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Asymmetric Effects of Digital Economy on Green Development of Sports Industry: The Moderating Role of Data Marketability and Provincial Spillover Dynamics

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Abstract

This study investigated the asymmetric effects of digital economy on the green development of the sports industry, emphasizing the moderating role of data marketability and provincial spillover dynamics. Using annual panel data from 31 Iranian provinces (2012–2025), the researchers applied a Panel Quantile Vector Autoregression (PQVAR) model and dynamic spillover network analysis. The PQVAR estimates showed a positive and significant effect of the digital economy on green development across all quantiles, with the strongest impact during crises (β = 0.452 at the 25th quantile) versus normal (β = 0.318 at the 50th) and boom (β = 0.214 at the 75th) conditions. The interaction between digital economy and data marketability was also positive and significant across quantiles (β = 0.158, 0.104, and 0.072), confirming that data marketability strengthened this relationship. Dynamic spillover analysis revealed a Total Connectedness Index (TCI) exceeding 93% across quantiles, with Zanjan, Isfahan, and Qom as net transmitters, and Alborz and Ardabil as primary net receivers. Robustness checks confirmed stability. Policy implications include data-sharing platforms in leading provinces, and resilience-building for net-receiver provinces to foster sustainable sports development.

Keywords

Digital Economy, Green Development, Sports Industry, Data Marketability.

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Introduction

In recent decades, the sports industry has emerged as one of the most dynamic and influential sectors of the global economy, playing an increasingly important role in GDP, employment generation, and public health improvement. However, its rapid growth has consistently been accompanied by significant environmental challenges, including high energy consumption, waste generation, occupation of green spaces, and increased carbon footprints. In this context, the concept of "green development" in the sports industry has been proposed as a new paradigm that emphasises reducing adverse environmental impacts, optimising resource use, and moving towards sustainability (Niu et al., 2023; Yu & Zhang, 2019).

Simultaneously, digital economy, as one of the most important structural transformations of the current era, relying on data as a fundamental factor of production and modern information technologies, has transcended traditional industry boundaries and created new patterns of production, distribution, and consumption (Bukht & Heeks, 2017; Goldfarb & Tucker, 2021). Numerous studies have shown that digital economy, through increasing productivity, reducing transaction costs, optimising resource allocation, and facilitating innovation, has brought about significant changes in various industries (Byrne, 2022; DCO, 2024; Jorgenson et al., 2008). However, the impact of this phenomenon on the sports industry, and particularly on its green development path, has not yet been systematically and comprehensively examined (Hou et al., 2024).

Although previous research has addressed the impact of the digital economy on productivity and economic growth at the macro level (Chen, 2024; Sun, 2024; Zhang et al., 2022), a significant gap remains in the existing literature:

1. Lack of attention to the sports industry: Most existing studies have focused on manufacturing, financial services, or information technology sectors, while the sports industry—with its unique characteristics (combining physical activities, mass events, spatial infrastructure, and energy consumption)—has received less attention.
2. Neglect of spatial and spillover dimensions: The impact of the digital economy on green development is inherently a spatial phenomenon that can spill over from one province to another. Nevertheless, most research has ignored this spatial dimension.
3. Overlooking the moderating role of data marketability: Although data is recognised as a new factor of production, the role of data marketability as a variable that can strengthen or weaken the relationship between the digital economy and green development, particularly in the context of the sports industry, has been underexplored (Li & Wei, 2024; Wang et al., 2023).

Furthermore, in Iran, despite considerable provincial diversity in digital infrastructure, economic development levels, and sports capacities, no comprehensive study has yet examined the impact of the digital economy on the green development of the sports industry while considering provincial heterogeneity, spatial spillover effects, and the moderating role of data marketability.

This research aimed to fill the aforementioned gap by investigating the impact of the digital economy on the green development of Iran's sports industry, with a focus on the

moderating role of data marketability. To this end, the study employed the PQVAR methodology and dynamic spillover network analysis. This approach allows for the examination of both direct and indirect (spillover) effects of the digital economy, the moderating role of data marketability, and provincial heterogeneity across different quantiles (25th, 50th, and 75th). Unlike mean-based approaches, the PQVAR method can separately model variable behaviour under crisis (lower quantile), normal (median quantile), and boom (upper quantile) conditions, thereby providing a more comprehensive picture of nonlinear and asymmetric relationships.

