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Challenges and Strategies for Transitioning to a Circular Economy in the Petrochemical Industry: A Comparative Analysis of Perspectives Across Specialized Functional Areas at Tabriz Petrochemical Complex

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A B S T R A C T

The present study aimed to identify and compare the challenges and strategies associated with the transition to a circular economy in the petrochemical industry from the perspectives of specialized functional areas within Tabriz Petrochemical Complex. This qualitative and exploratory study employed a qualitative content analysis strategy and semi-structured interviews with 22 experts from seven functional areas: production and process, HSE and environment, maintenance and repair, finance and planning, human resources and training, research and innovation, and communications and strategy. The data were analyzed through open, axial, and selective coding, and the perspectives of the functional areas were comparatively examined. The findings indicated that each functional area perceived the challenges from the perspective of its own responsibilities. Equipment obsolescence and polymer waste were prominent in production; pollution and the prioritization of production over health in HSE; dependence on imports and energy subsidies in maintenance; information-system incompatibility and low return on investment in finance; shortages of sustainability expertise and generational gaps in human resources; technological gaps and inadequate budgets in research; and public distrust and short-termism in communications and strategy. Cultural-behavioral barriers and information infrastructure and coordination barriers each accounted for five of the 22 identified barriers. The proposed strategies were categorized into four patterns: energy and water recovery, closing material loops and creating value from waste, data-driven decision-making, and source prevention. Conclusion: The transition to a circular economy at Tabriz Petrochemical Complex is not merely a technological issue; rather, it requires cross-functional coordination, cultural development, information integration, financial and regulatory support, and phased planning.

Keywords: *circular economy, petrochemical industry, Tabriz Petrochemical Complex, qualitative content analysis, specialized functional areas, sustainable transition.*

1. Introduction

The transition from linear production and consumption systems toward a circular economy has become one of the central strategic concerns of contemporary industrial management, particularly in resource-intensive sectors whose operations are associated with substantial material throughput, energy consumption, emissions, and waste generation. The conventional linear model of "take, make, use, and dispose" is increasingly incompatible with the simultaneous pressures of resource scarcity, environmental degradation, climate change, volatile input markets, and tightening sustainability expectations. In contrast, the circular economy seeks to retain the value of materials, products, energy, water, and other resources within economic systems for as long as possible through strategies such as reduction, reuse, recovery, remanufacturing, recycling, regeneration, and redesign. However, a sustainable circular economy should not be reduced to waste recycling alone; rather, it requires systemic changes in resource use, production design, governance, business models, organizational behavior, and interorganizational relationships. Velenturf and Purnell emphasize that circularity must be integrated with the broader principles of sustainability so that material circulation does not merely improve resource efficiency but also contributes to environmental integrity, social well-being, and long-term economic resilience (Velenturf & Purnell, 2021). From an innovation perspective, the transition also depends on the development of a circular innovation ecosystem in which technological capabilities, policy mechanisms, business actors, knowledge institutions, and market incentives operate in a mutually reinforcing manner (Asgari & Asgari, 2022). Accordingly, the circular economy is increasingly understood not as a discrete environmental program but as a multidimensional transformation of industrial systems involving technological, managerial, financial, regulatory, behavioral, and strategic components.

The petrochemical industry occupies a particularly important position in this transformation because it is simultaneously a major consumer of energy and raw materials, a producer of high-value chemical and polymer products, and a significant source of emissions, process losses, wastewater, hazardous materials, and post-consumption waste. Petrochemical production is characterized by highly integrated process systems in which inefficiencies in heat transfer, material conversion, equipment performance, water consumption, and operational control can generate substantial economic and environmental consequences. At the same time, many petrochemical outputs, especially plastics and carbon-based chemical products, remain embedded in linear value chains characterized by limited recovery and recycling. Recent international scholarship has therefore emphasized the need to redesign carbon and plastics systems in ways that maintain carbon within productive cycles, reduce dependence on virgin fossil feedstocks, improve recyclability, and align chemical production with long-term sustainability objectives (Vidal et al., 2024). Barner similarly argues that although complete circularity in the chemical industry faces thermodynamic, technological, economic, and infrastructural limitations, substantial progress remains possible through improved product design, feedstock substitution, material recovery, chemical recycling, renewable energy integration, and cross-sectoral collaboration (Barner, 2025). The relevance of these issues is especially pronounced in oil, gas, and petrochemical industries because circular practices in these sectors require the integration of upstream resource management, process optimization, downstream recovery, industrial symbiosis, and lifecycle thinking. A recent bibliometric analysis of circular economy research in the oil and gas industry demonstrates that the field has rapidly expanded, with growing attention to resource efficiency, digital technologies, waste valorization, decarbonization, industrial ecology, and sustainable business models (Adedayo-Ojo et al., 2025). These developments indicate that circularity in petrochemical operations must be treated as a strategic industrial transformation rather than as an isolated environmental intervention.

One of the defining characteristics of the circular transition in petrochemical systems is the strong interdependence among energy, water, carbon, materials, and digital information. Energy-intensive process units consume large quantities of fuel and electricity, while cooling, steam generation, separation, and treatment systems create significant water demands. Carbon emissions are linked not only to direct combustion but also to process inefficiencies, product losses, flaring, equipment deterioration, and inefficient energy management. For this reason, contemporary research increasingly conceptualizes circularity through integrated resource nexuses rather than through single-variable optimization. Zhang et al. identify the water-energy-carbon nexus as a critical framework for understanding circular transformation in petrochemical industries and emphasize the enabling role of digital

intelligence, including advanced monitoring, data analytics, artificial intelligence, process optimization, and intelligent decision-support systems (Zhang et al., 2026). In the Iranian petrochemical sector, energy efficiency also represents a substantial pathway for greenhouse gas mitigation, particularly because improvements in equipment performance, energy management, heat recovery, and process efficiency can simultaneously reduce costs and environmental burdens (Modirzadeh et al., 2024). Similarly, environmental efficiency assessment in petrochemical companies indicates that undesirable outputs should be incorporated directly into managerial performance evaluation rather than treated as external consequences of production (Mousavi & Naderizadeh, 2024). These findings reinforce the proposition that the circular economy in petrochemical complexes requires a shift from end-of-pipe environmental control toward preventive, integrated, and data-driven management in which material losses, emissions, energy consumption, wastewater, and waste generation are treated as interconnected indicators of operational inefficiency and lost economic value.

