inadequate public awareness and knowledge about values and adopting CE	0.03590	15	14	29	15
F2 Lack of market enthusiasm/pressure for circular technologies and products	0.05841	10	6	16	8

5. Discussion

This study has three main streams of findings. The first stream originates from the interpretation of DEMATEL results. Referring to Table 5, the cause group consists of three dimensions, namely, government policies, culture, and financial issues, and the effect group includes the dimensions of management and collaboration issues, production issues, and technical and technological capabilities. This is while Sharma et al. [69] introduced government policies, technology and techniques, and knowledge and awareness as the driving factors in the CE implementation in food supply chains in India. In this vein, government policies to promote the CE significantly rely on infrastructure, fundraising guidance, financial assistance, and logistics [70]. However, there is still room for further research and developments to evaluate the effect of such government policies on the success of the CE in different regions. Realizing these influential relationships enables decision makers and top managers to make effective policy decisions. Based on $(r + s)$ values, the highest- to lowest-ranked dimensions are technical and technological capabilities (C), financial issues (D), production issues (A), management and collaboration issues (B), government policies (E), and culture (F), respectively. Improving more influential dimensions would result in higher levels of improvement in the system. In addition, the net effect $(r - s)$ values show that government policies (E), culture (F), and financial issues (D) are the most significant cause dimensions, which can leverage the elimination of effect dimensions in the long term.

Furthermore, as can be seen in Figure 2, the limited engagement of top managers in CE practices affects five specific barriers, including lack of circular design and innovative packaging to reduce food waste (A1); insufficient use of reusable, recyclable, and recoverable materials (A2); insufficient/ineffective collaboration among supply chain players (B2); limited technical expertise (C3); and insufficient food waste to energy recovery (C4), and is impacted by five other barriers, namely, the high cost of CE implementation (D1), low economic benefits in the short term (D3), lack of effective regulations and environmental enforcement (E1), lack of governmental support and incentives (E2), and lack of market enthusiasm/pressure for circular technologies and products (F2). This is in line with the research conducted by Singh et al. [71] highlighting the critical role of top management participation in facilitating the CE transition. As highlighted by Zhao et al. [72], the backing from top management within organizations, combined with governmental support and regulations, emerges as a crucial driver for advancing a low-carbon circular economy aimed at achieving net-zero emissions. This highlights the importance of senior managers' commitment to sustainability issues and also sheds light on the business environment factors that can cause challenges for the activities and decision-making of the managers. Moreover, in a survey examining the link among top management commitment, external pressures, and supplier relationship management in fostering the CE, Dubey et al. [73] showed that the effect of external institutional pressures on supplier relationship management can be positively mediated by top management commitment. However, engagement of top management levels in effectively implementing the CE faces some challenges. For instance, Koistinen et al. [74], in a qualitative research study interviewing 34 top managers, outlined that (i) power is a key characteristic of how top managers, as agents of the sustainability transition to a CE, exercise their agency; (ii) the top managers' agency is often limited by structural constraints on multiple levels in their organizations, while they are perceived as the most powerful members of their organizations; and (iii) top managers' power in transitioning towards a CE is significantly dependent on their abilities to secure business profitability.