The key research questions are:

1. Does digital economy have a positive and significant impact on the green development of Iran's sports industry?
2. Does data marketability strengthen this impact?
3. Is this impact homogeneous across provinces, or does it vary?
4. Do spillover effects (the influence of neighbouring provinces) play a role in this relationship?
5. Which variable is the most important predictor of green development of the sports industry?

The research data included information from 31 provinces of Iran over the period 2012–2025 (1391–1404). The findings of this study can enrich the existing theoretical literature while providing practical guidance for policymakers in the fields of sports, digital economy, and regional development in Iran. The structure of the paper is as follows: after this introduction, the theoretical foundations and literature review are presented; then the methodology, data, and analytical models are described; next, the findings are reported and interpreted in the form of tables and figures; and finally, conclusions and policy recommendations are offered.

Theoretical Gap and Contribution: Despite the rich theoretical foundations outlined above, three critical gaps persist in the existing literature. First, while the general theory of the digital economy and sustainable development theory have been extensively developed, their integration in the specific context of the sports industry remains underexplored. The sports industry, with its unique combination of physical infrastructure, mass events, and high energy consumption, presents distinct theoretical challenges that are not adequately addressed by general models of digital transformation. Second, the role of data marketability as a moderating variable—despite its theoretical articulation in knowledge economy and growth accounting frameworks—has received limited empirical attention, particularly in the context of green development. Third, the existing theories largely assume homogeneous effects across regions and economic conditions, overlooking the asymmetric and spillover dynamics that are central to understanding provincial-level transformations. This study contributes to the theoretical literature by: (1) extending digital economy theory to the sports sector, (2) integrating data marketability as a key moderating mechanism, (3) incorporating provincial spillover dynamics into the theoretical framework, and (4) recognizing the nonlinear, quantile-specific nature of these relationships. These

theoretical extensions guide the empirical analysis and hypothesis formulation that follow.

Literature Review

Digital Economy and Industrial Transformation

The concept of digital economy is rooted in the expansion of information networks and communication technologies, which have gradually transformed traditional economic structures. Bukht and Heeks (2017) and Goldfarb and Tucker (2021) defined this phenomenon as an economy based on information networks and data, driving business models from linear structures toward platform-based innovations. In contemporary literature, digital economy is recognised as a paradigm in which data serves as a fundamental factor of production, digital technology acts as the primary driving force, and network operations represent the defining feature. By removing information barriers and improving resource allocation efficiency, this paradigm pushes various industries—including the sports sector—toward structural transformation (Hou et al., 2024; Wen & Luo, 2024).

In recent years, digital economy has grown at a remarkable pace, and its impact on productivity through investment in information and communication technology is evident (DCO, 2024). Nevertheless, Brynjolfsson et al. (2017) and Byrne (2022) emphasised that the productivity effects of the digital economy are gradual and context-dependent, requiring institutional and organisational transitions—a phenomenon referred to in literature as the "productivity paradox" (Jorgenson et al., 2008).

The impact of the digital economy on the sports industry can be observed through two main channels. On one hand, digital technologies increase transparency and measurability of sports production factors, enabling firms to make data-driven decisions and optimise energy consumption, thereby reducing resource waste (Yu & Zhang, 2019). On the other hand, the emergence of digital platforms facilitates virtualisation and servitisation of sports consumption, shifting sports activities from heavy reliance on material resources toward lightweight, low-energy operational models (Wen & Luo, 2024). These developments indicate that digital economy provides a foundation for the sports industry to transition toward sustainable and green patterns (Zhang et al., 2026).

Digital Economy and Sustainable Industrial Development

Theories of the digital economy are built upon general equilibrium models and platform innovation. Four main theoretical approaches can be identified in the literature:

- General Theory of Digital Economy introduces data, computing, and algorithms as factors of production, enhancing productivity through algorithmic innovation (Chen, 2024).
- Theory of Digital Economy Development emphasises platform innovation, market competition, and the role of government, justifying productivity gains through platform scalability (Sun, 2024).
- Knowledge Economy Theory describes digital economy as an economy based on

knowledge sharing, which increases productivity through information and communication technology (Bukht & Heeks, 2017; Jabłoński & Jabłoński, 2020).

