




Analysis and Optimization of the Relationships Between Sustainable Performance Management Dimensions and Innovative and Economic Production Methods in the Petrochemical Industry Using Structural Equation Modeling and Metaheuristic Algorithms

1. Fatemeh. Hendokolaii  : Department of Industrial Management, Ra.C.,Islamic Azad University, Rasht, Iran
2. Mohammad. Taleghani  : Department of Industrial Management, Ra.C.,Islamic Azad University, Rasht, Iran
3. Mahdi. Homayounfar  : Department of Industrial Management, Ra.C.,Islamic Azad University, Rasht, Iran

*corresponding author's email: m.taleghani@iau.ac.ir

ABSTRACT

In today's turbulent environment, organizational sustainability has become a strategic necessity for survival and competitiveness in large-scale and complex industries such as the petrochemical sector. The primary objective of this study was to analyze the causal relationships between sustainable performance management dimensions and the implementation of innovative and economic production methods in Iran's petrochemical industry under sanctions conditions. In terms of purpose, this research is applied, and in terms of nature, it is a descriptive-analytical study based on a quantitative approach. The statistical population consisted of senior managers, production experts, and specialists in the fields of sustainability and innovation within the country's petrochemical companies. Using Cochran's formula, a sample size of 384 participants was determined. Data were collected through a researcher-developed questionnaire and analyzed using Pearson correlation analysis, multiple regression analysis, and Structural Equation Modeling (SEM). Furthermore, to enhance prediction accuracy and prioritize indicators, the metaheuristic algorithms Adaptive Neuro-Fuzzy Inference System (ANFIS), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO) were employed. The findings revealed that the environmental dimension, sustainable innovation, economic dimension, and sustainable supply chain management exerted the strongest effects on the implementation of innovative production methods, whereas the human rights and diversity and inclusion dimensions did not demonstrate statistically significant effects. The results further indicate that emphasizing resource management, green technologies, and supply chain resilience can facilitate the advancement of resilience and sustainability in Iran's petrochemical industry under sanctions conditions.

Keywords: Sustainable performance management, innovative and economic production methods, petrochemical industry, structural equation modeling, metaheuristic algorithms.

Introduction

In contemporary industrial competition, sustainable performance management has moved beyond a voluntary corporate responsibility agenda and has become a strategic requirement for organizational survival, operational resilience, and long-term value creation. Industries with high capital intensity, complex supply networks,



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environmental exposure, and technological dependence are particularly affected by this shift, because their performance can no longer be evaluated only through short-term financial indicators. Sustainable performance management integrates economic efficiency, environmental responsibility, social accountability, governance quality, innovation capability, and stakeholder-oriented decision-making into a coherent managerial system. This orientation is especially relevant in process industries such as oil, gas, refining, and petrochemicals, where production continuity, energy intensity, resource consumption, emissions control, safety requirements, and global market volatility create simultaneous pressures for efficiency and sustainability. Recent studies emphasize that performance management systems must be aligned with sustainability goals so that organizations can translate broad sustainability commitments into measurable operational indicators, strategic priorities, and continuous improvement mechanisms (1). Therefore, sustainable performance management provides a managerial architecture through which organizations can connect strategy, operations, innovation, and accountability in a measurable and controllable framework.

The petrochemical industry occupies a critical position in national economic development because it links hydrocarbon resources to a wide range of downstream industrial products, export revenues, employment opportunities, and technological capabilities. However, the same industry is also exposed to environmental risks, energy inefficiencies, complex logistics, volatile global prices, and increasing pressure to adopt cleaner and more efficient production technologies. In countries whose petrochemical industries operate under sanctions, these challenges become more severe because firms face restricted access to advanced technologies, international finance, foreign suppliers, specialized equipment, and global knowledge networks. In the Iranian petrochemical industry, such constraints have intensified the need for domestic technological capability, supply chain resilience, resource optimization, and strategic self-reliance. Research on the current status and outlook of Iran's petrochemical sector indicates that the industry's competitiveness depends not only on production capacity and export potential but also on its ability to modernize technologies, improve operational efficiency, and respond to regional competitive pressures (2). Accordingly, sustainable performance in this sector must be studied as a multidimensional and dynamic phenomenon rather than as a narrow financial or environmental outcome.

Sustainability in industrial organizations is commonly interpreted through the triple bottom line perspective, which integrates economic, environmental, and social dimensions of performance. Although the triple bottom line has provided a valuable conceptual foundation for sustainability assessment, it has also been criticized for oversimplifying complex organizational realities and for treating sustainability dimensions as separable domains rather than interdependent systems (3). In the petrochemical context, this critique is particularly important because economic performance, environmental performance, technological innovation, supply chain decisions, and stakeholder pressures are deeply interconnected. For example, energy optimization may reduce production costs while simultaneously lowering emissions; sustainable supply chain practices may increase resilience while also improving environmental and social performance; and innovation may enhance both productivity and ecological efficiency. Therefore, a more advanced sustainable performance management approach should examine causal relationships among multiple sustainability dimensions and their effects on innovative and economic production methods.

Innovative and economic production methods are central to the transformation of petrochemical operations under uncertainty. These methods include energy optimization, process intensification, green and lean production, digitalization, Industry 4.0 technologies, innovation management, eco-efficiency, and production flexibility. Such

practices allow firms to reduce waste, optimize resource consumption, improve process reliability, reduce costs, and strengthen technological adaptability. Evidence from sustainable manufacturing research shows that sustainable manufacturing practices can improve sustainability performance by integrating operational efficiency with environmental and social considerations (4). In petrochemical companies, these practices are not merely technical choices; they are strategic mechanisms for maintaining competitiveness under resource constraints and institutional pressures. Therefore, the implementation of innovative production methods depends on the organization's broader sustainability orientation, including environmental management, economic planning, governance mechanisms, green human resource practices, supply chain coordination, and stakeholder engagement.

Environmental sustainability is one of the most influential dimensions of sustainable performance management in petrochemical industries, primarily because production processes are energy-intensive and potentially associated with significant emissions, waste, and ecological risks. Companies that prioritize environmental management are more likely to invest in cleaner technologies, energy-saving systems, waste reduction, recycling, and pollution prevention. Empirical research on green management in petrochemical companies has confirmed the relationship between green management and sustainable performance, indicating that environmental orientation can improve organizational outcomes by institutionalizing ecological responsibility in managerial and operational practices (5). Similarly, research on green human resource management and environmental-oriented actions in downstream petrochemical industries shows that sustainability performance is strengthened when environmental values are embedded in organizational behavior, employee capabilities, and managerial routines (6). These findings suggest that environmental sustainability is not an isolated technical concern but a managerial capability that supports innovative production through cultural, technological, and process-level transformation.