The supply chain constitutes another critical dimension of circularity because petrochemical companies are embedded in extensive networks of feedstock suppliers, equipment manufacturers, contractors, logistics providers, warehouses, customers, recyclers, and downstream industries. Circular economy implementation therefore depends not only on internal process improvements but also on the ability to establish sustainable material flows across organizational boundaries. Research on the petrochemical industry has highlighted the need for circular supply chain models incorporating resource efficiency, sustainable procurement, recycling, reverse logistics, supplier collaboration, and long-term coordination (Dehkordi et al., 2024). Sustainability indicators within petrochemical supply chains also require systematic prioritization because environmental, economic, operational, and social criteria do not necessarily have equal strategic importance across different stages of the chain (Raoofi Rad & Fathi, 2024). In this context, trust and commitment between supply chain actors can enhance sustainable performance by improving supply flexibility, facilitating cooperation, and reducing coordination problems under changing operational conditions (Shirazi et al., 2024). Waste management similarly becomes more effective when waste is understood as a potentially valuable secondary resource rather than merely as a disposal burden. Circular approaches to waste management emphasize source reduction, segregation, reuse, recycling, recovery, and the development of markets for secondary materials, thereby linking environmental performance with economic value creation (Mozaffar & Houshyari, 2024). In downstream petroleum industries, interpretive modeling has likewise shown that successful circular economy implementation depends on interconnected factors rather than a single technological solution, highlighting relationships among organizational, technological, policy, and market variables (Ghorbanpour & Hossinpour, 2021). Consequently, circular transition in petrochemical companies requires coordinated management of internal processes and external value-chain relationships.

Despite its technical dimensions, circular transformation is also profoundly shaped by organizational capabilities and managerial choices. Petrochemical complexes are usually large, functionally differentiated organizations in which production, maintenance, HSE, finance, procurement, human resources, research, planning, and strategic management may evaluate sustainability initiatives according to different performance criteria. Production managers may prioritize continuity, throughput, and product quality; HSE professionals may emphasize emissions, workplace exposure, safety, and regulatory compliance; maintenance units may focus on equipment reliability and energy efficiency; financial managers may assess investment return and capital constraints; research units may emphasize technology and innovation; and human resource managers may concentrate on employee capabilities, training, and behavioral change. These differences can generate both complementary insights and organizational tensions. Sustainable value chain optimization in the Iranian petrochemical industry has therefore been linked to multiple strategic drivers that require prioritization through a long-term and foresight-oriented approach rather than through fragmented operational interventions (Bakhshizadeh et al., 2025). Financial considerations are particularly significant because petrochemical companies operate under market volatility, capital-intensive investment requirements, exchange-rate exposure, and various forms of financial shock that can influence investment priorities and organizational risk tolerance (Torkaman et al., 2025). Under such conditions, circular projects that require upfront capital expenditure may be postponed even when they promise long-term resource savings. Thus, implementation is influenced not only by the technical feasibility of circular solutions but also by management commitment, investment horizons, budgeting procedures, performance metrics, and the capacity to coordinate across functional boundaries.

Policy and institutional conditions further shape the feasibility of circular economy strategies. Industrial companies do not operate in isolation; their decisions are influenced by energy prices, environmental regulations, taxation, import policies, product standards, industrial development priorities, and national sustainability strategies. In Iran, industrial policy in the petrochemical sector is embedded within broader national economic and strategic frameworks, making alignment between enterprise-level circular initiatives and macro-level policies particularly important (Yarahmadi & Sadeghi Shahdani, 2024). If energy remains artificially inexpensive, the financial incentive for efficiency investment may weaken; if product standards restrict the use of secondary materials, recycling opportunities may remain limited; and if green technologies face import barriers or inadequate financing, technologically feasible projects may not be implemented. Conversely, appropriate regulations, financial incentives, performance standards, and industrial policies can create favorable conditions for circular innovation and investment. Circular transformation should therefore be analyzed not only as an internal corporate process but also as a transition influenced by institutional incentives, regulatory signals, and industrial policy. Moreover, because petrochemical operations involve substantial technological and operational risks, new sustainability initiatives must be integrated with risk-management practices. Experience in oil, gas, and petrochemical project management indicates that risk assessment should reflect industry-specific operational, financial, technical, and contextual conditions (Zaeimi & Zaeimi, 2021). Circular initiatives that modify processes, substitute materials, introduce refurbished components, or deploy unfamiliar technologies must consequently be evaluated in relation to safety, reliability, quality, and continuity of operations.

Another critical requirement is the integration of human capital, organizational culture, and learning mechanisms into the transition process. Circular economy strategies cannot be sustained merely through equipment upgrades or formal policies if employees do not possess the necessary knowledge, incentives, skills, and willingness to change established work routines. Petrochemical plants often depend on tacit knowledge accumulated through years of operational experience, particularly in production and maintenance environments where experienced personnel can identify early warning signs, process irregularities, and equipment problems that may not be fully captured by automated systems. At the same time, digitalization and emerging technologies require new competencies in data analysis, intelligent monitoring, automation, predictive maintenance, and integrated decision-making. These developments generate a dual organizational challenge: preserving and transferring experiential knowledge while simultaneously developing new sustainability and digital capabilities. A circular innovation ecosystem consequently requires organizational learning, knowledge exchange, cross-disciplinary collaboration, and mechanisms that connect technical innovation with managerial implementation (Asgari & Asgari, 2022). Such requirements are especially relevant in large industrial organizations where functional silos may inhibit communication and where sustainability objectives may compete with short-term production targets. The effectiveness of circular strategies therefore depends on whether sustainability responsibilities are institutionalized in job roles, performance evaluation, training systems, managerial incentives, reporting practices, and decision-making structures.