- Technology-Based Theory divides digital economy into technology-oriented domains and the impact of information technology (Zhang et al., 2026).

Concerning sustainable industrial development, sustainable development theory provides an important framework. According to this theory, digital economy contributes to rebalancing the sports industry ecosystem; its digital features embed green principles throughout the sports industry life cycle, promote energy conservation, and encourage low-carbon behaviour (Niu et al., 2023). Moreover, the openness and sustainability logic of the digital economy create a new institutional foundation for building a green governance system in the sports industry, enabling firms to strike a dynamic balance between environmental performance and economic efficiency (Sun, 2024).

Productivity theories in digital economy rest on classical growth models, including endogenous growth theory, creative destruction theory, and growth accounting theory. Endogenous growth theory views innovation as the driver of productivity, with artificial intelligence (AI) and big data playing key roles in the digital economy (Dong et al., 2025; Zhang et al., 2022). The creative destruction theory posits that digital economy destroys old models and generates new productivity through structural change (Dong et al., 2025; Zhang et al., 2022).

For the purpose of this study, the green development of the sports industry is operationally defined as a multidimensional composite index encompassing four key environmental and performance dimensions: (1) energy consumption intensity (measured as energy use per unit of sports facility output), (2) carbon emission reduction (measured as CO_2 equivalent emissions from sports events and facilities), (3) green space utilization (measured as the ratio of green areas to total sports infrastructure footprint), and (4) waste management efficiency (measured as the percentage of waste recycled or composted in sports facilities). These components collectively reflect the industry's transition toward sustainability, resource optimization, and reduced environmental footprint, consistent with the theoretical framework of sustainable development (Niu et al., 2023) and the operationalization adopted in prior empirical studies (Ouyang et al., 2024; Yang et al., 2024).

Digital Economy and Green Development of the Sports Industry

Through its systemic and evolutionary mechanisms, digital economy redefines the operational logic and development patterns of the sports industry, steering it toward green transformation (Sun, 2024). At its core, digital economy is more than a technological revolution—it is a paradigm in which data serves as a fundamental factor of production and network infrastructure provides the main support (Hou et al., 2024).

The impact of the digital economy on the green development of the sports industry can be analysed at three levels:

First, at the technological level, digital economy, through widespread application of technologies such as Big Data, AI, and Blockchain, makes production processes

information-based and intelligent. This increases energy efficiency and factor allocation, creating a path for green development based on technological innovation (Qian et al., 2024). Digital technologies also empower sports firms to optimise the energy consumption (Lan & Liu, 2025).

Second, at the structural level, digital economy reduces information asymmetry, optimises resource flows across industrial chains, and enhances market matching efficiency for green factors (Zhang et al., 2022). The rise of digital platforms facilitates the virtualisation of sports consumption, shifting activities from heavy material dependence toward low-energy models (Wen & Luo, 2024).

Third, at the institutional level, the expansion of digital technologies reshapes corporate governance structures and regulatory models, promoting environmental information disclosure and institutional green innovation, thus establishing a new paradigm of data-driven governance (Dong et al., 2025; Kuang & Di, 2025). By creating a new institutional foundation, digital economy enables firms to achieve a dynamic balance between environmental performance and economic efficiency.

Drawing on sustainable development theory, digital economy helps rebalance the sports industry ecosystem and embeds green principles across its entire life cycle (Niu et al., 2023). Therefore, digital economy is not only a key driver of green transformation but also the internal logical foundation for achieving high-quality and sustainable development in this sector (Zhang et al., 2026).

