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Presenting a Circular Economy Model for Tabriz Petrochemical Complex with an Emphasis on Sustainability

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ABSTRACT

High energy consumption, the generation of substantial volumes of industrial waste, and increasing environmental pressures have compelled process industries, such as the petrochemical industry, to reconsider traditional production and consumption patterns. As an alternative to the linear production-and-disposal model, the circular economy represents an effective approach to addressing these challenges at the Tabriz Petrochemical Complex. The present study aimed to develop a sustainable circular economy model for the Tabriz Petrochemical Complex. The study employed a mixed-methods qualitative–quantitative approach. In the qualitative phase, data were collected through semi-structured interviews with 22 experts and analyzed using three-stage coding. The structural relationships among the factors were subsequently determined through interpretive structural modeling and MICMAC analysis. In the quantitative phase, a 20-item questionnaire was administered to a sample of 350 participants, and the proposed model was validated through confirmatory factor analysis and structural equation modeling using LISREL. The findings indicated that the components and dimensions of the circular economy were extracted in four economic, environmental, social, and technological–operational dimensions based on 220 open codes and 30 axial codes. The analysis of relationships among the factors showed that technological–operational factors functioned as fundamental driving forces, whereas economic and social factors represented the ultimate outcomes of the model. Regarding validity and applicability, the developed model confirmed that all four dimensions had positive and significant effects on the sustainable circular economy. The technological–operational dimension had the strongest effect, with a coefficient of 0.35, while the coefficient of determination of 0.72 indicated that the model adequately explained the variance in the dependent variable. The proposed model can provide a practical framework for promoting sustainability in the Tabriz petrochemical industry and other comparable industries.

Keywords: circular economy, resource optimization, environmental sustainability, Tabriz Petrochemical Complex.

Introduction

The intensification of environmental degradation, resource scarcity, industrial waste generation, greenhouse gas emissions, and energy demand has increasingly challenged the long-term viability of conventional production systems. Traditional industrial models are predominantly based on a linear pattern of resource extraction, production, consumption, and disposal, in which substantial quantities of materials and energy are lost at the end of each production cycle. Although this model has historically supported industrial growth, it has also created extensive environmental pressures, inefficient resource utilization, and escalating waste-management costs. These

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concerns are particularly significant in process industries, where production systems are highly dependent on fossil resources, energy-intensive operations, complex material flows, and interconnected technological infrastructures. Consequently, the transition from linear production to circular production has become a major strategic priority for industries seeking to reconcile economic performance with environmental protection, technological development, and social responsibility.

The circular economy has emerged as a comprehensive alternative to the linear economic model by emphasizing the reduction of resource consumption, extension of product and material life cycles, reuse of by-products, recovery of valuable materials, recycling of industrial waste, and regeneration of natural and technical systems. Rather than treating waste as an inevitable endpoint of production, the circular economy conceptualizes residual materials, emissions, and by-products as potential inputs for new production cycles. In this framework, economic value is preserved for as long as possible, while material losses and environmental externalities are minimized. Circularity therefore extends beyond waste recycling and involves a systemic redesign of production processes, supply chains, organizational practices, technologies, financial mechanisms, and stakeholder relationships. A four-dimensional understanding of circular economy implementation also suggests that economic, environmental, social, and technological considerations must be addressed simultaneously in sustainable industrial design (1).

The relevance of the circular economy is especially pronounced in the oil, gas, petroleum, and petrochemical sectors. These industries are central to national economies, international trade, industrial manufacturing, and energy security, yet they are also associated with high levels of material consumption, carbon emissions, hazardous waste generation, and ecological risk. A growing body of research has therefore examined the application of circular economy principles to the oil and gas industry. Bibliometric evidence indicates that circular economy research in this sector has expanded rapidly, particularly around waste valorization, decarbonization, resource efficiency, industrial symbiosis, sustainable supply chain management, and technological innovation (2). Nevertheless, the literature remains fragmented across different technological, managerial, economic, and environmental domains, which highlights the need for integrated implementation models tailored to specific industrial contexts.

Innovation is a central mechanism through which circular economy principles can be translated into practical industrial action. In the oil and gas sector, circular innovation includes advanced recycling processes, low-carbon technologies, carbon capture and utilization, process intensification, digital monitoring, predictive maintenance, industrial symbiosis, and the conversion of waste streams into usable feedstocks. A systematic review of circular economy and innovation in the oil and gas industry has shown that technological development and organizational innovation are closely interconnected, because the adoption of circular technologies requires corresponding changes in governance, investment priorities, supply chain coordination, and managerial decision-making (3). Accordingly, circular economy implementation should not be viewed solely as a technical intervention; it is a multidimensional transformation that depends on the alignment of technology, strategy, organizational culture, environmental objectives, and financial feasibility.

Petroleum-based industrial waste represents one of the most important areas for circular economy intervention. Refining, petrochemical processing, transportation, storage, and downstream operations generate diverse waste streams, including sludge, spent catalysts, contaminated water, polymer residues, gaseous emissions, and other hazardous or recoverable materials. These wastes can create serious environmental and health risks when disposed of through conventional methods, but they may also contain valuable materials that can be recovered, reused, or converted into secondary resources. The circular management of petroleum-based industrial waste therefore requires integrated processes for waste characterization, separation, treatment, reuse, recycling, and value recovery (4). Such an approach can reduce dependence on virgin resources, lower disposal costs, mitigate greenhouse gas emissions, and improve the overall environmental efficiency of petrochemical production.

The significance of circularity is not limited to petroleum-related industries. Research on resource-intensive sectors such as steel demonstrates that circular economy principles can improve material recovery, enhance energy efficiency, reduce production waste, and support cleaner industrial development (5). These cross-sectoral experiences suggest that industrial circularity is shaped by common factors, including access to appropriate technologies, managerial commitment, environmental regulation, supply chain collaboration, resource monitoring, and investment in research and development. However, the operationalization of these factors differs across industries because each sector possesses distinct production technologies, waste compositions, market structures, and regulatory constraints. Therefore, circular economy models should be designed with careful attention to industry-specific conditions rather than transferred directly from one industrial context to another.

Within the petrochemical industry, circular economy implementation is closely connected to sustainable supply chain management. Petrochemical supply chains encompass feedstock procurement, production, storage, transportation, distribution, customer relationships, waste flows, and reverse logistics. These systems are highly complex and vulnerable to environmental pressures, technological disruptions, market volatility, and regulatory change. Sustainable supply chain management seeks to integrate economic performance, environmental protection, and social responsibility throughout these interconnected activities. Research on sustainability indicators in petrochemical supply chains has emphasized the importance of identifying and prioritizing indicators related to resource consumption, environmental performance, operational resilience, stakeholder coordination, and long-term value creation (6). Such prioritization can support more informed decision-making and enable managers to allocate limited resources toward the most influential sustainability drivers.