Economic sustainability is another core dimension of sustainable performance management, especially under sanctions conditions. Petrochemical companies must maintain profitability, control costs, reduce dependency on imported inputs, improve productivity, and allocate investment efficiently while facing financial and technological restrictions. In such an environment, innovation becomes economically necessary rather than optional. Research on open innovation in industrial research and development units has shown that innovation can improve economic, innovative, and sustainable performance by expanding knowledge flows and strengthening organizational adaptability (7). However, under sanctions, access to external innovation networks may be restricted, making internal R&D capability, domestic collaboration, and localized technological development more important. International evidence also suggests that sanctions can influence firms' innovation behavior by changing external pressures, market incentives, and resource constraints (8). Therefore, petrochemical companies operating under sanctions must use sustainability-oriented innovation not only to improve environmental and operational outcomes but also to compensate for restricted access to international technologies and markets.

Technology management plays a decisive role in improving sustainability performance in petroleum and petrochemical organizations. Advanced production systems, process control technologies, digital monitoring, automation, data analytics, and smart manufacturing tools can support energy efficiency, predictive maintenance, quality improvement, and resource optimization. Studies in petroleum refineries and petrochemical companies have shown that technology management contributes to improved sustainability performance by enhancing operational control, strategic alignment, and technological capability (9). In addition, Industry 4.0 and cyber-physical systems create new opportunities for energy efficiency optimization in smart manufacturing by enabling real-time monitoring,

adaptive control, and integrated decision-making (10). For the petrochemical industry, these technologies can support digitalized production systems, reduce downtime, improve safety, optimize energy flows, and increase responsiveness to market and supply chain disruptions. Consequently, digitalization and technology management should be treated as key enablers of innovative and economic production methods within sustainable performance management models.

Supply chain sustainability is also essential for petrochemical performance because petrochemical production depends on stable access to feedstock, equipment, catalysts, spare parts, logistics infrastructure, and downstream markets. Under sanctions, supply chains become more vulnerable to disruption, supplier limitations, financial constraints, and transportation barriers. Therefore, sustainable supply chain management must integrate resilience, flexibility, localization, risk management, supplier evaluation, and environmental responsibility. A study on the petrochemical supply chain using hybrid Shapley value and MULTIMOORA methods demonstrated the importance of sustainable operational management systems for evaluating and improving supply chain performance (11). Such findings indicate that supply chain decisions are not merely logistical matters; they directly influence sustainable performance, innovation capacity, cost control, and production continuity. In sanction-affected petrochemical companies, resilient and sustainable supply chains can facilitate the implementation of innovative production methods by reducing dependency on unstable external sources and supporting domestic substitution strategies.

Governance and performance evaluation mechanisms provide the institutional foundation for sustainable performance management. Without appropriate indicators, monitoring systems, accountability structures, and decision-making processes, sustainability strategies may remain symbolic and fail to influence operational behavior. Performance management literature emphasizes the need for systematic measurement, feedback, benchmarking, and continuous improvement in order to translate strategic objectives into organizational results (12). In sustainability contexts, performance evaluation must include financial and non-financial indicators and should reflect environmental, social, governance, innovation, and operational criteria. Hybrid evaluation models such as sustainability-balanced scorecards and multi-criteria decision-making frameworks have been used to establish comprehensive sustainable performance evaluation systems in complex service and infrastructure sectors (13). Similarly, research on key performance indicators of sustainable development in the petrochemical industry has shown that systematic comparison and prioritization of sustainability indicators can support better managerial decision-making (14). These studies highlight the importance of measurement models capable of evaluating the multidimensional structure of sustainable performance.

Corporate social responsibility, stakeholder responsibility, and social sustainability also contribute to sustainable performance, although their effects may be more indirect than environmental or economic dimensions in production-intensive industries. Research on total quality management and green performance shows that corporate social responsibility can mediate the relationship between managerial quality practices and green corporate performance (15). This indicates that sustainable performance is shaped not only by technical systems but also by organizational responsibility, stakeholder trust, social legitimacy, and quality-oriented management. In petroleum-related industries, sustainable business performance is influenced by multiple determinants, including organizational capabilities, environmental orientation, stakeholder engagement, and strategic management practices (16). Therefore, social and stakeholder-related dimensions should be incorporated into sustainable performance models, even when their direct statistical effects on production innovation may be weaker than technological or

environmental dimensions. Their importance lies in creating organizational acceptance, legitimacy, and participation necessary for long-term sustainability transformation.

Sanctions create a distinctive context for studying sustainable performance because they affect both environmental and innovation outcomes. On the one hand, sanctions may restrict access to cleaner technologies, international environmental standards, and advanced equipment, thereby weakening environmental performance. Research on the impact of international sanctions on environmental performance demonstrates that sanctions can have significant environmental consequences by reshaping trade, investment, technological access, and regulatory capacity (17). On the other hand, sanctions may stimulate domestic innovation, substitution strategies, and internal capability development when firms are forced to reduce external dependency. In Iran's petrochemical sector, sanctions have been associated with structural challenges related to financing, technology transfer, export markets, supply chains, and implementation of resistance economy policies (18). Therefore, the sanctions context requires analytical models that can capture both constraints and adaptive responses, particularly the ways in which sustainable performance dimensions contribute to innovative and economic production methods.

Recent Iranian studies have increasingly emphasized the need to identify and prioritize the drivers of sustainable performance optimization in oil, gas, and petrochemical organizations. A futures studies approach to sustainable performance optimization has shown that such organizations require proactive identification of key drivers, strategic uncertainties, and future-oriented capabilities (19). Similarly, research on innovative technology development indicates that technological innovation can improve environmental and economic performance, especially when supported by appropriate institutional and governmental mechanisms (20). These studies suggest that sustainable performance is not static; it depends on the interaction of technological, environmental, economic, institutional, and policy-related factors. Therefore, petrochemical firms need integrated models that can explain how sustainability dimensions influence innovation-oriented production practices and how these relationships can be optimized under uncertainty.