Tabriz Petrochemical Complex provides a particularly relevant context for examining these issues because of its industrial scale, diversified production activities, resource-intensive processes, and strategic position within Iran's petrochemical sector. The complex must simultaneously address operational efficiency, environmental performance, technological modernization, competitive pressures, resource constraints, and changing sustainability expectations. Recent research has specifically proposed a circular economy model for Tabriz Petrochemical Company with an emphasis on sustainability, demonstrating the growing organizational and scholarly attention to the integration of economic, environmental, and social dimensions within the company's transition process (Teimouri et al., 2026). However, the practical implementation of such models requires a more detailed understanding of how different specialized functional areas perceive the barriers and possible solutions. A corporate-level model may identify general dimensions of circularity, but implementation decisions occur within departments and professional domains that possess different responsibilities, technical languages, performance indicators, and operational priorities. A maintenance manager may interpret circularity through equipment life extension, refurbishment, predictive maintenance, and energy efficiency, whereas an HSE expert may focus on pollution prevention, occupational health, emissions, and waste reduction. Financial managers may focus on return on investment and cost allocation, while

research specialists may emphasize recycling technologies, new materials, and product redesign. Without recognizing these differences, circular economy programs may remain conceptually comprehensive but operationally fragmented.

Existing research therefore reveals a significant need for context-specific, cross-functional analysis. The literature has addressed circular economy principles, carbon and plastics circularity, circular innovation ecosystems, circularity in oil and gas, energy and emission efficiency, sustainable petrochemical supply chains, environmental efficiency, industrial policy, risk, waste management, and strategic value-chain optimization (Adedayo-Ojo et al., 2025; Asgari & Asgari, 2022; Bakhshizadeh et al., 2025; Barner, 2025; Dehkordi et al., 2024; Ghorbanpour & Hossinpour, 2021; Modirzadeh et al., 2024; Mousavi & Naderizadeh, 2024; Mozaffar & Houshyari, 2024; Raoofi Rad & Fathi, 2024; Shirazi et al., 2024; Teimouri et al., 2026; Torkaman et al., 2025; Velenturf & Purnell, 2021; Vidal et al., 2024; Yarahmadi & Sadeghi Shahdani, 2024; Zaeimi & Zaeimi, 2021; Zhang et al., 2026). Nevertheless, comparatively less attention has been paid to how the organizational meaning of circular transition differs across specialized professional domains within a single petrochemical complex. Such an analysis is important because barriers identified by one function may be consequences of decisions made by another, while solutions may require coordinated action across several organizational units. For example, waste recovery may require simultaneous changes in process design, quality standards, procurement contracts, accounting systems, storage procedures, and customer requirements. Energy efficiency may require technical upgrades, capital allocation, maintenance planning, regulatory incentives, and employee participation. Similarly, digital transformation may improve monitoring and integration while creating concerns regarding overreliance on automation and the loss of experiential knowledge. A comparative functional perspective can therefore reveal both convergence and divergence among organizational actors and help identify where circular transition requires coordination, negotiation, policy intervention, or capability development.

Accordingly, the aim of the present study was to identify and comparatively analyze the challenges, barriers, opportunities, strategies, and organizational and policy requirements associated with the transition to a circular economy from the perspectives of different specialized functional areas within Tabriz Petrochemical Complex.

2. Methods and Materials

The present study is applied in terms of purpose and qualitative and exploratory in terms of approach, employing a qualitative content analysis strategy. The nature of the subject, namely understanding differences among the perspectives of specialized functional areas regarding the challenges and strategies associated with the transition to a circular economy in an industrial complex, required the use of experts' experience and tacit knowledge. In this article, content analysis was applied through a conceptual and interpretive approach and served as a tool for describing and comparing themes rather than for statistical hypothesis testing. The data presented in this article were derived from the qualitative section of the underlying dissertation. The quantitative section and structural modeling component of the same research were previously reported in a separate article.

The participants consisted of managers and experts from Tabriz Petrochemical Complex representing seven specialized functional areas: production and process, HSE and environment, maintenance and repair, finance and planning, human resources and training, research and innovation, and communications and strategy. Stratified purposive sampling was employed. First, the specialized functional areas of the complex were defined as strata; subsequently, experts were selected from each stratum based on relevant specialized knowledge, at least 10 years of effective work experience, familiarity with the complex's processes, and willingness to participate. Sample size was determined according to the principle of theoretical saturation, and interviewing continued until no new data emerged. Consequently, 22 experts were interviewed, with a mean work experience of 16.3 years (Table 1 in the Findings section). Each expert was classified into one of the seven functional areas according to their academic discipline and organizational position. To preserve anonymity, the experts were identified by codes K1 through K22.

Data were collected through semi-structured interviews. The interview guide contained ten open-ended questions covering the following themes: (1) environmental and economic challenges; (2) economic components that strengthen the circular economy; (3) environmental measures for reducing waste and optimizing energy and water consumption; (4) the role of emerging technologies; (5) structural, cultural, and managerial barriers; (6) social measures and improvement of employee conditions; (7) directing processes toward closed-loop systems; (8) the role

of senior management, policymaking, and government support; (9) successful experiences; and (10) three key priorities. The interviews were recorded and subsequently transcribed verbatim. For recording and reporting purposes, each expert's response to each question was summarized in the coding table, and these responses constituted the units of analysis.

The analysis was conducted in four stages. In the first stage, the interview transcripts were read several times to enable the researcher to develop an in-depth familiarity with the data. In the second stage, line-by-line open coding was performed, and one or more codes were extracted from each response. In total, 220 open codes were generated, each representing a challenge, opportunity, strategy, or perspective. Coding was conducted manually using constant comparison between the codes from each interview and previously identified codes. In the third stage, the experts were classified into seven groups according to their specialized functional areas, and the responses were examined question by question and functional area by functional area. Codes related to challenges (Question 1), barriers (Question 5), and policy and organizational requirements (Question 8) were grouped into specific themes based on conceptual similarity, and the number of experts within each functional area referring to each theme was counted to describe the distribution of perspectives. These counts were purely descriptive and did not constitute a basis for statistical inference. Strategies (Questions 3, 4, and 7), economic opportunities (Question 2), social measures (Question 6), successful experiences (Question 9), and priorities (Question 10) were reported thematically and separately by functional area. In the fourth stage, the perspectives of the functional areas were compared to identify common dimensions, function-specific barriers, and points of tension.