A circular petrochemical supply chain differs from a conventional supply chain because it incorporates reverse flows of materials, recovered products, industrial waste, recyclable inputs, and remanufactured resources. Designing such a system requires the simultaneous consideration of economic costs and environmental impacts. Mathematical modeling has shown that circular supply chain decisions in petrochemical product manufacturing can be formulated as bi-objective optimization problems that seek to minimize both operational costs and environmental pollution (7). This dual emphasis is essential because circular initiatives that are environmentally beneficial but financially unsustainable may not be maintained over time, while economically profitable initiatives that fail to reduce emissions or waste do not meet the core objectives of circularity. Effective models must therefore balance financial efficiency with pollution control, resource conservation, and operational feasibility.

The transition toward circular supply chains also depends on the identification of causal relationships among managerial, technological, environmental, and organizational variables. Fuzzy cognitive mapping has been used to design sustainable supply chain management models within the circular economy of the petrochemical industry, demonstrating the interconnected nature of supply chain coordination, environmental management, resource efficiency, technological capability, and strategic decision-making (8). These interdependencies indicate that isolated interventions are unlikely to produce sustainable outcomes. For example, investment in recycling technology may have limited effectiveness if supply chain partners do not coordinate material flows, if managers lack reliable environmental information, or if financial evaluation systems do not recognize the long-term benefits of waste recovery.

Recent technological developments have further expanded the potential scope of circularity in petrochemical supply chains. In particular, the integration of waste streams and captured carbon dioxide into low-carbon production systems offers opportunities to reduce emissions while creating new material and economic value. The incorporation of carbon capture, utilization, and storage into petrochemical supply chains can support the conversion of captured carbon and industrial waste into production inputs, thereby linking decarbonization with resource circularity (9). This approach illustrates the evolution of the circular economy from conventional recycling toward more advanced low-carbon industrial ecosystems in which emissions, waste, and by-products are reintegrated into production cycles. However, such systems require sophisticated infrastructure, technological readiness, cross-sector collaboration, investment capacity, and supportive policy frameworks.

Technology alone cannot ensure successful circular economy implementation. Sustainable industrial performance also depends on relational and organizational factors within the supply chain. Trust, commitment, and supply flexibility can improve sustainable supply chain performance by facilitating information sharing, cooperation, adaptation, and long-term coordination among petrochemical supply chain partners (10). Circular supply chains require firms to exchange data on material composition, waste availability, environmental performance, production schedules, and recovery opportunities. Without trust and commitment, firms may be reluctant to share sensitive operational information or invest in joint circular initiatives. Supply flexibility is equally important because circular production systems must respond to fluctuations in the quality, quantity, and timing of recovered materials.

Organizational culture and human factors are therefore integral to circular transformation. Employees, managers, engineers, and technical specialists must understand the objectives of circularity, participate in process redesign, accept new technologies, and adapt to altered responsibilities. Resistance to organizational change can delay digitalization, hinder waste-separation practices, reduce interdepartmental coordination, and weaken the effectiveness of environmental initiatives. Conversely, training, employee involvement, occupational safety, knowledge sharing, and organizational learning can strengthen the social foundations of circular economy implementation. These considerations support the inclusion of a distinct social dimension alongside economic, environmental, and technological–operational dimensions.

The economic dimension of circular economy implementation is similarly complex. Circular initiatives require capital investment in equipment, digital systems, waste-processing facilities, research and development, infrastructure modernization, and employee training. Petrochemical managers must therefore evaluate not only direct financial returns but also avoided disposal costs, resource savings, reduced environmental liabilities, energy-efficiency gains, regulatory compliance benefits, and long-term strategic value. The development of financial, technical, and economic evaluation models for petrochemical industries reflects the need to assess investment projects through integrated criteria rather than conventional short-term profitability measures alone (11). A circular economy model that lacks financial evaluation mechanisms may be theoretically desirable but difficult to implement within capital-intensive industrial settings.

Financial conditions in the petrochemical industry are also influenced by external shocks, market volatility, exchange-rate changes, sanctions, policy uncertainty, feedstock-price fluctuations, and changes in international demand. The classification of financial shocks and their effects on Iran's petrochemical industry demonstrates that financial instability can influence investment capacity, production planning, technological modernization, export performance, and strategic decision-making (12). These conditions may either constrain circular economy investments or increase their strategic importance. For example, resource recovery and energy efficiency can reduce exposure to volatile input prices, while domestic technological development can decrease dependence on imported equipment. Accordingly, the economic resilience of circular economy initiatives should be considered within the broader financial environment of the petrochemical sector.

Strategic financial risks also affect the feasibility and continuity of petrochemical projects. Interpretive structural modeling of financial strategic risks in Iran's petrochemical industry has shown that these risks form hierarchical relationships in which some factors function as underlying drivers and others emerge as dependent consequences (13). This type of structural reasoning is directly relevant to circular economy research because circular transformation also involves multiple factors with different levels of influence and dependence. Identifying foundational drivers allows managers to sequence interventions more effectively and avoid investing in outcome-level initiatives before establishing the necessary technological, organizational, and financial infrastructure.

The interpretive structural modeling approach has previously been applied to circular economy practices in the downstream petroleum industry, demonstrating its usefulness for identifying relationships among enabling factors and arranging them within a hierarchical structure (14). In complex industrial systems, circular economy factors rarely operate independently. Digitalization may influence process optimization; process optimization may improve energy efficiency; energy efficiency may reduce emissions; emission reduction may improve regulatory compliance and social legitimacy; and these outcomes may ultimately generate economic value. Interpretive structural modeling can clarify these directional relationships and distinguish foundational enablers from intermediate mechanisms and final outcomes.

MICMAC analysis complements interpretive structural modeling by classifying factors according to their driving power and dependence power. This distinction is important for managerial prioritization because driving factors require early strategic attention, linkage factors require careful monitoring due to their instability, dependent factors largely reflect the outcomes of other interventions, and autonomous factors have relatively weak connections to the system. Although efficiency assessment has also been applied to circular economy performance in areas such as municipal solid waste management across Persian Gulf countries, the results reinforce the broader importance of evaluating circularity through measurable system-level indicators rather than isolated environmental outputs (15). Such assessments provide valuable comparative insights, but firm-level and industry-specific models are still necessary to explain the mechanisms through which circularity can be achieved.