Despite the growing body of research on sustainability, petrochemical management, green practices, technology management, and performance evaluation, several research gaps remain. First, many studies examine sustainability dimensions separately, while petrochemical performance requires an integrated model that simultaneously evaluates environmental, economic, social, governance, ethical, supply chain, innovation, and stakeholder dimensions. Second, conventional statistical approaches often estimate linear relationships but may not fully capture nonlinear interactions among sustainability indicators and innovative production outcomes. Third, although structural equation modeling is useful for testing causal models, it can be strengthened by computational intelligence techniques that improve prediction accuracy and optimize indicator weighting. Fourth, there is limited empirical evidence on how sustainable performance management dimensions affect innovative and economic production methods in Iran's petrochemical industry specifically under sanctions conditions. Addressing these gaps requires a combined analytical approach that integrates SEM with metaheuristic and intelligent optimization algorithms such as ANFIS, GA, and PSO.

Accordingly, the present study is designed around the premise that sustainable performance management can serve as a strategic mechanism for improving innovative and economic production methods in the petrochemical industry. By integrating sustainability dimensions with advanced analytical techniques, the study seeks to provide both theoretical and practical contributions. Theoretically, it extends sustainable performance management research by modeling causal relationships among multiple sustainability dimensions and production innovation

outcomes. Methodologically, it combines structural equation modeling with metaheuristic algorithms to improve explanation, prediction, and prioritization. Practically, it provides petrochemical managers with evidence-based priorities for resource allocation, technology development, supply chain resilience, and sustainability-oriented decision-making under sanctions. The importance of this integrated approach is reinforced by the multidimensional nature of sustainability performance, the strategic role of technology and innovation, and the specific vulnerabilities of petrochemical firms operating in restricted international environments.

Therefore, the aim of this study is to analyze and optimize the relationships between sustainable performance management dimensions and the implementation of innovative and economic production methods in Iran's petrochemical industry under sanctions conditions using structural equation modeling and metaheuristic algorithms.

Methods and Materials

In terms of purpose, the present study falls within the category of applied research, because its findings can be used in decision-making and in improving the performance of the petrochemical industry, particularly under sanctions conditions. In terms of research nature and approach, this study is descriptive–analytical and was conducted based on quantitative data. With regard to research philosophy, the present study is based on a positivist approach; that is, the relationships among variables are examined on the basis of empirical evidence and statistical tests. In terms of reasoning logic, the research follows an inductive–confirmatory path, in such a way that after extracting the dimensions and indicators in the qualitative phase, the relationships among them are quantitatively tested and validated in this phase.

The research data were collected through a researcher-developed questionnaire designed based on the dimensions and indicators identified in the qualitative phase, namely the systematic review and fuzzy Delphi method. The items were designed based on a five-point Likert scale, ranging from “strongly disagree” to “strongly agree.” The statistical population consisted of senior managers, production and operations experts, and specialists in sustainability and innovation in Iranian petrochemical companies. Proportionate stratified random sampling was employed according to company size, and the final sample size was determined as 384 participants using Cochran's formula. Subsequently, the questionnaires were distributed both in person and online, and after incomplete responses were removed, valid data were selected for analysis. In addition, the content validity of the questionnaire was confirmed by expert judgment, and its reliability was confirmed with a Cronbach's alpha coefficient greater than 0.7.

A multi-stage approach was used to analyze the data. In the first step, descriptive analyses and preliminary tests, including Pearson correlation and multiple regression, were conducted to identify the initial relationships among variables. In the second step, Structural Equation Modeling (SEM) was performed using AMOS software to examine causal relationships and assess the fit of the conceptual model. In the third step, to increase prediction accuracy and rank the indicators, the resulting model was optimized using metaheuristic algorithms, including Adaptive Neuro-Fuzzy Inference System (ANFIS), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO), in MATLAB and Python environments. This combination of statistical methods and computational intelligence enabled a more precise analysis, reduced model error, and facilitated the extraction of the optimal pattern of relationships among the dimensions.

Findings and Results

To examine the relationships between sustainable performance management dimensions and innovative and economic production methods in the petrochemical industry, Pearson correlation analysis was used. The significance level in all tests was less than 0.05, indicating statistically significant relationships among the variables.

Table 1. Pearson Correlation Matrix Between Sustainable Performance Management Dimensions and Innovative and Economic Production Methods

Sustainable Performance Management Dimensions	Energy Optimization	Process Intensification	Lean and Green Lean	Digitalization and Industry 4.0	Innovation Management	Eco-Efficiency	Production Resilience and Flexibility
Environmental	0.62**	0.58**	0.54**	0.49**	0.46**	0.60**	0.57**
Social	0.55**	0.50**	0.59**	0.44**	0.48**	0.52**	0.50**
Economic	0.68**	0.63**	0.56**	0.61**	0.66**	0.64**	0.62**
Governance	0.47**	0.43**	0.40**	0.52**	0.51**	0.45**	0.48**
Ethical	0.44**	0.41**	0.38*	0.46**	0.42**	0.40**	0.39*
Human Rights	0.49**	0.46**	0.44**	0.40**	0.42**	0.43**	0.41**
Diversity and Inclusion	0.45**	0.41**	0.47**	0.38*	0.40**	0.42**	0.39*
Sustainable Supply Chain Management	0.59**	0.61**	0.53**	0.55**	0.58**	0.63**	0.60**
Sustainable Innovation	0.64**	0.66**	0.61**	0.62**	0.70**	0.68**	0.65**
Stakeholder Responsibility	0.53**	0.49**	0.51**	0.44**	0.46**	0.52**	0.50**

The results of the above table showed that all dimensions of sustainable performance management have a positive and significant relationship with innovative and economic production methods. Among the examined dimensions, the economic dimension and sustainable innovation showed the highest correlation coefficients with components of innovative production, including digitalization, eco-efficiency, and innovation management. These findings also indicate the central role of sustainable profitability, technological investment, and resource efficiency in developing innovative approaches to production.

Moreover, the environmental dimension showed a relatively strong correlation with the indicators of energy optimization and eco-efficiency, indicating the effect of environmental requirements on companies' tendency toward clean and resource-saving technologies. In contrast, although the governance, ethical, and diversity and inclusion dimensions had positive and significant relationships, the strength of their correlations ranged from 0.38 to 0.52, suggesting that they mainly play an infrastructural and institutional role in facilitating innovation. The findings also confirm that improving different dimensions of organizational sustainability, particularly in the economic, environmental, and innovation domains, can provide the basis for implementing innovative and economic production methods in the petrochemical industry, even under sanctions conditions.

Regression Results Analysis

The independent variables included the main dimensions of sustainable performance management, namely environmental, social, economic, governance, ethical, human rights, diversity and inclusion, sustainable supply chain management, sustainable innovation, and stakeholder responsibility. The dependent variable was the level of implementation of innovative and economic production methods in petrochemical companies.