In addition, barriers with high net effect $(r - s)$ values have the greatest long-term impact on other barriers [4]; hence, effective policies should be made to address these issues. Considering the quadrants specified in Figure 2, it can be observed that poor logistics and reverse logistics networks (C1), limited technical expertise (C2), high cost of CE implementation (D1), insufficient financial resources for CE implementation (D2), low economic benefits in the short term (D3), lack of effective regulations and environmental enforcement (E1), lack of governmental support and incentives (E2), inadequate public awareness and knowledge about values and adopting CE (F1), and lack of market enthusiasm/pressure for circular technologies and products (F2), which are located in quadrant 1, are distinguished as cause barriers with positive net effect $(r - s)$ values, whose elimination leads to a decrease in the effect imposed on barriers affected by them. Quadrant 4 includes effect barriers with negative net effect $(r - s)$ values, namely, lack of circular design and innovative packaging to reduce food waste (A1); insufficient use of reusable, recyclable, and recoverable materials (A2); limited top managers' engagement in CE practices (B1); insufficient/ineffective collaboration among supply chain players (B2); absence of an information exchange system among supply chain partners (C3); and insufficient food waste to energy recovery (C4). Some of these barriers—such as lack of circular design and innovative packaging to reduce food waste (A1), limited top managers' engagement in CE practices (B1), and insufficient use of reusable, recyclable, and recoverable materials (A2) have high $(r + s)$ values, implying that the elimination of these barriers is vital but must be done simultaneously with the elimination of their "cause" barriers. A key point is that policymakers must consider the entire system (based on the generated INRM) to reduce the gap between the linear economy and the CE and facilitate the transition to the CE. Elimination of the variables with the highest $(r_i + s_i)$ values, which are known as the most effective barriers (A1, D1, and B1), might strongly influence the whole system directly and indirectly.

To gain insight into the causal relationships between hard and soft barriers, DEMATEL was employed, taking into account the type of barriers. As can be seen in Table 8, results confirm that hard barriers affect each other significantly, and soft barriers have a significant effect on hard barriers. In addition, the role hard barriers play in the long term is more crucial than soft barriers. However, soft barriers are the cause factors with key roles, acting as the main drivers to eliminate hard barriers.

Table 8. Sum of the influences given and received by different types of barriers.

Type of Barriers	Hard Barriers	Soft Barriers	r_i	s_i	$(r_i - s_i)$	$(r_i + s_i)$
Hard barriers	7.55518	5.50654	13.06172	14.79700	−1.73528	27.85872
Soft barriers	7.24182	5.16186	12.40368	10.66840	1.73528	23.07208

The second stream of results focuses on the influential weights of barriers. According to the second column of Table 7, the highest relative weights are assigned to the lack of circular design and innovative packaging to reduce food waste (A1); the high cost of CE implementation (D1); insufficient use of reusable, recyclable, and recoverable materials (A2); insufficient/ ineffective collaboration among supply chain players (B2); and limited top managers' engagement in CE practices (B1). In this regard, technology plays an important role in enabling food waste reduction platforms by providing opportunities for sharing food surpluses among suppliers and consumers and, also, monitoring frameworks for food waste data for different stakeholders within the food supply chain [75]. Design-driven innovations to generate a higher quality of products and processes have been acknowledged in the literature as an effective solution to contribute to the CE transition [76]. Moreover, the need to align product design with the CE principles to increase the circularity of the system has been highlighted by scholars [77–79]. On the other side, the high cost of implementing the CE, as a challenge hindering the CE transition, has been investigated in the literature. In this vein, proper life-cycle management practices in reducing sustainable CE costs can have profound effects on CE adoption [80]. In addition, providing platforms to create internal and external collaboration networks for advancing CE practices has been highlighted in previous studies through eco-centric dynamic capabilities and knowledge-sharing routines [81]. Hence, in line with extant studies, our results highlight that, to pave the way for the CE implementation, decision makers must focus their strategies on promoting circular design; reducing the cost of CE implementation; facilitating the use of reusable, recyclable, and recoverable materials; and providing a platform for more collaboration among supply chain players. Nevertheless, the link among different players of the food supply chain—such as product/packaging system design, manufacturing, materials supply, and the return flow of recyclable materials to the food waste management stream—needs a more holistic approach to enhance the CE transition in food systems [82].

Moreover, the low ranking of the barrier targeting lack of governmental support and incentives (E2) underscores that, even though the influence of government support and incentives is emphasized by experts, the priority assigned to enhancing such support for CE implementation remains relatively low. This is also confirmed in the case of Pakistan, as another developing country, where lack of government support to promote the CE has been identified as the lowest-ranked barrier to CE implementation in food waste management [27]. Moreover, despite a low $(r + s)$ value for insufficient/ineffective collaboration among supply chain players (B2), the priority of collaboration among supply chain players for CE implementation is still relatively high.