Strategic foresight offers another useful perspective for addressing circular economy implementation in the petrochemical industry. The identification and prioritization of drivers of sustainable value chain optimization in Iran's petrochemical industry demonstrates that long-term sustainability depends on anticipating technological trends, environmental regulations, market developments, supply chain disruptions, and organizational capabilities (16). Circular economy planning should therefore not be restricted to current operational problems. It should also consider future scenarios, emerging technologies, evolving stakeholder expectations, decarbonization requirements, and potential changes in resource availability.

Despite the expansion of circular economy research, several gaps remain. First, many studies focus on a single aspect of circularity, such as waste management, supply chain optimization, environmental efficiency, financial evaluation, or technological innovation. Second, models developed for general manufacturing, municipal waste management, oil and gas systems, or other resource-intensive industries may not adequately capture the specific operational realities of petrochemical complexes. Third, limited attention has been paid to the simultaneous integration of economic, environmental, social, and technological–operational dimensions within a single empirically validated model. Fourth, many conceptual or qualitative models do not proceed to quantitative validation, which limits the assessment of their explanatory power and practical applicability. Finally, relatively few studies combine qualitative coding, interpretive structural modeling, MICMAC analysis, confirmatory factor analysis, and structural equation modeling in a sequential mixed-methods design.

These gaps are especially relevant to the Tabriz Petrochemical Complex, where energy consumption, industrial waste, process integration, environmental requirements, technological capabilities, human resources, and economic constraints interact within a complex production system. Developing an applicable model for this setting requires the identification of context-specific factors through expert knowledge, the clarification of structural relationships among those factors, and the empirical validation of the resulting dimensions among managers, engineers, and specialists. An exploratory sequential mixed-methods approach is therefore appropriate because it allows the conceptual structure of the model to emerge from the industrial context before being tested quantitatively.

Accordingly, the aim of the present study was to develop and validate a sustainable circular economy model for the Tabriz Petrochemical Complex by identifying its economic, environmental, social, and technological–operational dimensions and examining the structural relationships among them.

Methods and Materials

In terms of purpose, the present study is applied research, and in terms of its implementation approach, it follows an exploratory sequential mixed-methods design in which the findings of the qualitative phase form the basis for developing the quantitative measurement instrument. The multidimensional and complex nature of implementing the circular economy in process industries necessitates the simultaneous use of the analytical depth of qualitative methods and the statistical precision of quantitative methods. The research strategy combines survey research and a case study, with the Tabriz Petrochemical Complex selected as the field setting. Pragmatism constituted the philosophical foundation for selecting the mixed-methods approach because the primary objective of the research was to solve a practical industrial problem and develop an applicable model rather than merely test a predetermined theoretical framework.

The statistical population of the qualitative phase consisted of academic and industry experts familiar with the fields of circular economy, chemical engineering, and environmental management. Participants were selected through purposive stratified sampling, and sampling continued according to the principle of theoretical saturation until interviews had been conducted with 22 experts. Table 1 presents the professional composition of the qualitative sample by field of activity.

Table 1. Professional Composition of the Qualitative Sample by Field of Activity

Field of Activity	Number of Experts	Mean Work Experience (Years)
Production and process operations	5	18.8
Environment, HSE, and safety	4	15.3
Maintenance, energy, and utilities	3	19.0
Finance, planning, and supply chain	4	17.3
Technology, control, and research and development	3	13.0
Human resources and communications	2	13.0
Warehousing and logistics	1	13.0
Total	22	16.3

The statistical population of the quantitative phase comprised managers, engineers, and specialists employed at the Tabriz Petrochemical Complex. The sample size was calculated according to Kline’s rule for structural equation modeling, which recommends a ratio of 10 to 20 participants for each questionnaire item. Given the 20 final questionnaire items, a sample of 350 participants was selected through purposive stratified sampling from the production, engineering and maintenance, HSE, planning, and administrative–financial departments. This sample provided a ratio of 17.5 participants per item and ensured sufficient statistical power for conducting confirmatory factor analysis and structural equation modeling.

The qualitative data collection instrument was a semi-structured interview guide on the sustainable circular economy, designed to elicit experts' experiences and tacit knowledge concerning the dimensions of the circular economy. The instrument was researcher-developed, and no pre-existing standardized questionnaire or checklist was used. Each interview included 10 open-ended questions covering the economic, environmental, social, and technological–operational dimensions of circular economy implementation.

In the quantitative phase, data were collected using the researcher-developed Tabriz Petrochemical Sustainable Circular Economy Questionnaire. The questionnaire was designed on a five-point Likert scale and corresponded to the four dimensions identified during the qualitative phase. This questionnaire was also nonstandardized and was developed directly from the axial codes extracted through the analysis of expert interviews. It consisted of 20 items, with each of the economic, environmental, social, and technological–operational dimensions measured by five items. Before final administration, its content validity was reviewed and confirmed by academic and industry experts.

The qualitative data were analyzed using content analysis and three-stage open, axial, and selective coding, resulting in the identification of the principal dimensions and components of the model. Interpretive structural modeling and MICMAC analysis were used to explain the structural relationships among the key factors and determine their hierarchical levels. These methods respectively identified the hierarchical position of the factors and their driving and dependence power within the system structure.

In the quantitative phase, the reliability of the instrument was assessed using Cronbach's alpha, and construct validity was evaluated through confirmatory factor analysis. The relationships between the four dimensions and the sustainable circular economy variable were tested through structural equation modeling using LISREL. Descriptive and inferential statistical analyses were also performed using SPSS.

Findings and Results

The findings of the present study are presented in three main sections. The first section describes the demographic characteristics of the quantitative sample. The second section presents the qualitative findings obtained through interview coding and the structural analysis of the key factors. The third section reports the quantitative statistical findings, including reliability, validity, descriptive statistics, and structural equation modeling results.

The quantitative sample consisted of 350 managers, engineers, and specialists employed at the Tabriz Petrochemical Complex. Table 2 presents the demographic characteristics of the sample in terms of gender, age, educational level, work experience, organizational position, and field of activity. These characteristics were reported to assess the representativeness of the sample in relation to the target population and determine the generalizability of the findings. The distribution of these variables also provides the necessary context for interpreting the qualitative and quantitative findings presented in the subsequent sections.