Table 2. Results of Multiple Regression Between Sustainable Performance Management and Innovative Production Methods

Independent Variable	Standardized Coefficient β	t Statistic	Sig. (p)	Result
Environmental	0.28	6.15	0.000	Significant
Social	0.19	4.82	0.000	Significant
Economic	0.24	5.47	0.000	Significant
Governance	0.11	2.65	0.008	Significant
Ethical	0.09	2.12	0.035	Significant
Human Rights	0.07	1.76	0.079	Non-significant
Diversity and Inclusion	0.06	1.59	0.112	Non-significant
Sustainable Supply Chain Management	0.21	5.12	0.000	Significant
Sustainable Innovation	0.27	6.33	0.000	Significant
Stakeholder Responsibility	0.18	4.45	0.000	Significant

Multiple regression analysis was used to examine the effects of sustainable performance management dimensions on the implementation of innovative and economic production methods in the petrochemical industry. The results showed that the overall model had an acceptable fit, such that approximately 62% of the variance in the level of implementation of innovative and economic production methods was explained by the dimensions of sustainable performance management. In addition, the F statistic, with a significance level below 0.05, indicated that the overall model was statistically significant.

The findings also showed that all dimensions, except “human rights” and “diversity and inclusion,” had positive and significant effects on the implementation of innovative and economic production methods. Among the variables, the environmental dimension and sustainable innovation had the greatest effects; this means that the more organizations focus on reducing energy consumption, recycling resources, and developing green technologies, the greater their capacity becomes to achieve process and economic innovations. These were followed by the economic dimension and sustainable supply chain management, which play an important role in reducing costs, managing financial risk, and substituting domestic suppliers during the sanctions period.

On the other hand, the social dimension and stakeholder responsibility also showed positive and significant effects, indicating the importance of capable human capital, a participatory culture, and interaction with internal and external stakeholders in accepting and implementing innovations. In contrast, although the governance and ethical dimensions had positive effects, the intensity of their effects was lower, and they mainly play an institutional facilitating role in the innovation process.

Overall, the results indicate that implementing strategies related to the environmental dimension, sustainable innovation, the economic dimension, and sustainable supply chain management plays the greatest role in improving innovative and economic production methods in Iran’s petrochemical industry. These findings also emphasize that companies’ focus on resource management, energy optimization, development of indigenous technologies, and strengthening supply chain resilience can provide an appropriate path for increasing productivity, reducing vulnerability, and enhancing competitiveness during the sanctions period.

Investigation of the Causal Model of the Effect of Sustainable Performance Management Indicators on Innovative and Economic Production Methods

To comprehensively analyze the relationships between sustainable performance management dimensions and innovative and economic production methods, Structural Equation Modeling (SEM) was employed after conducting correlation and multiple regression tests. Regression analysis only determines the intensity and direction of effects,

but it cannot simultaneously explain direct and indirect relationships among variables; whereas SEM enables the simultaneous assessment of the measurement model and the structural model, through which validity, reliability, and the overall model fit can be examined.

Furthermore, given the complexities and limitations of the petrochemical industry during the sanctions period, metaheuristic algorithms, including Adaptive Neuro-Fuzzy Inference System, Genetic Algorithm, and Particle Swarm Optimization, were also used to increase the accuracy and robustness of the model. This combination of statistical methods and computational intelligence enabled the ranking and optimization of indicators and improved the accuracy of explaining causal relationships among the dimensions. Accordingly, the final model, in addition to having an appropriate statistical fit, has high operational capability and adaptability to sanctions conditions. In this regard, and in order to examine common method bias, Harman's Single-Factor Test was conducted. The results showed that the first factor explained only 34% of the total variance, which is below the 50% threshold; therefore, it can be stated that common method bias is not a serious concern.

Assessment of the Measurement Model: Reliability and Validity

Before analyzing the structural model, it is necessary to evaluate the measurement model, which specifies the relationship between observable indicators, namely questionnaire items, and latent variables, namely the dimensions of sustainable performance management and innovative and economic production methods. This stage includes the assessment of reliability, convergent validity, and discriminant validity.

A) Assessment of Internal Consistency

Cronbach's alpha and Composite Reliability (CR) were used to assess construct reliability.

A Cronbach's alpha value greater than 0.7 indicates acceptable construct reliability.

A CR value greater than 0.7 also indicates response stability and internal consistency among the items.

Table 3. Results of Internal Consistency Assessment of the Constructs

Construct / Dimension	Cronbach's Alpha	Composite Reliability (CR)	Result
Environmental	0.83	0.86	Reliable
Social	0.81	0.85	Reliable
Economic	0.84	0.88	Reliable
Governance	0.79	0.83	Reliable
Ethical	0.77	0.82	Reliable
Human Rights	0.76	0.82	Reliable
Diversity and Inclusion	0.75	0.81	Reliable
Sustainable Supply Chain	0.80	0.85	Reliable
Sustainable Innovation	0.82	0.87	Reliable
Stakeholder Responsibility	0.81	0.86	Reliable
Innovative and Economic Production Methods	0.85	0.89	Reliable

The results of the table show that all constructs have acceptable internal consistency.

Average Variance Extracted (AVE) was used to examine convergent validity. The AVE value should be greater than 0.5, indicating that the items of each construct explain a substantial proportion of the variance of their corresponding latent variable.

Table 4. Results of Convergent Validity

Construct / Dimension	AVE	Result
Environmental	0.58	Confirmed
Social	0.55	Confirmed
Economic	0.60	Confirmed
Governance	0.53	Confirmed

Ethical	0.52	Confirmed
Human Rights	0.54	Confirmed
Diversity and Inclusion	0.51	Confirmed
Sustainable Supply Chain Management	0.57	Confirmed
Sustainable Innovation	0.59	Confirmed
Stakeholder Responsibility	0.56	Confirmed
Innovative and Economic Production Methods	0.61	Confirmed

All AVE values were greater than 0.5; therefore, convergent validity was also confirmed.

The Fornell–Larcker Criterion was used to examine the distinction among constructs. According to this criterion, the square root of the AVE of each construct should be greater than the correlation of that construct with other constructs.