Finally, the last column of Table 7 pertains to the third stream of results. Based on the overall ranking presented, lack of circular design and innovative packaging to reduce food waste (A1); high cost of CE implementation (D1); insufficient use of reusable, recyclable, and recoverable materials (A2); limited top managers' engagement in CE practices (B1); and low economic benefits in the short term (D3), respectively, are the key barriers to transitioning towards CE in the food sector in Iran. This is in line with the findings of

Gedam et al. [26], who highlighted technology and innovation limitations, supply chain challenges, and lack of economic benefits and high cost of investment among critical barriers to CE implementation in developing economies.

Considering the overall results, the findings align with previous studies conducted in the context of developing countries [27,83]. These results were expected, given that inadequate infrastructure, transportation, food industries, and packaging industries contribute to significant food losses in developing countries. Both the public and private sectors play a role in reducing food loss. Additionally, as emphasized in previous studies, food waste at the consumer level is minimal in developing countries [83]. The insights provided can be valuable in effectively supporting the government and associated authorities, policymakers, and all stakeholders within the food supply chain in their efforts toward a successful CE transition in the food sector.

6. Conclusions

This research aimed to comprehensively identify, categorize, and prioritize the factors and their causal relationships that have hindered the transition to a CE in the food sector of Iran, a developing country. Through the application of the DANP method, a total of 15 barriers were identified and ranked across six distinct categories. These categories encompass production issues, management and collaboration issues, technical and technological capabilities, financial challenges, government policies, and culture. On this basis, the following items were ranked as the main three influential barriers, respectively, based on their calculated weights: (i) the lack of circular design and innovative packaging to reduce food waste, (ii) the high cost of CE implementation, and (iii) insufficient use of reusable, recyclable, and recoverable materials. On the contrary, (i) poor logistics and reverse logistics networks, (ii) insufficient financial resources for CE implementation, and (iii) inadequate public awareness and knowledge about values and adopting CE were ranked as the three least influential barriers among the 15 identified barriers, respectively.

The findings of this study make significant contributions to both theoretical and practical aspects. The theoretical contribution includes, first, extending the extant studies on the identification of the CE barriers in food supply chains and, second, providing a comprehensive understanding of these barriers in the context of transitioning toward a CE in the food sector of Iran. From a practical perspective, the research outcomes serve as a valuable guideline for practitioners, stakeholders, government, and policymakers involved in the transition toward a CE in food supply chains. The identified barriers and their ranks can effectively support decision makers to monitor the most influential and critical points in order to better mobilize their efforts. In particular, the provided insights can influence policymakers and associated authorities of the food sector to prioritize their resources and actions with a focus on initiatives for circular design and innovative packaging, reducing the CE implementation costs, and more effectively using reusable, recyclable, and recoverable materials.

The present research has some limitations, which open up avenues for future research. Although the identified barriers meet the research objectives, they are not exhaustive due to the following reasons. First, the study was carried out based on the current situation of the food supply chain in Iran. The results may differ from other countries, in particular, developed countries. Hence, conducting research employing the same method for other countries and territories may provide additional insights into the topic. Second, the current study was informed by literature and panel experts' opinions, which might limit the accuracy of the analysis. Therefore, using other qualitative or quantitative methods, with a particular focus on systems thinking to consider the food supply chain as a whole, is of high interest for future research. Third, this study presented a ranking of the barriers to CE implementation based on their effects. Further studies could prioritize the removal of barriers based on countries' capabilities. Finally, policy makers can launch policies for transitioning from a linear economy to a CE in Iran by jointly improving barriers based on the digraph of INRM. However, it is not possible to eliminate all the barriers at once; both public and private sectors must work together to address the key influential barriers. Since the barriers are likely to differ across developing and developed regions, scholars could compare the results of this study with other previous research in terms of the geographical scope. In addition, the results of this study could help organizations recognize their roles in CE implementation.

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