Table 2. Frequency Distribution of the Demographic Characteristics of the Statistical Sample

Variable	Category	Frequency	Percentage
Gender	Male	322	92.0
	Female	28	8.0
Age	Under 30 years	35	10.0
	30–40 years	154	44.0
	41–50 years	123	35.1
	Over 50 years	38	10.9
Educational level	High school diploma or associate degree	21	6.0
	Bachelor’s degree	158	45.1
	Master’s degree	154	44.0
	Doctoral degree	17	4.9
Work experience	Less than 5 years	28	8.0
	5–10 years	77	22.0
	11–15 years	112	32.0
	16–20 years	84	24.0
	More than 20 years	49	14.0
Organizational position	Senior manager	35	10.0
	Middle manager	70	20.0
	Technical specialist or engineer	196	56.0
	HSE and optimization specialist	35	10.0
	Other	14	4.0
Field of activity	Production	140	40.0
	Engineering and maintenance	105	30.0
	HSE and environment	53	15.1
	Planning and optimization	35	10.0
	Administrative–financial and other	17	4.9

The results presented in Table 2 show that 92.0% of the respondents were men and only 8.0% were women, which is consistent with the operational and shift-based nature of employment in the petrochemical industry. In terms of age, 79.1% of the sample were between 30 and 50 years old, indicating the predominance of a middle-aged and experienced workforce within the complex. The sample also had a relatively high educational level, as 89.9% of the respondents held a bachelor’s degree or higher. This finding confirms that the participants possessed an appropriate level of technical knowledge to evaluate the technological and operational dimensions of the circular economy. Regarding work experience, 70% of the respondents had more than 10 years of experience, reflecting their practical familiarity with the actual challenges of the industry. In terms of organizational position, technical specialists and engineers constituted the largest group, accounting for 56.0% of the sample, while senior and middle managers together represented 30.0%. This composition provided a balanced combination of operational and strategic perspectives. The production and engineering and maintenance departments together accounted for 70% of the sample, which is consistent with the study’s emphasis on optimizing production processes.

The qualitative data obtained from interviews with 22 experts from the Tabriz petrochemical industry were analyzed using a three-stage coding approach. During open coding, the interview transcripts were examined line by line, resulting in the extraction of 220 open codes. During axial coding, the open codes were classified into 30 axial codes based on conceptual similarity. During selective coding, the axial codes were integrated into four overarching dimensions. Table 3 presents the distribution of axial codes across the four dimensions.

Table 3. Distribution of Axial Codes and Relative Contribution of the Four Model Dimensions

Dimension	Number of Axial Codes	Relative Contribution (%)
Economic	6	20.0
Environmental	7	23.3

Social	7	23.3
Technological–operational	10	33.3
Total	30	100.0

The results presented in Table 3 show that the technological–operational dimension, with 10 axial codes and a relative contribution of 33.3%, accounted for the largest conceptual share among the four dimensions. These codes included process optimization, advanced automation and control, digitalization, maintenance and asset management, technology localization, and research and development, indicating the considerable importance assigned by experts to technical infrastructure. The environmental and social dimensions each included seven axial codes and accounted for 23.3% of the total. The environmental dimension encompassed concepts such as emission management, energy consumption optimization, and closed-loop material cycles, which reflect the philosophical core of the circular economy. The social dimension covered employee health and safety, organizational culture and resistance, and social responsibility. The economic dimension, with six axial codes and a contribution of 20%, had the smallest conceptual share, although its components, such as operating cost management and value creation from waste, were among the most frequently recurring themes in the interviews. This distribution indicates that, from the experts' perspective, implementing the circular economy in the petrochemical industry primarily requires the transformation of technological and operational infrastructure, while the economic, environmental, and social dimensions perform complementary functions.

Following the identification of the qualitative dimensions and components, 12 key factors representing the four principal dimensions were selected based on expert judgment, and the pairwise relationships among them were examined using interpretive structural modeling. Through the development of a structural self-interaction matrix and a final reachability matrix, this method places the factors within hierarchical levels. Table 4 presents the final hierarchical classification of the 12 key factors, obtained through five iterative stages.

Table 4. Final Hierarchical Classification of Key Circular Economy Factors Based on Interpretive Structural Modeling

Key Factor	Related Dimension	Level
Value creation from waste	Economic	1
Social responsibility and communications	Social	1
Emission management	Environmental	2
Human resource development	Social	2
Advanced automation and control	Technological–operational	3
Energy consumption optimization	Environmental	3
Financial feasibility of projects	Economic	3
Process optimization	Technological–operational	4
Maintenance and asset management	Technological–operational	4
Organizational culture and resistance	Social	4
Digitalization and information systems	Technological–operational	5
Research and development	Technological–operational	5

The results presented in Table 4 indicate that digitalization and information systems and research and development were positioned at the lowest structural level, Level 5, and function as the fundamental drivers of the circular economy system. This position indicates that technological transformation and investment in innovation are essential prerequisites for achieving the other outcomes of the model. Process optimization, maintenance and asset management, and organizational culture and resistance were placed at Level 4, where they perform an intermediary role between foundational infrastructure and ultimate outcomes. Levels 3 and 2 included factors such as automation, energy consumption optimization, financial feasibility, emission management, and human resource development, all of which have mediating and linking functions. At the highest level, Level 1, value creation from waste and social responsibility and communications were identified as the ultimate outcomes of the system. This five-level structure demonstrates that the achievement of desirable economic and social outcomes depends on the prior establishment of technological and operational infrastructure. The logical sequence among the factors also provides managers with a clearly defined implementation pathway. Figure 1 illustrates the hierarchical structure derived from this classification as a five-level directed graph in which lower-level nodes affect higher-level nodes, and the arrows indicate the direction of influence among the factors.

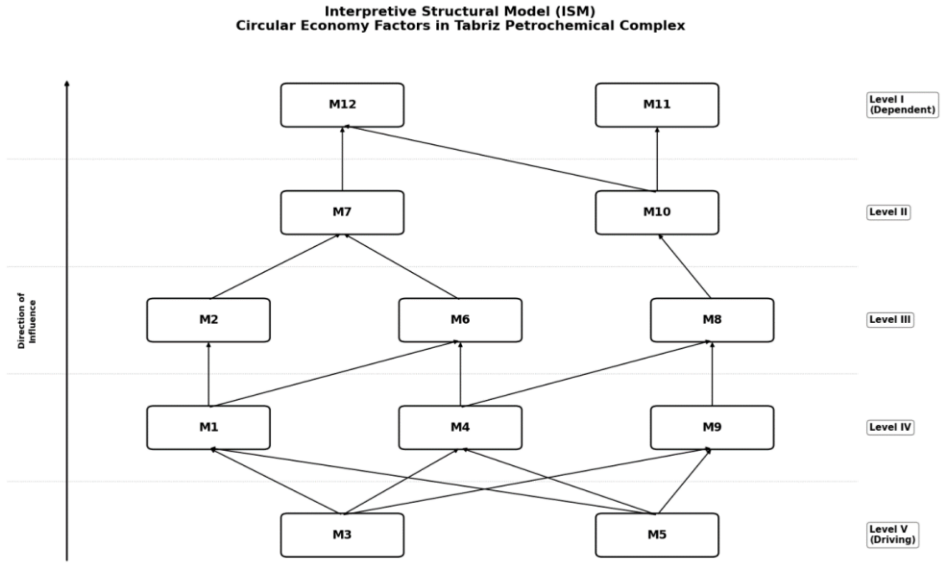

Figure 1. Interpretive structural model of the factors influencing the circular economy at the Tabriz Petrochemical Complex

After determining the structural levels of the factors, MICMAC analysis was conducted to examine the driving and dependence power of the 12 key factors and determine their positions in the four categories of driving, linkage, dependent, and autonomous factors. Table 5 presents the final classification of the factors based on this analysis.