Table 5. Assessment of Discriminant Validity Based on the Fornell–Larcker Criterion

Constructs / √AVE	Environmen tal	Soci al	Econom ic	Governan ce	Ethic al	Huma n Right s	Diversit y and Inclusi on	Sustainab le Supply Chain	Sustainab le Innovatio n	Stakeholde r Responsibil ity
Environmen tal	0.76									
Social	0.48	0.74								
Economic	0.50	0.47	0.77							
Governance	0.44	0.41	0.45	0.73						
Ethical	0.42	0.40	0.43	0.39	0.72					
Human Rights	0.41	0.39	0.42	0.38	0.37	0.71				
Diversity and Inclusion	0.43	0.40	0.41	0.37	0.38	0.36	0.71			
Sustainable Supply Chain	0.49	0.46	0.50	0.44	0.41	0.43	0.42	0.75		
Sustainable Innovation	0.53	0.50	0.54	0.46	0.43	0.45	0.44	0.51	0.77	
Stakeholder Responsibili ty	0.46	0.44	0.47	0.42	0.40	0.41	0.39	0.48	0.49	0.74
Innovative Methods	0.55	0.52	0.57	0.48	0.44	0.45	0.43	0.53	0.59	0.51

In the above table, the values on the main diagonal, namely the square roots of AVE, are greater than the inter-construct correlation coefficients; therefore, discriminant validity was also confirmed. Overall, the reliability and validity results show that the research measurement model has the required validity, and consequently, the structural model of this study can be analyzed.

After confirming the reliability and validity of the measurement model, the structural model was assessed. At this stage, the causal relationships between sustainable performance management dimensions as independent variables and innovative and economic production methods as the dependent variable were tested. The aim was to measure the intensity and direction of the effect of each sustainability dimension on the implementation of innovative production methods in Iran's petrochemical industry during the sanctions period.

Several common indices were used to assess the overall model fit:

χ^2/df , or chi-square divided by degrees of freedom: a value less than 3 indicates acceptable fit.

RMSEA, or Root Mean Square Error of Approximation: values less than 0.08 are considered acceptable, and values less than 0.05 are considered very good.

CFI, or Comparative Fit Index, and TLI, or Tucker–Lewis Index: values greater than 0.90 indicate acceptable fit. SRMR, or Standardized Root Mean Square Residual: a value less than 0.08 indicates good fit.

Table 6. Fit Indices of the Structural Model

Fit Index	Calculated Value	Reference Value	Result
χ^2/df	2.41	Less than 3	Acceptable
RMSEA	0.054	Less than 0.08	Acceptable
CFI	0.93	Greater than 0.90	Acceptable
TLI	0.91	Greater than 0.90	Acceptable
SRMR	0.046	Less than 0.08	Acceptable

The results of the above table show that the structural model has an acceptable fit, and therefore, the causal paths can be analyzed.

In this section, the direct paths between sustainable performance management dimensions and innovative and economic production methods were tested. The path coefficients (β), t statistics, and significance levels are reported in Table 7.

Table 7. Results of Testing Causal Paths in the Structural Model

Hypothesized Path	Standardized Coefficient β	t Statistic	Sig. (p)	Result
Environmental → Innovative Methods	0.31	6.48	0.000	Significant
Social → Innovative Methods	0.18	4.15	0.000	Significant
Economic → Innovative Methods	0.26	5.92	0.000	Significant
Governance → Innovative Methods	0.10	2.12	0.034	Significant
Ethical → Innovative Methods	0.07	1.64	0.102	Non-significant
Human Rights → Innovative Methods	0.06	1.42	0.156	Non-significant
Diversity and Inclusion → Innovative Methods	0.05	1.27	0.205	Non-significant
Sustainable Supply Chain → Innovative Methods	0.22	5.01	0.000	Significant
Sustainable Innovation → Innovative Methods	0.29	6.87	0.000	Significant
Stakeholder Responsibility → Innovative Methods	0.16	3.87	0.000	Significant

The results show that most dimensions of sustainable performance management have positive and significant effects on the implementation of innovative and economic production methods. Among them, the strongest effects are related to the environmental dimension and sustainable innovation, whereas the human rights, ethical, and diversity and inclusion dimensions did not show significant effects. Overall, it can be concluded that companies' focus on resource management, technological innovation, and strengthening supply chain resilience plays the greatest role in enhancing the innovative performance of the petrochemical industry under sanctions conditions.

At this stage, the dependent variable of the model, namely the composite score of the implementation of innovative and economic production methods, was considered as the target function, and the sustainable performance management dimensions were introduced into the model as input variables. The purpose of the algorithms was to reduce prediction error, measured by RMSE, and increase the coefficient of determination, R^2 , in the test set. After evaluating the conceptual model using Structural Equation Modeling, the research model was tested and optimized in this section using metaheuristic algorithms. The purpose of this stage was to increase the prediction accuracy of relationships among indicators, reduce model error, and identify the optimal configuration of variables under the complex and uncertain conditions of the petrochemical industry, particularly during the sanctions period. The data were divided into training and testing sets, with 70% allocated to training and 30% to testing, and model performance was evaluated using five-fold cross-validation.

Before implementing the metaheuristic algorithms, the data were divided into training and testing sets, with 70% assigned to training and 30% to testing, in order to increase analytical accuracy and enable comparison of model performance. In the training phase, the algorithm parameters were optimized, and in the testing phase, the generalizability of the models was evaluated. In addition, to prevent overfitting, the training process was controlled using cross-validation.

Table 8. Key Algorithm Settings

Algorithm	Key Parameter	Set Value	Description
ANFIS	Type of membership functions	Gaussian	Selected due to smoothness and better learning capability
ANFIS	Number of membership functions	3 for each input	Appropriate to the sample size and used to prevent excessive complexity
ANFIS	Learning method	Hybrid	Combination of least squares and gradient descent
GA	Population size	100	Number of individuals in each generation
GA	Number of generations	200	Evolutionary iterations until convergence
GA	Mutation rate	0.05	Used to prevent entrapment in a local optimum
GA	Crossover rate	0.8	Used to generate genetic diversity among chromosomes
PSO	Number of particles	50	Population size in the search space
PSO	Maximum iterations	150	Stopping point in the absence of further improvement
PSO	Individual learning coefficient (c1)	2	Degree of influence of each particle's personal experience
PSO	Social learning coefficient (c2)	2	Degree of influence of the best particle in the group
PSO	Inertia coefficient (w)	0.7	Balance between global and local search

These parameters were set based on the literature review and preliminary pilot runs to establish an appropriate balance among accuracy, speed, convergence, and model stability.

The ANFIS model is a combination of neural networks and fuzzy logic that has the capacity to learn complex data patterns. In this study, ANFIS was used to simulate nonlinear relationships between sustainable performance management dimensions and innovative production methods. The results showed that prediction accuracy, reflected in lower RMSE and MAPE values, improved compared with the regression model, and a substantial improvement in model fit was achieved.