To enhance the credibility and dependability of the findings, the following strategies were employed: obtaining feedback from interviewees to confirm the accuracy of the researchers' interpretations, simultaneous coding by two independent coders followed by comparison of the results, constant comparison of the data throughout the analytical process, and the inclusion of direct quotations from experts in reporting the findings.

The geographical scope of the study was Tabriz Petrochemical Complex. With a nominal production capacity of 870,000 tons of various polymeric and chemical products, its position as the largest industrial hub in northwestern Iran, and its presence in export markets across Europe, Asia, and Africa, the complex constituted an appropriate case for this study. The research covered the period from 2024 to 2026.

3. Findings and Results

The findings presented in this section were derived from the qualitative content analysis of 22 semi-structured interviews with experts from Tabriz Petrochemical Complex. Each interview contained ten open-ended questions addressing the following themes: challenges, economic components, environmental measures, the role of technology, barriers, social measures, strategies for closing material loops, the role of management and policymaking, successful experiences, and key priorities. In total, 220 responses and 220 open codes were obtained. To address the research questions, the experts were classified into seven groups based on specialized functional area, and the responses were analyzed both question by question and functional area by functional area. In the report, the experts are identified by codes K1 through K22.

The experts had an average of 16.3 years of work experience, ranging from 11 to 24 years. Among them, six individuals (27.3%) held doctoral degrees, 15 (68.2%) held master's degrees, and one (4.5%) held a bachelor's degree. Their distribution across specialized functional areas is presented in Table 1.

Table 1

Composition of Experts by Specialized Functional Area

Functional Area	Expert Codes	Number	Mean Experience (Years)	Educational Qualification
Production and Process	K1, K3, K10, K13, K17	5	18.8	2 doctoral, 2 master's, 1 bachelor's
HSE and Environment	K2, K11, K16, K19	4	15.3	4 master's
Maintenance and Repair (including instrumentation, utilities, and energy)	K4, K7, K12, K14	4	17.5	1 doctoral, 3 master's

Finance and Planning (including supply chain and warehousing)	K5, K6, K15, K20	4	15.0	4 master's
Human Resources and Training	K9	1	14.0	1 master's
Research and Innovation (including laboratory)	K8, K18	2	13.0	2 doctoral
Communications and Strategy	K21, K22	2	17.0	1 doctoral, 1 master's
Total		22	16.3	

Responses to the first question concerning economic and environmental challenges and the fifth question concerning structural, cultural, and managerial barriers indicated that each functional area perceived the challenges through the lens of its own responsibilities (Table 2).

Table 2

Key Challenges and Barriers by Functional Area

Functional Area	Core Challenges (Question 1)	Key Barriers (Question 5)
Production and Process	Aging production infrastructure; fluctuations in feedstock costs and unplanned maintenance costs; product losses; waste resulting from equipment failure; high levels of polymer waste	Organizational resistance to change; insufficient funding for green projects; technical complexity of processes; limited experience among the new generation; product-standard constraints
HSE and Environment	Air pollution and wastewater; occupational noise and chemical pollution; volatile organic compound emissions; high costs of accidents	Production-oriented culture; prioritization of production over health; shortage of environmental specialists; concealment of accidents and near misses
Maintenance and Repair	Energy consumption by aging equipment; inaccuracy of aging sensors; poor building insulation; high energy intensity	Contractors' resistance to refurbished components; dependence on imported spare parts; outdated building regulations; adverse effects of energy subsidies
Finance and Planning	Interdepartmental misalignment; low return on investment in green projects; dependence on foreign suppliers; waste of expired materials	Incompatibility among information systems; conflict between short-term and long-term interests; poor quality of domestic suppliers; misalignment between warehousing and consuming units
Human Resources and Training	Shortage of sustainability expertise	Generational gap in environmental attitudes
Research and Innovation	Technological gap relative to international developments; improper disposal of laboratory materials	Insufficient research funding; absence of material-recycling protocols
Communications and Strategy	Negative public reputation of the industry; pressures arising from global competition	Public distrust; strategic short-termism

Table 3

Distribution of Challenge Themes (Question 1) and Barrier Themes (Question 5) by Functional Area (Number of Experts)

Theme	Production	HSE	Maintenance	Finance	Human Resources	Research	Communications	Total
Challenges								
Aging and technical-energy inefficiency	2	0	4	0	0	1	0	7
Material loss and waste	2	0	0	1	0	1	0	4
Pollution, health, and safety	0	4	0	0	0	0	0	4
Cost, market, and supply pressures	1	0	0	2	0	0	1	4
Weaknesses in coordination, expertise, and social trust	0	0	0	1	1	0	1	3
Barriers								
Cultural and behavioral	1	3	1	0	0	0	0	5
Information infrastructure, coordination, and supply	1	0	1	3	0	0	0	5
Financial constraints, budgets, and short-termism	1	0	0	1	0	1	1	4
Regulations, standards, and pricing	1	0	2	0	0	1	0	4
Expertise gaps and transfer of experience	1	1	0	0	1	0	0	3
Social trust	0	0	0	0	0	0	1	1

Experts in the production area perceived the challenges as operational and tangible. K1 referred to "exorbitant energy costs and the deterioration of major equipment," some of which had been in operation for more than 30 years,

while K10 discussed ethylene losses resulting from leakage and incomplete recovery. From the perspective of this group, the principal barriers were resource constraints and the risks associated with change. K3 stated that green projects "are always placed at the bottom of the priority list," while K17 indicated that the product standards imposed by major customers hinder the use of recycled materials.

In the HSE area, the challenges were more strongly associated with environmental compliance and employee health, whereas the primary barrier was cultural. Three of the four experts referred to this barrier. K2 criticized the "production at any cost" culture, K11 stated that "production takes priority" in decision-making, and K19 referred to the concealment of near misses because employees fear punishment.

In the maintenance and energy area, aging equipment, inaccurate sensors, and dependence on imports were emphasized. K7 stated that they sometimes "wait for a spare part for months," while K14 argued that energy subsidies "eliminate the incentive to conserve energy." Contractors' resistance to refurbished components, as reported by K4, represents an example of a behavioral-contractual barrier.

Experts in finance and planning emphasized weak integration more strongly than technological limitations. K5 stated that the information systems were incompatible and that data were "transferred manually," whereas K6 regarded "financial short-termism and a focus on quarterly profits" as a barrier to long-term investment.