Table 5. Classification of Key Factors Based on MICMAC Analysis

Key Factor	MICMAC Category
Process optimization	Driving
Digitalization and information systems	Driving
Maintenance and asset management	Driving
Research and development	Driving
Organizational culture and resistance	Driving
Advanced automation and control	Linkage
Energy consumption optimization	Linkage
Emission management	Linkage
Financial feasibility of projects	Linkage
Human resource development	Linkage
Value creation from waste	Dependent
Social responsibility and communications	Dependent

The results presented in Table 5 indicate that five factors—process optimization, digitalization and information systems, maintenance and asset management, research and development, and organizational culture and resistance—were located in the driving quadrant and therefore perform foundational and driving roles in the circular economy system. The predominance of technological–operational factors in this quadrant confirms the importance of transforming technical and information infrastructure for implementing the circular economy. Five other factors—advanced automation and control, energy consumption optimization, emission management, financial feasibility of projects, and human resource development—were located in the linkage quadrant. These factors possess both high driving power and high dependence power and are therefore characterized by considerable structural sensitivity. Value creation from waste and social responsibility and communications were positioned in the dependent quadrant, indicating their outcome-oriented nature. In other words, the realization of these factors requires the prior establishment of foundational and linkage factors. No factor was located in the autonomous quadrant, indicating a high degree of structural integration among the selected factors and relatively strong interconnectedness within the system under investigation. Figure 2 displays the positions of the 12 key factors on the driving power–dependence power map. The horizontal axis represents the degree of dependence, while the vertical axis represents the driving power of each factor. The four driving, linkage, dependent, and autonomous quadrants are shown separately.

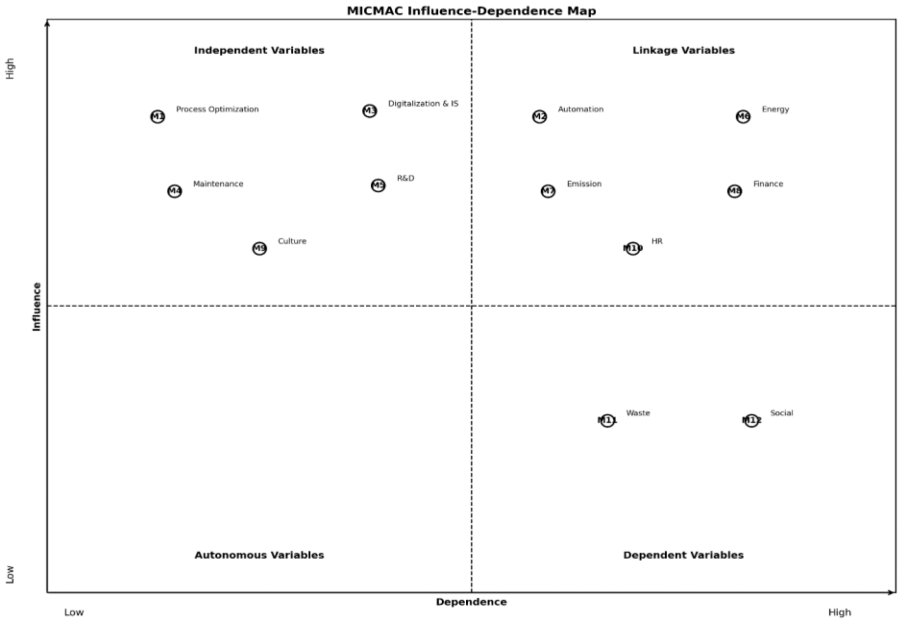

Figure 2. Driving power–dependence power map of key circular economy factors based on MICMAC analysis

The reliability of the 20-item questionnaire was assessed using Cronbach's alpha for each of the four dimensions and for the questionnaire as a whole. This coefficient represents the internal consistency of the items within each dimension, with values above 0.70 generally considered acceptable. Table 6 presents the results.

Table 6. Cronbach's Alpha Coefficients for the Questionnaire Dimensions

Dimension	Number of Items	Cronbach's Alpha
Economic	5	0.854
Environmental	5	0.871
Social	5	0.842
Technological–operational	5	0.883
Total questionnaire	20	0.905

The results presented in Table 6 indicate that Cronbach's alpha coefficients for all dimensions exceeded 0.80, representing good to excellent reliability. The technological–operational dimension had the highest internal consistency, with a coefficient of 0.883, while the social dimension had the lowest coefficient, at 0.842; nevertheless, both values were within the desirable range. Cronbach's alpha for the questionnaire as a whole was 0.905, confirming the excellent reliability of the measurement instrument. These results indicate that the items within each dimension consistently measure a single underlying concept and that the developed instrument possesses sufficient stability to produce reproducible results in comparable samples.

Following confirmation of the questionnaire's reliability, the mean, standard deviation, skewness, and kurtosis were calculated for each of the four dimensions to evaluate the respondents' overall perceptions of each dimension and the distribution of the data. Table 7 presents the results of this descriptive analysis.

Table 7. Descriptive Statistics for the Four Dimensions of the Circular Economy Model

Dimension	Mean	Standard Deviation	Skewness	Kurtosis
Economic	4.12	0.68	−0.43	0.21
Environmental	4.28	0.59	−0.51	0.35
Social	3.95	0.72	−0.38	0.18
Technological–operational	4.35	0.54	−0.62	0.48

The results presented in Table 7 show that the mean score for every dimension exceeded 3.95, confirming that respondents attributed considerable importance to all four dimensions in implementing a sustainable circular economy. The technological–operational dimension had the highest mean score, at 4.35, and the lowest standard deviation, at 0.54, indicating both the greatest perceived importance and the highest level of agreement among respondents. The environmental dimension ranked second, with a mean score of 4.28, reflecting the sample's high level of awareness regarding the environmental requirements of the industry. The social dimension received the lowest mean score, at 3.95, indicating relatively less attention to human-related components than to technical and environmental dimensions. The negative skewness values for all dimensions indicate that responses were concentrated toward the higher end of the scale. Furthermore, all skewness and kurtosis values were within the acceptable range of −2 to +2, supporting the assumption of normal data distribution required for subsequent parametric analyses.