In this section, the Genetic Algorithm, inspired by the process of natural evolution, was used to optimize the weighting of indicators and find the best combination of variables. The implementation of GA showed that the environmental, economic, and sustainable innovation dimensions had the greatest contribution to model optimization. In addition, GA made it possible to identify nonlinear relationships and complex interactions among indicators.

The PSO algorithm, by simulating the social behavior of particles, was used to search for the optimal configuration of model parameters. The results obtained from PSO also showed that the simultaneous adjustment of prediction model parameters increased model accuracy and produced faster convergence than GA.

Table 9. Comparison of the Outputs of Metaheuristic Algorithms

Algorithm	R ²	RMSE	MAPE	Strengths	Weaknesses
ANFIS	0.89	0.12	6.5%	High accuracy in nonlinear relationships	Requires more data for training
GA	0.85	0.15	7.2%	Identification of the optimal combination of indicators	Lower convergence speed
PSO	0.87	0.13	6.8%	Fast and stable convergence	Possibility of entrapment in a local optimum

To compare the performance of the algorithms, prediction accuracy indices, including RMSE, R², and MAPE, were examined. Overall:

ANFIS had the best performance in simulating nonlinear relationships and reducing error.

PSO showed a higher convergence speed than GA.

GA had a strong capability to identify the optimal combination of variables and prioritize indicators.

Based on these results, the combination of ANFIS and PSO provided the best model configuration. This means that the environmental dimension, economic dimension, sustainable innovation, and sustainable supply chain management were identified as the most influential indicators in the implementation of innovative and economic production methods. Moreover, the use of metaheuristic algorithms enabled the research model to have greater operational efficiency and stability in addition to appropriate statistical fit.

To evaluate the accuracy and efficiency of the metaheuristic models, their results were compared with the baseline model, namely linear multiple regression. The main comparison indices included the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE).

Table 10. Comparison of the Performance of the Research Models with the Baseline

Model	R^2	RMSE	MAPE	Result
Multiple Regression (Baseline)	0.62	0.24	11.3%	Moderate performance
ANFIS	0.89	0.12	6.5%	High accuracy and capability in nonlinear relationships
GA	0.85	0.15	7.2%	Identification of the optimal combination, but slower
PSO	0.87	0.13	6.8%	Fast and stable convergence

The comparison of algorithm performance showed that the ANFIS model had the highest predictive power in simulating nonlinear relationships, whereas PSO performed better than GA in terms of speed and stability. Ultimately, the combination of ANFIS and PSO results provided the best model configuration and showed that the environmental dimension, economic dimension, sustainable innovation, and sustainable supply chain management play the greatest role in implementing innovative and economic production methods. Moreover, the application of metaheuristic algorithms enabled the research model to have higher operational efficiency and stability in addition to appropriate statistical fit.

After testing and optimizing the model using metaheuristic algorithms, this stage ranks the dimensions and components of sustainable performance management in order to determine which ones have the greatest importance in explaining and improving innovative and economic production methods in the petrochemical industry, particularly under sanctions conditions.

Table 11. Ranking of Sustainable Performance Management Dimensions

Rank	Dimension	Final Weight (Mean of Three Algorithms)	Relative Importance (%)	Result
1	Environmental	0.28	16.5%	Very important
2	Sustainable Innovation	0.27	15.9%	Very important
3	Economic	0.24	14.1%	Important
4	Sustainable Supply Chain	0.21	12.4%	Important
5	Social	0.19	11.2%	Relatively important
6	Stakeholder Responsibility	0.18	10.6%	Relatively important
7	Governance	0.11	6.5%	Low importance
8	Ethical	0.09	5.3%	Low importance
9	Human Rights	0.07	4.1%	Low importance
10	Diversity and Inclusion	0.06	3.5%	Low importance

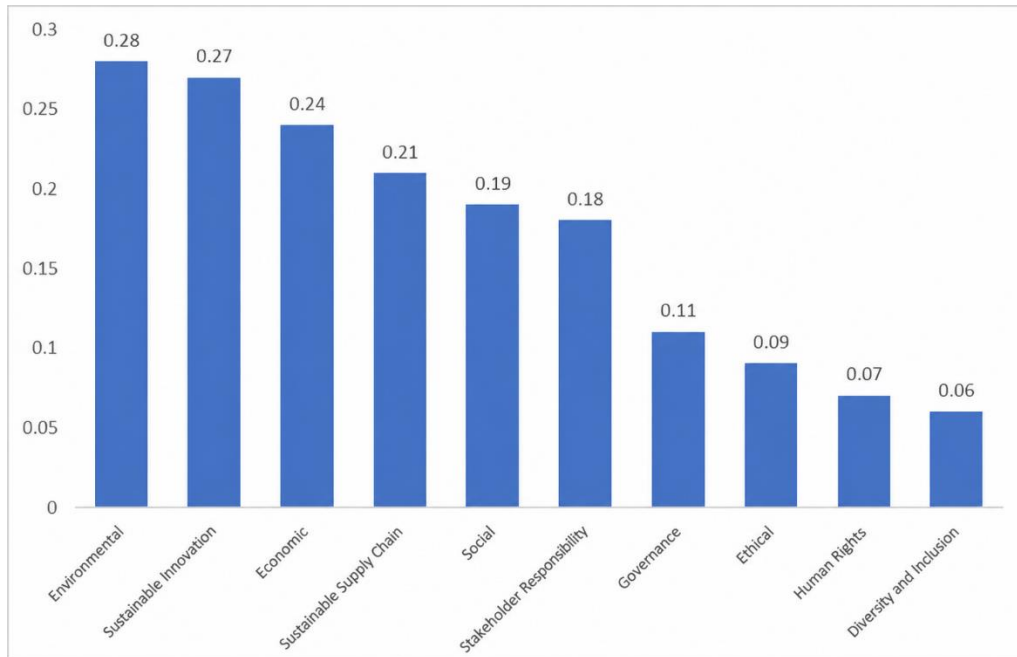


Figure 1. Ranking of Sustainable Performance Management Dimensions

For ranking purpose, a combination of the results of ANFIS, GA, and PSO algorithms was used. The main ranking criteria were as follows:

The weights obtained from algorithmic optimization,

The values of path coefficients (β) in the structural model,

The level of relative importance in reducing prediction errors, namely MAPE and RMSE.