In the human resources area, K9 highlighted the shortage of sustainability expertise and the generational gap. Notably, K13 from the production area also referred to the lack of practical experience among the new generation. In the research area, the technological gap and insufficient funding were emphasized, with K18 stating that "production and sales are always given priority." In the communications area, the major barriers were the public's historical distrust of industry, as noted by K21, and strategic short-termism, as identified by K22.

Overall, the two categories of "cultural-behavioral" barriers and "information infrastructure, coordination, and supply" barriers each accounted for five cases and together constituted 10 of the 22 identified barriers. This indicates that most barriers are organizational and behavioral in nature rather than purely technical.

The technical and operational strategies identified through Questions 3, 4, and 7 are presented by functional area in Table 4.

Table 4

Proposed Technical and Operational Strategies by Functional Area

Functional Area	Proposed Strategies
Production and Process	Heat recovery and heat integration; optimization of furnace temperatures and operating ratios; process modeling and simulation; insulation of steam lines; inter-industrial catalyst recycling; separation of output streams; in-house granulation of waste; online quality control; blending a specified percentage of waste materials into products
HSE and Environment	Upgrading wastewater treatment systems and recirculating cooling water; real-time and satellite-based pollutant monitoring; floating roofs for storage tanks; carbon capture technology; enclosure of pollution sources and improved ventilation; smart health monitoring; automatic fire suppression and simulation-based accident training; inherently safer design
Maintenance and Repair	IoT-based predictive maintenance; replacement of high-energy-consumption motors; refurbishment instead of replacement; upgrading measurement instrumentation and advanced process control (APC); energy auditing and ISO 50001 implementation; stack heat recovery; insulation, solar energy, and building information modeling (BIM) for green buildings
Finance and Planning	Integrated production-energy planning; enterprise resource planning (ERP) and material flow modeling; optimization of maintenance scheduling; financial dashboards; long-term waste sales contracts; green procurement and blockchain-based traceability; reverse logistics; first-in, first-out (FIFO), smart warehousing, and exchange of materials approaching expiration
Human Resources and Training	E-learning; recruitment based on sustainability values; incorporation of sustainability responsibilities into job descriptions; sustainable employee transportation
Research and Innovation	Research on biodegradable products; equipping laboratories for chemical recycling and pyrolysis; design for recycling; online analysis; reduction of sample volumes; solvent redistillation
Communications and Strategy	Comprehensive sustainability strategy; digital transformation; industrial collaboration for waste exchange; sustainability reporting, digital communications, and local community engagement

These strategies can be summarized into four patterns. The first is energy and water conservation and recovery, which recurred across production, maintenance, and HSE. The second is closing material loops and creating value from waste. Examples include inter-industrial catalyst recycling (K1), ethylene recovery from output streams (K10), waste granulation (K17), sulfur sales (K6), solvent redistillation (K8), and interorganizational material exchange (K20). The third is data-driven decision-making and precise control, including predictive maintenance, APC, ERP, and process

simulation. The fourth is source prevention rather than end-of-pipe management, such as enclosing pollution sources instead of relying on general ventilation (K11), inherently safer design (K19), and design for recycling (K18). The critical perspective of K13 is also noteworthy: automation is beneficial, "but it should not be complete" to the extent that it disregards operator experience.

Regarding economic opportunities (Question 2), the experts identified specific sources of revenue and cost savings, including the sale of by-products and waste materials such as sulfur, scrap metals, and polymer waste; recovery of products from streams otherwise sent for combustion; potential carbon-credit revenue (K16); and savings resulting from the prevention of fines and accidents (K2, K19). K6 proposed incorporating the actual costs of waste and pollution, including penalties and health-related costs, into accounting calculations so that the financial justification of green projects would be reassessed.

Human and social measures (Question 6) focused primarily on participation and psychological safety, including joint employee-management committees (K2), a non-punitive reporting system (K19), rewards for resource-saving ideas (K6), transfer of experiential knowledge from senior operators (K13), energy-consumption awareness initiatives (K14), and improvements in employee welfare and work flexibility (K3, K4, K5).

Responses to Question 8 concerning the role of senior management, policymaking, and government support were classified into four categories (Table 5).

Table 5

Organizational and Policy Requirements from the Experts' Perspectives (Number of Experts)

Category	Production	HSE	Maintenance	Finance	Human Resources	Research	Communications	Total	Examples
Standards and regulation	1	2	1	1	0	1	1	7	Revision of product standards to allow recycled materials; carbon-emission legislation; mandatory green-building requirements; environmental transparency legislation
Financial support, budgets, and incentives	1	0	2	2	0	1	0	6	Tax incentives; cost-reflective energy tariffs; customs exemptions for green equipment; dedicated sustainability budgets; support for domestic production and localization
Strategic governance and oversight	1	2	0	1	0	0	1	5	Centralized policymaking; circular economy steering committee; environmental performance indicators; independent safety oversight; national sustainability policy
Empowerment, authority, and management commitment	2	0	1	0	1	0	0	4	Delegation of authority for sustainable procurement; explicit managerial support for training; operator participation in decisions; use of specialized consultants

Thirteen of the 22 experts, representing six of the seven functional areas, called for financial support or regulatory mandates. This indicates that, from the experts' perspective, movement toward a circular economy will not be sustainable without changes in price signals and the regulatory framework.

In response to Question 9, all 22 experts reported a successful experience (Table 6). These cases, whose

outcomes were self-reported by the experts, indicate that circular practices are feasible within the complex itself and are often associated with a relatively rapid return on investment.