The construct validity of the four-factor measurement model was evaluated through confirmatory factor analysis using LISREL. The factor loading of each item and the model-fit indices of the measurement model were examined. Table 8 presents the mean factor loading for each dimension, the range of factor loadings, and the principal fit indices of the measurement model.

Table 8. Mean Factor Loadings of the Dimensions and Fit Indices of the Measurement Model

Dimension	Mean Factor Loading	Factor-Loading Range
Economic	0.76	0.71–0.82
Environmental	0.80	0.75–0.85
Social	0.77	0.71–0.84
Technological–operational	0.82	0.75–0.87

Fit Index	Value	Recommended Threshold
Chi-square/degrees of freedom	2.18	Less than 3
GFI	0.92	Greater than 0.90
CFI	0.95	Greater than 0.90
RMSEA	0.054	Less than 0.08
SRMR	0.042	Less than 0.08

The results presented in Table 8 show that the mean factor loadings for all dimensions exceeded 0.75, which is within the desirable range and confirms the satisfactory convergent validity of the measurement model. The technological–operational dimension had the highest mean factor loading, at 0.82, indicating a strong relationship between the items of this dimension and their corresponding construct. The *t* values for all items exceeded 1.96, confirming the statistical significance of all relationships at the 0.05 level.

Regarding the model-fit indices, the chi-square-to-degrees-of-freedom ratio was 2.18, which was below the critical threshold of 3. The GFI value of 0.92 and the CFI value of 0.95 were both above the recommended threshold of 0.90. The RMSEA value of 0.054 and the SRMR value of 0.042 were also within acceptable ranges. Collectively, these indices confirm that the proposed four-dimensional structure adequately fits the collected data and that the identified dimensions possess sufficient construct validity.

Following confirmation of the measurement model, the structural relationships between the four dimensions and the sustainable circular economy variable were tested through structural equation modeling. The purpose of this analysis was to determine the path coefficients and the extent to which the independent dimensions explained the variance in the dependent variable. Table 9 presents the standardized path coefficients, significance statistics, and coefficient of determination for the structural model.

Table 9. Path Coefficients of the Four Dimensions Predicting the Sustainable Circular Economy and the Model's Coefficient of Determination

Path	Standardized Coefficient	*t* Value	Result
Technological–operational dimension → Sustainable circular economy	0.35	7.29	Significant
Environmental dimension → Sustainable circular economy	0.31	6.08	Significant
Economic dimension → Sustainable circular economy	0.24	4.53	Significant
Social dimension → Sustainable circular economy	0.18	3.27	Significant
Coefficient of determination (R^2)	0.72	—	Strong

The results presented in Table 9 show that all four dimensions had positive and statistically significant effects on the sustainable circular economy, although the magnitude of these effects varied. The technological–operational dimension had the strongest effect, with a standardized coefficient of 0.35 and a *t* value of 7.29, confirming the importance of technological infrastructure, automation, and digitalization in implementing the circular economy in the petrochemical industry. The environmental dimension ranked second, with a coefficient of 0.31, reflecting the philosophical core of the circular economy, namely waste reduction and material recovery. The economic dimension had a moderate effect, with a coefficient of 0.24, and performed an important role in establishing the financial feasibility of sustainability projects. The social dimension had the weakest direct effect, with a coefficient of 0.18, which may be attributable to its indirect and supportive role in establishing the cultural and human foundations required for the other dimensions.

The coefficient of determination for the model was 0.72, which is considered strong and indicates that the four dimensions collectively explained 72% of the variance in the sustainable circular economy. This value confirms the substantial explanatory power of the proposed model and supports the scientific validity of the framework. Figure 3 illustrates the path diagram of the research structural model. The standardized coefficient of each path is presented on the arrows connecting the four dimensions to the sustainable circular economy variable, allowing the relative magnitude of each dimension's effect to be compared visually.

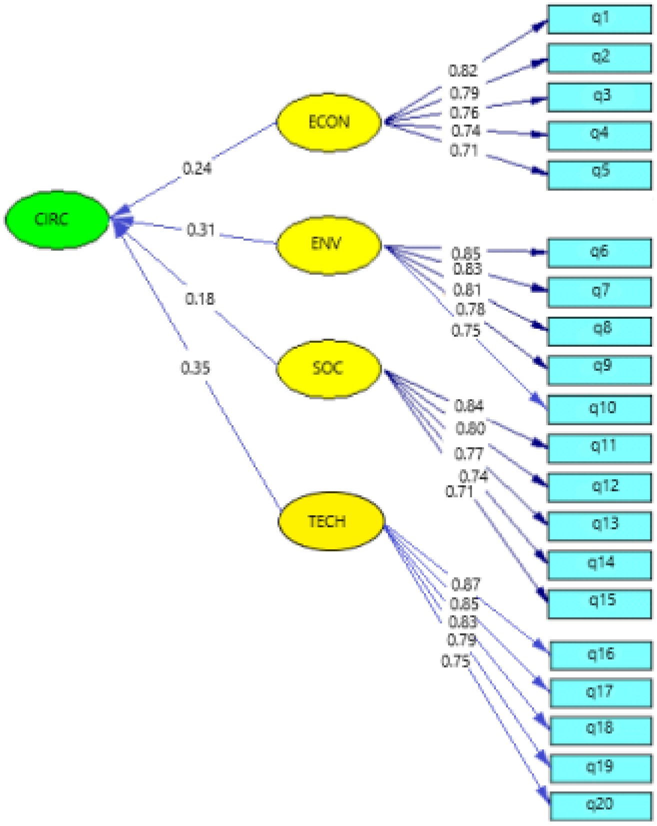

Figure 3. Research structural model with standardized path coefficients

Discussion and Conclusion

The present study aimed to develop and validate a sustainable circular economy model for the Tabriz Petrochemical Complex by integrating economic, environmental, social, and technological–operational dimensions. The qualitative findings showed that the proposed model comprised four principal dimensions derived from 220 open codes and 30 axial codes. Among these dimensions, the technological–operational dimension accounted for the largest proportion of axial codes, followed by the environmental and social dimensions, while the economic dimension contained the fewest axial codes. The interpretive structural modeling results further indicated that digitalization and information systems and research and development occupied the deepest and most influential level of the model, whereas value creation from waste and social responsibility and communications appeared at the highest level as final outcomes. MICMAC analysis similarly classified process optimization, digitalization, maintenance and asset management, research and development, and organizational culture and resistance as driving factors. The quantitative findings confirmed the reliability and construct validity of the four-dimensional model and demonstrated that all four dimensions exerted positive and statistically significant effects on the sustainable circular economy. The technological–operational dimension had the strongest effect, followed by the environmental, economic, and social dimensions. The model explained 72% of the variance in the sustainable circular economy, indicating substantial explanatory power.