The results show that the environmental dimension, sustainable innovation, economic dimension, and sustainable supply chain management play the greatest role in enhancing innovative methods. This indicates that under sanctions conditions, attention to resource management, development of green and indigenous technologies, and supply chain flexibility provide the highest returns for petrochemical industries. In contrast, dimensions such as human rights and diversity and inclusion, although important in the long term, have a lower direct and immediate effect under the constraints created by sanctions.

Discussion and Conclusion

The findings of the present study showed that the dimensions of sustainable performance management are positively associated with innovative and economic production methods in the petrochemical industry. The Pearson correlation results indicated that all examined dimensions, including environmental, social, economic, governance, ethical, human rights, diversity and inclusion, sustainable supply chain management, sustainable innovation, and stakeholder responsibility, had positive and statistically significant relationships with the components of innovative production. This finding confirms that sustainable production in the petrochemical industry is not driven by a single managerial factor, but rather by a multidimensional configuration of environmental, technological, economic, organizational, and stakeholder-related capabilities. This result is consistent with the broader logic of sustainable performance management, which argues that sustainability goals should be embedded within performance systems, operational indicators, and strategic control mechanisms rather than being treated as separate corporate responsibility activities (1). It also aligns with the sustainable manufacturing literature, which emphasizes that

sustainable manufacturing practices improve sustainability performance when they are integrated into production systems, resource management, and organizational decision-making (4).

One of the most important findings was that the economic dimension and sustainable innovation showed the strongest correlations with innovative and economic production methods, especially with digitalization, eco-efficiency, and innovation management. This result suggests that petrochemical firms are more likely to implement innovative production practices when sustainability is linked to economic efficiency, cost reduction, technological investment, and long-term competitiveness. In sanction-affected environments, economic sustainability becomes even more critical because firms must maintain production continuity, reduce dependency on imported equipment and technologies, and manage financial and operational risks. This finding is consistent with research showing that open innovation can enhance economic, innovative, and sustainable performance by improving organizational learning, technological development, and knowledge-based competitiveness (7). It also supports evidence that innovative technology development can improve both environmental and economic performance, particularly when it is supported by appropriate institutional and policy conditions (20). Therefore, the strong role of sustainable innovation in the present study indicates that innovation operates as a bridge between sustainability goals and economic production outcomes.

The environmental dimension also emerged as one of the strongest predictors of innovative and economic production methods. In both the regression and structural equation modeling results, environmental sustainability had the highest standardized effect on innovative production methods. This finding is theoretically meaningful because the petrochemical industry is highly energy-intensive and environmentally sensitive. Therefore, environmental management is directly connected to energy optimization, waste reduction, cleaner production, eco-efficiency, and adoption of green technologies. This result is aligned with previous studies showing that green management is positively related to sustainable performance in petrochemical companies (5). It is also supported by evidence from downstream petrochemical industries indicating that green human resource management and environmental-oriented organizational actions enhance sustainable performance by embedding environmental responsibility into managerial practices and employee behavior (6). The present finding therefore confirms that environmental sustainability is not merely a regulatory or reputational requirement; it is a practical driver of process innovation, resource efficiency, and production modernization.

The significant role of the economic dimension in the regression and SEM models further indicates that innovative production methods in the petrochemical industry are strongly shaped by economic rationality. Under sanctions conditions, petrochemical companies must simultaneously pursue cost control, productivity improvement, risk reduction, domestic substitution, and export competitiveness. The finding that economic sustainability had a substantial effect on innovative production methods is consistent with studies on Iran's petrochemical industry, which emphasize that the sector's regional competitiveness depends on technological modernization, productivity improvement, and strategic positioning in relation to neighboring countries (2). It also corresponds with research identifying sustainable performance optimization drivers in oil, gas, and petrochemical organizations, where future-oriented performance depends on economic resilience, technological capability, and strategic adaptability (19). Thus, the economic dimension in this study should be interpreted not simply as profitability, but as the organizational capacity to transform financial and resource constraints into efficiency-oriented and innovation-based production strategies.

The findings also demonstrated that sustainable supply chain management had a positive and significant effect on innovative and economic production methods. This result is particularly important in the petrochemical sector because production continuity depends on stable access to raw materials, catalysts, spare parts, equipment, logistics systems, and downstream markets. Under sanctions, supply chain disruption becomes one of the most serious threats to operational performance. The significant effect of sustainable supply chain management suggests that petrochemical firms can improve innovative production by developing resilient sourcing systems, domestic supplier networks, risk management mechanisms, and environmentally responsible procurement practices. This finding is consistent with research on petrochemical supply chains showing that sustainable operational management systems can improve performance through systematic evaluation, prioritization, and optimization of supply chain indicators (11). It also supports the broader view that sustainable business performance in petroleum-related industries depends on integrated determinants, including operational capability, environmental management, organizational learning, and strategic supply chain coordination (16).

The positive effects of digitalization and technology-related production methods in the correlation results are also consistent with previous research. The strong relationships between sustainable performance dimensions and digitalization, Industry 4.0, eco-efficiency, and innovation management indicate that petrochemical firms increasingly depend on technological systems to achieve sustainable production. This finding is aligned with evidence that technology management improves sustainability performance in petroleum refineries and petrochemical companies by enhancing process control, operational integration, and strategic technological capability (9). It is also consistent with research showing that cyber-physical systems and Industry 4.0 technologies can optimize energy efficiency in smart manufacturing by enabling real-time monitoring, adaptive control, and data-driven decision-making (10). Accordingly, the present study confirms that technological transformation is a core mechanism through which sustainable performance management is translated into innovative and economic production outcomes.

The results also showed that the social dimension and stakeholder responsibility had positive and significant effects on innovative and economic production methods. Although their effect sizes were lower than those of environmental, economic, sustainable innovation, and supply chain dimensions, their significance indicates that human capital, organizational participation, stakeholder trust, and social legitimacy contribute to innovation implementation. This finding is consistent with the argument that sustainable performance is strengthened when organizations integrate social responsibility and stakeholder engagement into quality and performance systems. Previous research has shown that corporate social responsibility can mediate the relationship between total quality management and corporate green performance, indicating that responsible organizational practices can enhance environmental and performance outcomes (15). Similarly, performance management literature emphasizes that organizational performance improvement requires alignment between strategic objectives, employee participation, measurement systems, and continuous learning (12). Therefore, the social and stakeholder-related findings of the present study indicate that innovation in petrochemical production requires not only technology and resources, but also organizational acceptance, workforce capability, and stakeholder coordination.