Table 6

Successful Experiences Reported by Experts

Functional Area	Expert	Measure	Reported Outcome
Production	K1	Flare gas recovery	Revenue generation and reduction of pollutant emissions
	K3	Optimization of the steam-to-carbon ratio in the cracker	12% reduction in steam consumption and improved quality
	K10	Replacement of distillation-column packing	10% improvement in separation efficiency
	K13	Detection of abnormal pump noise	Prevention of a major accident
	K17	Separation of waste by color and grade	Increased sales value of waste materials
HSE	K2	Water-consumption reduction program	20% savings
	K11	Noise-reduction campaign	Reduction in employee complaints
	K16	Improvement of sealing systems and valves	40% reduction in VOC emissions
	K19	Continuous investment in training and safety	Three years without a fatal accident
Maintenance	K4	Major overhaul of a compressor instead of replacement	10-year extension of service life
	K7	Installation of a new distributed control system (DCS)	15% reduction in energy consumption
	K12	Insulation of the warehouse roof	35% reduction in cooling costs, with a two-year payback period
	K14	Waste heat recovery system (WHRS)	20% reduction in steam consumption, with a two-year payback period
Finance	K5	Warehouse inventory reduction project	Release of tied-up capital and reduction of expiration risk
	K6	Sale of sulfur to a fertilizer plant	Annual revenue of several billion tomans instead of disposal costs
	K15	Localization of a critical pump component	Acceptable quality at a lower price
	K20	Expiration-alert system	50% reduction in expired materials
Human Resources	K9	Employee suggestion program	Cost-reduction ideas and increased employee participation
Research	K8	Optimization of the analytical method	30% reduction in acid consumption
	K18	Development of a low-waste polyethylene grade	15% reduction in production waste
Communications and Strategy	K21	“Green Petrochemical” campaign	20% improvement in the company’s image in survey results
	K22	Product diversification and entry into new markets	Reduced dependence and increased stability

In Question 10, the experts identified three key priorities. A synthesis of these priorities and the responses to the other questions reveals areas of convergence and divergence among the functional areas (Table 7).

Table 7

Convergence and Divergence Among the Perspectives of Functional Areas

Dimension	Type	Functional Areas Involved	Evidence
Training, cultural development, and human capital development	Shared	Production, HSE, maintenance, human resources, research	11 experts included it among their top three priorities
Digitalization, intelligent systems, and advanced control	Relatively shared	Production, maintenance, finance, communications and strategy	6 experts (K3, K4, K5, K7, K20, K22)
Energy and water conservation and emission reduction	Shared	Production, HSE, maintenance	7 experts
Financial support and regulatory mandates	Shared	Six functional areas	13 experts in Question 8
Production-oriented culture and prioritization of production over safety	HSE-specific	HSE	3 of 4 experts
Information-system incompatibility and interdepartmental coordination	Finance- and planning-specific	Finance	3 of 4 experts
Price signals and building and energy regulations	Maintenance- and energy-specific	Maintenance	K12, K14

Research funding and short-termism	Research- and strategy-specific	Research, communications and strategy	K18, K22
Social trust and transparency	Communications-specific	Communications	K21
Generational gap and experience transfer	Shared across two functional areas	Human resources, production	K9, K13

Despite the diversity of concerns, three dimensions were shared across multiple functional areas: human capital and cultural development, digitalization and data, and financial and regulatory support. At the same time, each functional area had its own specific barrier: safety culture for HSE, information integration for finance and planning, price signals for energy, budget constraints for research, and social trust for communications. Two points of tension were also identified. The first concerned differing views of automation: K22 regarded digital transformation as a prerequisite, whereas K13 did not support complete automation. The second involved a conflict between customer standards and recycling: K17 regarded customers' standards as a barrier to the incorporation of recycled materials, whereas K18 proposed design for recyclability as a solution.

4. Discussion and Conclusion

The findings of the present study showed that the transition to a circular economy in Tabriz Petrochemical Complex is a multidimensional organizational transformation rather than a purely technical or environmental intervention. Although all seven specialized functional areas recognized the importance of circularity, they interpreted its challenges and requirements through the lens of their own responsibilities. Production and process experts emphasized equipment obsolescence, polymer waste, product loss, and process inefficiency; HSE experts focused on pollution, occupational health, and the prioritization of production over safety and health; maintenance experts emphasized aging equipment, inefficient energy use, inaccurate instrumentation, and dependence on imported components; finance and planning experts highlighted weak information integration, low financial attractiveness of green projects, and supply-chain inefficiencies; human resource experts identified sustainability competency gaps and generational differences; research experts emphasized technological lag and limited research budgets; and communications and strategy experts stressed public distrust and strategic short-termism. This cross-functional diversity is important because the literature increasingly describes circular economy implementation as a systemic transformation involving technological, managerial, economic, institutional, and behavioral dimensions rather than a single set of recycling practices (Barner, 2025; Velenturf & Purnell, 2021). The present findings extend this perspective by showing that even within one petrochemical complex, circularity is interpreted differently across professional domains, and therefore implementation requires mechanisms capable of reconciling competing priorities and connecting departmental objectives.

One of the most significant findings was the prominence of aging equipment, technical inefficiency, and high energy intensity, particularly in production and maintenance. Experts referred to outdated equipment, excessive energy use, inaccurate sensors, heat losses, leakage, and limitations in process recovery. These observations are strongly consistent with research emphasizing the importance of energy efficiency and integrated resource management in petrochemical sustainability. Modirzadeh et al. showed that energy-efficiency improvement in Iran's petrochemical sector has substantial potential for greenhouse gas mitigation and can simultaneously reduce operating costs and environmental impacts (Modirzadeh et al., 2024). Similarly, Zhang et al. conceptualized petrochemical circularity through the water-energy-carbon nexus and argued that improvements in process efficiency, resource recovery, intelligent monitoring, and digital control are essential for reducing waste and emissions (Zhang et al., 2026). The present study adds an operational perspective to this literature by showing that inefficiency is not perceived as an abstract sustainability indicator but as a daily production and maintenance problem manifested in obsolete compressors, inaccurate instrumentation, poor insulation, unplanned losses, and unrecovered streams. The reported successful experiences, including waste heat recovery, optimization of steam use, installation of new control systems, and equipment refurbishment, further indicate that circularity can generate direct operational benefits when resource efficiency is incorporated into maintenance and process-management decisions.