The extraction of economic, environmental, social, and technological–operational dimensions supports the view that circular economy implementation in petrochemical industries is a multidimensional transformation rather than a limited waste-management initiative. Circularity requires the simultaneous redesign of resource flows, production systems, investment mechanisms, organizational relationships, and technological infrastructure. This result is consistent with the comprehensive four-dimensional approach proposed for sustainable circular design, which emphasizes that circular economy performance depends on the interaction of economic, environmental, social, and technical considerations (1). The finding also aligns with bibliometric evidence indicating that circular economy research in the oil and gas industry increasingly integrates resource efficiency, environmental protection, supply chain management, technological innovation, and organizational sustainability (2). Therefore, the four-dimensional structure identified in the present study reflects both the complexity of the petrochemical production system and the broader conceptual development of circular economy research.

The predominance of the technological–operational dimension in the qualitative findings and its stronger quantitative effect indicate that circular transformation in the Tabriz Petrochemical Complex is primarily dependent on technological capability and operational readiness. Petrochemical production is characterized by continuous processes, high energy intensity, complex chemical reactions, strict safety requirements, and highly interconnected equipment. Under such conditions, circular economy practices cannot be implemented effectively without advanced process control, accurate monitoring, digital data systems, preventive and predictive maintenance, efficient asset management, and continuous technological innovation. This interpretation is supported by research emphasizing the central role of innovation in the oil and gas industry's transition toward circularity. Technological innovation enables waste recovery, process intensification, resource efficiency, emissions reduction, and the development of new circular business models (3). The present findings therefore suggest that circular economy strategies in petrochemical industries should begin with strengthening technological and operational foundations before expecting substantial economic, environmental, or social outcomes.

The placement of digitalization and information systems and research and development at the foundational level of the interpretive structural model further confirms their role as primary drivers. Digital systems facilitate real-time monitoring of energy consumption, material flows, equipment performance, emissions, waste generation, and maintenance requirements. Such information enables managers to identify losses, optimize processes, predict equipment failures, and evaluate the circular potential of waste streams. Research and development similarly provides the knowledge required to convert industrial waste into secondary inputs, improve production technologies, and develop low-carbon processes. These findings are consistent with recent efforts to integrate industrial waste and captured carbon dioxide into low-carbon circular petrochemical supply chains. Such integration depends heavily on advanced technological capabilities, process innovation, and continuous research and development (9). The result also supports the strategic foresight perspective, according to which sustainable value chain optimization in the Iranian petrochemical industry is strongly influenced by technological development, innovation capacity, and preparedness for future industrial change (16).

The classification of process optimization, maintenance and asset management, and digitalization as driving factors indicates that circular economy implementation should be embedded in routine production and operational management. Circularity in petrochemical complexes is not achieved only through end-of-pipe recycling projects; rather, it requires reductions in material loss, improvement in equipment efficiency, extension of asset life, reduction of unplanned shutdowns, and minimization of energy and feedstock waste throughout production. The importance of process optimization is consistent with research on circular supply chain management in petrochemical manufacturing, where cost reduction and environmental pollution control are treated as simultaneous optimization objectives (7). The present findings extend this argument by showing that process optimization not only improves operational performance but also acts as a structural driver that enables other dimensions of the circular economy.

The environmental dimension had the second-strongest effect on the sustainable circular economy. This result is theoretically expected because the circular economy is fundamentally concerned with minimizing waste, reducing emissions, optimizing resource and energy consumption, and maintaining materials within closed-loop systems. In the petrochemical industry, environmental performance is particularly important because production processes generate hazardous waste, wastewater, gaseous emissions, spent catalysts, and polymer residues. The finding is consistent with research on petroleum-based industrial waste, which emphasizes that the recovery, reuse, and recycling of such wastes can reduce environmental risks and preserve valuable materials within industrial systems (4). It also corresponds with studies in other resource-intensive industries, such as steel, where circular economy practices have been linked to improved material efficiency, energy conservation, and industrial waste recovery (5). Thus, the strong environmental effect identified in this study confirms that reducing emissions and improving resource efficiency are central outcomes of circular economy implementation in petrochemical production.

The importance of energy consumption optimization and emission management as linkage factors is also noteworthy. Linkage factors possess both high driving power and high dependence, meaning that changes in these factors can influence the broader system while also being affected by technological, financial, and managerial conditions. Energy efficiency, for example, depends on equipment quality, process design, digital monitoring, maintenance practices, and employee expertise, yet it also affects production costs, emissions, and environmental performance. Similarly, emission management depends on monitoring systems and process innovation but influences regulatory compliance, organizational legitimacy, and social responsibility. This interconnected position is consistent with sustainable supply chain models that emphasize the causal relationships among environmental management, operational efficiency, technological capability, and strategic coordination in petrochemical systems (8). It also aligns with research on sustainability indicators in the petrochemical supply chain, which highlights energy efficiency, environmental performance, and resource optimization as high-priority indicators (6).

The economic dimension exerted a positive and significant effect, although its coefficient was lower than those of the technological–operational and environmental dimensions. This finding suggests that economic considerations are essential to circular economy implementation but may function partly as enabling and evaluative mechanisms rather than as the primary source of transformation. Circular projects require substantial investment in new equipment, waste-treatment systems, digital infrastructure, training, and research and development. Therefore, project selection depends on financial feasibility, expected cost savings, resource recovery benefits, avoided environmental liabilities, and long-term value creation. This result is consistent with attempts to develop integrated financial, technical, and economic evaluation models for petrochemical industries, which demonstrate that sustainability-related projects should be assessed using multidimensional criteria rather than short-term financial returns alone (11). The economic effect identified in the present study therefore reflects the necessity of translating environmental and technological benefits into financially defensible investment decisions.

The position of financial feasibility as a linkage factor indicates that financial evaluation both influences and is influenced by other dimensions of the model. Projects with strong technological potential may not be implemented if their costs, risks, or expected returns are unclear. Conversely, successful process optimization, waste valorization, and energy savings can improve the financial attractiveness of circular investments. This relationship becomes especially important in the Iranian petrochemical industry, where financial shocks, market volatility, exchange-rate fluctuations, sanctions, and changes in international demand may constrain long-term investment capacity (12). The findings also correspond with studies of strategic financial risks in Iran's petrochemical industry, which show that financial risks are structurally interconnected and that some risks function as foundational drivers while others emerge as dependent consequences (13). Accordingly, circular economy planning should include financial risk assessment and scenario analysis to ensure the continuity of investment under unstable economic conditions.