The governance dimension had a positive and significant effect, but its effect was weaker than the environmental, economic, innovation, and supply chain dimensions. This suggests that governance contributes to innovative production indirectly by creating institutional order, accountability, transparency, decision-making discipline, and performance monitoring. In complex industries such as petrochemicals, governance structures are essential for

coordinating sustainability initiatives and ensuring that innovation investments are aligned with organizational strategy. This result is consistent with studies emphasizing the importance of sustainable performance evaluation systems and key performance indicators in the petrochemical industry (14). It also aligns with research using hybrid sustainability-balanced scorecard and multi-criteria decision-making models, which highlights the need for comprehensive performance evaluation structures to manage multidimensional sustainability objectives (13). Therefore, although governance may not have the strongest direct effect on production innovation, it functions as a necessary institutional infrastructure for sustainable performance management.

An important finding of the SEM analysis was that ethical, human rights, and diversity and inclusion dimensions did not have significant direct effects on innovative and economic production methods. This does not mean that these dimensions are unimportant; rather, it suggests that their effects may be indirect, long-term, or mediated through organizational culture, legitimacy, human resource practices, and stakeholder trust. The weaker direct effect of these dimensions may also reflect the specific conditions of the petrochemical industry under sanctions, where firms prioritize immediate operational survival, energy efficiency, technological substitution, and supply chain resilience. This interpretation is compatible with critiques of the triple bottom line, which argue that sustainability dimensions are often complex, unevenly operationalized, and difficult to aggregate into direct performance outcomes (3). In other words, ethical, human rights, and inclusion-related indicators may contribute to organizational sustainability, but their influence on production innovation may require longer time horizons or operate through intermediate organizational mechanisms.

The sanctions context provides a crucial explanation for several findings. The stronger effects of environmental, economic, sustainable innovation, and supply chain dimensions suggest that petrochemical companies under sanctions focus primarily on dimensions that directly reduce vulnerability and improve operational continuity. Previous research has shown that international sanctions can affect environmental performance by restricting access to technologies, investment, trade, and environmental management capacity (17). At the same time, sanctions may create pressure for local innovation, internal capability development, and substitution of foreign technologies. Evidence from research on sanctions and innovation indicates that sanctions can influence firms' innovation behavior by changing external constraints and incentives (8). In the Iranian petrochemical industry, challenges associated with resistance economy policies, technology access, financing, supply chains, and market restrictions have made operational resilience a central strategic concern (18). Therefore, the present results show that sustainable performance management under sanctions becomes most effective when it is linked to resource optimization, technological self-reliance, green production, and supply chain flexibility.

The results of the metaheuristic algorithm analysis further strengthened the statistical findings. Compared with the baseline multiple regression model, ANFIS, GA, and PSO showed higher predictive accuracy, with ANFIS producing the best performance in modeling nonlinear relationships and PSO showing rapid and stable convergence. This indicates that the relationships between sustainable performance dimensions and innovative production methods are not purely linear and can be better understood through computational intelligence models. The superiority of ANFIS suggests that fuzzy and nonlinear interactions exist among sustainability indicators, while the performance of GA and PSO indicates that optimal weighting and configuration of variables can improve model efficiency. These findings are methodologically important because they demonstrate that SEM can identify causal structures, while metaheuristic algorithms can enhance prediction, prioritization, and optimization. This combined

approach is especially appropriate for petrochemical industries, where production systems are complex, uncertain, and influenced by multiple interacting technical, economic, environmental, and institutional factors.

Finally, the ranking results showed that environmental sustainability, sustainable innovation, economic sustainability, and sustainable supply chain management were the most important dimensions in explaining and improving innovative and economic production methods. This prioritization is consistent with the overall empirical pattern of the study and confirms that petrochemical companies should focus first on the dimensions that have the strongest operational and strategic effects. Environmental sustainability supports cleaner production and energy efficiency; sustainable innovation enables technological renewal and process improvement; economic sustainability ensures cost control and competitiveness; and sustainable supply chain management strengthens resilience under uncertainty. Taken together, these findings show that the development of innovative and economic production methods in the petrochemical industry requires an integrated sustainability-oriented management model that combines environmental responsibility, technological innovation, economic rationality, and supply chain resilience. The study therefore contributes to the literature by demonstrating that sustainable performance management can function as both a strategic framework and an operational mechanism for enhancing production innovation in sanction-constrained petrochemical environments.

This study has several limitations that should be considered when interpreting the findings. First, the data were collected through a researcher-developed questionnaire, and although validity and reliability were confirmed, self-report data may still be affected by perceptual bias, respondent interpretation, and organizational sensitivity. Second, the study focused on the Iranian petrochemical industry under sanctions conditions, which improves contextual relevance but may limit the generalizability of the findings to petrochemical industries in countries with different institutional, technological, and market conditions. Third, the cross-sectional design restricts the ability to examine how sustainable performance management dimensions influence innovative production methods over time. Fourth, although SEM and metaheuristic algorithms were combined to improve explanatory and predictive accuracy, the model still depends on the selected indicators and available data, and alternative model specifications may produce different prioritization patterns.

Future studies should examine the proposed model in other energy-intensive industries, such as steel, cement, refining, and mining, to determine whether the same sustainability dimensions have similar effects on innovative and economic production methods. Longitudinal research is also recommended to investigate how the effects of environmental sustainability, sustainable innovation, economic performance, and supply chain resilience evolve over time, especially as sanctions, market conditions, and technology access change. Future researchers may also test mediating and moderating mechanisms, such as organizational learning, absorptive capacity, government support, digital maturity, green human resource management, and innovation culture. In addition, future studies can compare different computational intelligence approaches, such as deep learning, ensemble models, hybrid neural networks, and evolutionary optimization methods, to improve prediction accuracy and provide more robust managerial decision-support models.

Managers in the petrochemical industry should prioritize sustainability initiatives that have the strongest operational impact, particularly environmental management, sustainable innovation, economic efficiency, and sustainable supply chain resilience. Companies should invest in energy optimization, cleaner production technologies, process intensification, digital monitoring systems, and domestic technological capabilities to reduce vulnerability under sanctions. Supply chain managers should develop flexible sourcing strategies, strengthen

domestic supplier networks, and establish risk-based procurement systems to improve production continuity. At the same time, senior managers should not neglect social, ethical, governance, human rights, and inclusion-related dimensions, because these factors support long-term legitimacy, organizational trust, and stakeholder cooperation. A practical sustainable performance dashboard should be developed to monitor key indicators, evaluate progress, prioritize investments, and connect sustainability objectives directly to production innovation and economic performance.

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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 adhered 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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