Another major finding concerned the importance of material losses, waste generation, and opportunities for closing material loops. Production, finance, and research experts identified polymer waste, expired materials,

laboratory residues, and valuable by-products as areas where waste could be reduced or transformed into economic value. Proposed strategies included waste granulation, inter-industrial catalyst recycling, ethylene recovery, solvent redistillation, reverse logistics, and exchange of materials approaching expiration. These results are aligned with the core logic of the circular economy, which seeks to preserve material value and prevent unnecessary resource leakage from industrial systems (Velenturf & Purnell, 2021). The findings also support Vidal et al.'s argument that the future of chemical and plastics industries requires redesigning carbon and plastics flows so that materials remain in productive circulation for longer periods and reliance on virgin feedstocks is reduced (Vidal et al., 2024). Barner similarly emphasized that greater circularity in the chemical sector depends on material recovery, recycling technologies, product redesign, and industrial collaboration, despite technical and thermodynamic constraints (Barner, 2025). The findings from Tabriz Petrochemical Complex demonstrate that these principles can be translated into specific operational practices, including internal segregation, recovery of valuable streams, and interorganizational exchange. They also suggest that waste management should be reframed from a disposal issue into a value-chain management issue, which is consistent with research emphasizing the role of the circular economy in improving waste-management processes (Mozaffar & Houshyari, 2024).

The prominence of cultural and behavioral barriers was another important result. Cultural-behavioral barriers constituted one of the two largest categories of obstacles, and HSE experts in particular described a production-oriented culture in which production continuity may take precedence over health, environmental protection, and transparent reporting of near misses. This finding is important because it indicates that circular transition may fail even when technical solutions are available if organizational norms and incentives continue to reward short-term output above long-term sustainability. Circular economy scholarship increasingly recognizes that organizational transformation requires not only technological innovation but also changes in institutional behavior, managerial priorities, and employee engagement (Asgari & Asgari, 2022). The need for a circular innovation ecosystem implies that technical solutions must be supported by cultural acceptance, learning, knowledge sharing, and cross-functional cooperation. The present findings further show that psychological safety is relevant to circular and sustainable performance. Non-punitive reporting, employee participation, and recognition of operational knowledge were repeatedly emphasized by the experts. These observations also align with broader supply-chain research showing that trust and commitment contribute to sustainable performance by improving flexibility and cooperation (Shirazi et al., 2024). Although that study focused on supply-chain relationships, the underlying logic is equally applicable internally: trust reduces information concealment, facilitates learning, and supports coordinated action.

The second major barrier category concerned information infrastructure, coordination, and supply. Finance and planning experts were particularly critical of incompatible information systems, manual data transfer, poor coordination between warehouses and consuming units, and fragmented organizational decision-making. These problems indicate that circular economy implementation depends heavily on data integration and visibility across functional boundaries. This is consistent with Zhang et al., who emphasized digital intelligence as a major enabler of integrated water, energy, carbon, and material management in petrochemical systems (Zhang et al., 2026). The experts' recommendations concerning ERP systems, advanced process control, predictive maintenance, smart warehousing, blockchain-based traceability, process simulation, and financial dashboards all reflect a transition toward data-driven management. The findings also correspond with sustainable supply-chain research in the petrochemical industry, which has highlighted the importance of integrated decision structures and systematic management of circular supply-chain relationships (Dehkordi et al., 2024). Raoofi Rad and Fathi likewise emphasized the need to model and prioritize sustainability indicators in petrochemical supply chains, indicating that sustainability management requires coordinated measurement rather than isolated performance indicators (Raoofi Rad & Fathi, 2024). The present results suggest that digitalization is not only an efficiency tool but also an organizational integration mechanism capable of connecting production, maintenance, inventory, finance, environmental management, and strategic decision-making.

Financial barriers and short-term investment horizons also emerged prominently. Experts referred to low perceived returns on green projects, insufficient sustainability budgets, financial short-termism, and prioritization of production and sales over long-term environmental investments. This is particularly important in petrochemical industries because circular investments often require substantial initial capital while benefits may appear gradually through lower resource

consumption, reduced risk, avoided penalties, and improved operational resilience. Bakhshizadeh et al. emphasized that sustainable value-chain optimization in Iran's petrochemical industry depends on strategic drivers that must be considered through a long-term and foresight-oriented approach (Bakhshizadeh et al., 2025). The current findings reinforce this argument by showing that short-term budgeting practices can systematically disadvantage circular initiatives. Financial volatility may intensify this problem. Torkaman et al. demonstrated that the Iranian petrochemical industry is affected by multidimensional financial shocks, which can influence investment decisions and organizational risk tolerance (Torkaman et al., 2025). Under such conditions, managers may favor projects with rapid and visible returns. Nevertheless, the successful cases reported in this study, including reductions in water, steam, energy, acid consumption, expired materials, and cooling costs, suggest that many circular initiatives can generate measurable financial returns. The experts' proposal to include the real costs of pollution, waste, health impacts, accidents, and penalties in investment evaluation is therefore particularly relevant because conventional financial accounting may underestimate the economic value of prevention.

The findings also demonstrated that supply-chain and procurement conditions can either facilitate or obstruct circular transition. Dependence on imported spare parts, inconsistent quality among domestic suppliers, resistance to refurbished components, and limited coordination between inventory and consumption were all identified as barriers. These findings are consistent with research emphasizing sustainable and circular supply-chain management in petrochemical industries (Dehkordi et al., 2024). Ghorbanpour and Hossinpour also showed that circular economy implementation in downstream petroleum industries is influenced by an interconnected set of organizational, technological, economic, and policy factors (Ghorbanpour & Hossinpour, 2021). The present study provides concrete examples of these interdependencies. For instance, using refurbished components requires technical confidence, contractor acceptance, procurement rules, quality standards, and managerial authorization. Similarly, reverse logistics requires coordination among purchasing, warehousing, suppliers, and waste-management units. Sustainable supply chains therefore cannot be developed through procurement policies alone; they require trust, flexibility, information exchange, and long-term supplier relationships, which is also consistent with Shirazi et al.'s findings regarding the role of trust, commitment, and supply flexibility in sustainable petrochemical supply-chain performance (Shirazi et al., 2024).