The social dimension had the weakest direct effect on the sustainable circular economy, although its influence remained positive and statistically significant. This result should not be interpreted as evidence that social factors are unimportant. Rather, social variables may operate indirectly by creating the organizational and human conditions required for technological and environmental initiatives. Employee participation, safety, training, organizational learning, trust, commitment, and resistance to change all influence the success of circular transformation. The classification of organizational culture and resistance as a driving factor supports this interpretation. Even advanced technologies may fail to generate sustainable outcomes when employees resist new procedures, departments do not share information, or managers fail to create a supportive organizational climate. The finding is consistent with evidence that trust and commitment improve sustainable supply chain performance through supply flexibility and stronger interorganizational coordination in the petrochemical industry (10). Circular economy implementation therefore requires both technical investment and systematic management of organizational change.

The placement of social responsibility and communications at the highest level of the interpretive structural model and within the dependent category of MICMAC analysis indicates that these outcomes are largely produced by the successful implementation of underlying technological, environmental, economic, and organizational mechanisms. A petrochemical company is more likely to demonstrate credible social responsibility when it reduces emissions, improves employee safety, manages waste effectively, communicates transparently, and creates value for surrounding communities. Thus, social responsibility should not be treated merely as a symbolic or promotional activity; it should emerge from measurable improvements in industrial performance. This interpretation is consistent with broader assessments of circular economy efficiency, which emphasize the importance of evaluating tangible environmental and resource-management outcomes rather than relying exclusively on policy statements or formal commitments (15).

Value creation from waste was also identified as a final dependent outcome. This finding reflects the logic of circular production: waste valorization becomes feasible only after appropriate technologies, material-separation systems, data infrastructure, process redesign, financial evaluation, and market linkages have been established. The outcome is consistent with the application of circular economy principles in downstream petroleum industries, where interpretive structural modeling has demonstrated that waste recovery and value creation depend on several underlying organizational and technological enablers (14). The result also corresponds with the broader literature on petroleum-based industrial waste, which shows that waste can be transformed into economically useful inputs when suitable treatment and recovery processes are available (4). Therefore, managers should avoid approaching waste valorization as an isolated project and instead develop the supporting infrastructure needed to ensure its technical and economic viability.

The absence of autonomous factors in the MICMAC analysis indicates a high degree of structural integration among the selected variables. All 12 key factors were connected to the broader system through meaningful driving or dependence relationships. This finding confirms that circular economy implementation in the petrochemical industry is systemic and that isolated managerial actions are unlikely to produce lasting results. The interdependence of the factors is compatible with circular supply chain research, which emphasizes the need for coordination among production, logistics, environmental management, finance, technology, and human resources (8). It also supports the view that circular value creation requires integrated supply chain relationships and organizational flexibility rather than fragmented departmental initiatives (10).

The strong measurement-model results and acceptable fit indices confirmed the validity of the four-dimensional structure. High factor loadings indicated that the questionnaire items adequately represented their respective constructs, while the reliability coefficients demonstrated strong internal consistency. More importantly, the structural model explained 72% of the variance in the sustainable circular economy. This level of explanatory power suggests that the proposed model captures a substantial proportion of the principal mechanisms involved in circular economy implementation at the Tabriz Petrochemical Complex. The result is consistent with the growing literature that conceptualizes circularity as the combined outcome of technological innovation, environmental management, sustainable supply chain practices, financial feasibility, and organizational capability (2, 3). The model therefore offers both theoretical value, by integrating fragmented dimensions of circularity, and practical value, by identifying a clear hierarchy of managerial priorities.

Overall, the findings suggest that the transition toward a sustainable circular economy at the Tabriz Petrochemical Complex should proceed through a sequenced approach. The first stage should strengthen research and development, digitalization, information systems, organizational culture, process optimization, and asset management. The second stage should focus on advanced automation, energy efficiency, emission management, human resource development, and financial feasibility. The final stage should target measurable outcomes such as waste valorization, social responsibility, stakeholder communication, and sustained economic value. This sequence is consistent with strategic foresight approaches that emphasize prioritizing foundational drivers before pursuing higher-level value chain outcomes (16). It also corresponds with low-carbon circular supply chain frameworks in which technological and infrastructural integration precedes the large-scale reuse of waste and captured carbon (9).

The present study had several limitations. First, it was conducted within a single petrochemical complex, and the organizational, technological, environmental, and regulatory conditions of the Tabriz Petrochemical Complex may differ from those of other petrochemical companies. Consequently, caution should be exercised when generalizing the findings to the entire petrochemical industry. Second, the qualitative findings were based on expert judgments, which may have been influenced by participants' professional backgrounds, organizational positions, and subjective interpretations. Third, the quantitative data were collected through a self-report questionnaire and may therefore have been affected by social desirability, response bias, or differences in respondents' familiarity with circular economy concepts. Fourth, the cross-sectional design did not allow changes in circular economy performance to be assessed over time. Finally, the model focused on four principal dimensions and may not fully capture external variables such as regulatory pressures, international sanctions, market demand, regional infrastructure, and interorganizational partnerships.

Future studies should test the proposed model in other petrochemical complexes and related process industries to evaluate its generalizability and identify context-specific differences. Comparative studies could examine whether the hierarchy and influence of the four dimensions vary across public and private companies, upstream and downstream industries, or organizations with different levels of technological maturity. Longitudinal research is also recommended to assess changes in circular economy implementation before and after the adoption of digital systems, energy-efficiency programs, or waste-recovery projects. Future researchers could incorporate external variables such as environmental regulation, market uncertainty, government incentives, sanctions, stakeholder pressure, and supply chain collaboration into the model. The use of objective operational data, including energy intensity, emission levels, waste-recovery rates, production efficiency, and financial returns, would also strengthen the validity of future findings.

Managers of the Tabriz Petrochemical Complex should prioritize investment in digital infrastructure, research and development, process monitoring, predictive maintenance, and advanced control systems because these factors form the foundation of the proposed model. A cross-functional circular economy committee should be established with representatives from production, engineering, maintenance, HSE, finance, supply chain, human resources, and research and development. Circular projects should be evaluated through integrated technical, environmental, financial, and social criteria rather than solely through short-term profitability. Employee training, participation, and change-management programs should accompany technological investments to reduce organizational resistance. Finally, measurable performance indicators should be developed for energy consumption, emissions, material recovery, waste valorization, equipment efficiency, employee safety, and stakeholder engagement so that progress toward circular economy objectives can be monitored and continuously improved.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adheried in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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