The policy-related findings were equally important. Thirteen of the 22 experts called for financial support or regulatory requirements, including tax incentives, cost-reflective energy pricing, customs exemptions for green technologies, product-standard reform, carbon-emission regulations, and environmental transparency requirements. This finding indicates that organizational willingness alone may be insufficient when external price signals and regulatory structures do not reward resource efficiency. Yarahmadi and Sadeghi Shahdani emphasized that the petrochemical industry in Iran is strongly influenced by macro-level industrial policy and broader national strategic frameworks (Yarahmadi & Sadeghi Shahdani, 2024). The current findings show how those macro-level conditions are experienced operationally. Energy subsidies, for example, were perceived by maintenance experts as reducing incentives for conservation, while product standards were identified as potential obstacles to the use of recycled materials. This supports the broader circular economy view that policy must create coherent incentives across production, markets, technology, and consumption (Asgari & Asgari, 2022). The findings therefore suggest that circular transition requires regulatory alignment as well as internal organizational transformation.

Another important theme concerned technological innovation and research capacity. Research experts identified a technology gap, inadequate funding, and insufficient recycling protocols, while proposing chemical recycling, pyrolysis, biodegradable products, design for recycling, and improved analytical methods. These recommendations align with international research emphasizing the central role of technological innovation in creating circular carbon and plastics systems (Vidal et al., 2024). Barner also noted that the chemical industry's circularity will depend on the development of economically and technically viable recycling and feedstock solutions (Barner, 2025). The bibliometric analysis conducted by Adedayo-Ojo et al. similarly shows increasing research attention to digital technologies, resource recovery, decarbonization, and sustainable business models in the oil and gas sector (Adedayo-Ojo et al., 2025). The current study suggests that the main issue is not simply access to technology but the institutional capacity to fund, test, scale, and integrate new technologies into existing operations. This is especially relevant in mature industrial plants where

technological change must be balanced against safety, reliability, product quality, and operational continuity.

The study also identified human capital development and intergenerational knowledge transfer as critical requirements. Experts referred to shortages of sustainability expertise, generational gaps in environmental attitudes, and insufficient practical experience among younger personnel. At the same time, experienced operators were seen as important sources of tacit operational knowledge. These findings indicate that circular transition requires both new competencies and preservation of accumulated expertise. The need for training, employee participation, sustainability-oriented recruitment, and integration of sustainability responsibilities into job descriptions is consistent with the broader concept of a circular innovation ecosystem, which depends on knowledge creation, organizational learning, and collaboration (Asgari & Asgari, 2022). The tension identified between digital transformation and complete automation is particularly noteworthy. While digitalization can improve monitoring, efficiency, and predictive capability, experts cautioned against disregarding operator experience. This suggests that technological modernization should be designed as augmentation rather than simple substitution of human expertise.

Finally, the findings strongly support the relevance of a context-specific circular economy framework for Tabriz Petrochemical Complex. Teimouri et al. proposed a circular economy model for Tabriz Petrochemical Company emphasizing sustainability (Teimouri et al., 2026). The present study complements that work by showing how circular economy requirements are perceived differently across specialized organizational domains. It also demonstrates that successful circular practices are already present within the complex, including flare-gas recovery, water conservation, VOC reduction, waste heat recovery, component localization, waste sales, inventory optimization, and development of lower-waste product grades. These cases indicate that the transition does not necessarily begin with a comprehensive system redesign; it may emerge through a portfolio of operational, technological, financial, human, and strategic interventions. However, the effectiveness of these initiatives ultimately depends on whether they are integrated through a coherent governance structure. Risk assessment is also essential because circular interventions in petrochemical environments may affect process safety, equipment integrity, quality, and reliability. The importance of industry-specific risk assessment in oil, gas, and petrochemical projects has previously been emphasized (Zaeimi & Zaeimi, 2021). Therefore, circular transition should be understood as a managed transformation that simultaneously addresses resource efficiency, organizational coordination, technological innovation, safety, financial viability, policy alignment, and stakeholder trust.

The present study has several limitations. First, the study was conducted in a single petrochemical complex, and therefore the findings should be interpreted within the organizational, technological, and institutional context of Tabriz Petrochemical Complex. Second, although participants were selected from seven specialized functional areas, some areas were represented by only one or two experts, which may limit the breadth of viewpoints within those functions. Third, the findings were based on self-reported expert perceptions and reported successful experiences, and the reported percentages of improvement, cost reduction, and operational benefits were not independently verified using technical or financial records. Fourth, the qualitative design was intended to identify patterns and differences among functional perspectives rather than to determine causal relationships or statistically generalizable effects. Finally, although independent coding and participant feedback were used to strengthen credibility, qualitative interpretation inevitably involves researcher judgment.

Future research should extend the present study through comparative designs involving multiple petrochemical complexes in different geographical and technological contexts. Quantitative studies could test the relative importance of the identified barriers and strategies using larger samples and multivariate or structural equation modeling approaches. Longitudinal research would also be valuable for examining how circular economy initiatives evolve over time and whether improvements in resource efficiency, environmental performance, and financial outcomes are sustained. Future studies may integrate interview data with objective operational indicators such as energy intensity, water consumption, waste generation, equipment availability, emission levels, recycling rates, and investment returns. Additional research should also investigate interdependencies among functional areas, particularly how decisions in finance, procurement, maintenance, HSE, and production influence one another. Comparative studies of different technological pathways, including chemical recycling, carbon capture, industrial symbiosis, digital twins, artificial intelligence, and predictive maintenance, could further clarify the conditions

under which specific circular strategies are technically and economically feasible.

For practice, Tabriz Petrochemical Complex and similar organizations should establish an integrated circular economy governance structure with clear responsibility across production, HSE, maintenance, finance, human resources, research, procurement, and strategy. Circular economy objectives should be incorporated into performance indicators, budgeting processes, procurement criteria, maintenance planning, and job descriptions rather than being managed as isolated environmental projects. Priority should be given to initiatives with simultaneous environmental and economic benefits, such as energy recovery, water recirculation, predictive maintenance, material recovery, reduction of expired inventory, and waste valorization. Management should also strengthen data integration through interoperable information systems and real-time dashboards, while preserving the role of experienced personnel in operational decision-making. Non-punitive reporting, employee participation, sustainability training, and structured knowledge transfer between experienced and younger employees should be institutionalized. Finally, the complex should actively engage regulators, suppliers, customers, research institutions, and neighboring industries to develop supportive standards, incentives, secondary-material markets, industrial exchange networks, and collaborative innovation mechanisms.

Authors' Contributions

Authors contributed equally to this article.

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In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

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