The moderating role of data marketability in the digital economy–green development nexus can be further justified through classical growth theories. Endogenous growth theory posits that innovation, driven by investments in human capital and knowledge, is the primary engine of productivity growth (Dong et al., 2025). In this context, data marketability acts as a catalyst that accelerates innovation by enabling firms to monetize data assets, thereby incentivizing R&D investments in green technologies. The creative destruction theory suggests that digital economy disrupts traditional, resource-intensive models and replaces them with more efficient, data-driven alternatives (Zhang et al., 2022). Data marketability facilitates this process by creating a transparent pricing mechanism for data, allowing new, green-oriented firms to enter the market and outcompete inefficient incumbents. The growth accounting theory emphasizes the contribution of factor productivity to economic growth (Jorgenson et al., 2008). In our framework, data marketability enhances total factor productivity by reducing information asymmetries and improving resource allocation efficiency, thereby amplifying the positive spillover effects of the digital economy on green development. These theoretical perspectives collectively support the hypothesis that data marketability strengthens the digital economy's impact on green transformation.

Table 1.
The Theoretical Frameworks and their Link to Research Variables

Theoretical Framework	Core Proposition	Link to Digital Economy	Link to Green Development	Link to Data Marketability
General Theory of Digital Economy (Chen, 2024)	Data, computing, and algorithms as factors of production	Digital economy enhances productivity through algorithmic innovation (Chen, 2024)	Algorithmic efficiency reduces resource waste and optimizes energy use	Data as a tradable commodity enables market-driven resource allocation
Theory of Digital Economy Development (Sun, 2024)	Platform innovation, market competition, and government role	Platforms create new business models and reduce transaction costs	Platform-based consumption reduces material dependence (Wen & Luo, 2024)	Data marketability provides institutional foundation for platform growth
Knowledge Economy Theory (Jabłoński & Jabłoński, 2020; Bukht & Heeks, 2017)	Economy based on knowledge sharing and ICT	ICT infrastructure enables knowledge diffusion and innovation (Jabłoński & Jabłoński, 2020)	Knowledge sharing promotes green practices and low-carbon behavior	Data marketability facilitates knowledge monetization and exchange
Technology-Based Theory (Zhang et al., 2026)	Technology-oriented domains and IT impact	Technology drives digital transformation across industries (Zhang et al., 2026)	Digital technologies enable energy optimization and carbon reduction	Marketable data incentivizes technological adoption and innovation

(Source: The Researcher's Findings)

Related Studies and Theoretical Gap

Several studies have directly examined the relationship between digital economy and green development across various industries. Yang et al. (2024), using panel data from 30 Chinese provinces, found that digital economy significantly reduces carbon emissions in the sports industry through energy optimization and infrastructure improvements. Similarly, Ouyang et al. (2024) confirmed that digitalization promotes low-carbon development in the sports sector, with digital infrastructure playing a critical role. He and Xu (2024) provided broader evidence that the digital economy contributes to green development through improved resource efficiency, reduced energy consumption, and technological innovation, while also acknowledging challenges such as increased energy use and data security concerns. Chen et al. (2023) identified three main mechanisms—factor allocation optimization, industrial structure upgrading, and digital governance leadership—through which digital economy drives green development in China's sporting goods manufacturing industry.

A growing body of research has explored the channels through which digital economy influences green development. Wang and Shao (2024), using a quasi-natural experiment based on national big data comprehensive pilot zones, demonstrated that the digital economy promotes urban green development through industrial structure upgrading, technological innovation, and human capital accumulation, with heterogeneous effects across cities. Zhang et al. (2026) specifically examined the moderating role of data

marketability in the relationship between digital economy and green transformation of the sports industry, finding that data factor marketization strengthens this relationship through resource allocation, technological empowerment, and governance channels. Du and Li (2025) further confirmed that data element market construction enhances urban green innovation by improving data transparency and incentivizing R&D investments. Qian et al. (2024) and Dong et al. (2025) provided evidence that the digital economy's effect on green total factor productivity is mediated by industrial structure upgrading and technological innovation.

Although these studies recognized the importance of mediating and moderating mechanisms, the role of data marketability as a moderator remained underexplored, particularly in the context of the sports industry and at the provincial level. Most studies used aggregate national or city-level data, overlooking provincial heterogeneity and spillover dynamics that are central to understanding the regional disparities in green development outcomes. The present study advances this literature by explicitly modeling the moderating effect of data marketability within a quantile-based spatial spillover framework, allowing for differentiated effects across provinces and economic conditions.

Within the Iranian context, several studies have examined the intersection of digital economy, sports, and sustainable development from institutional and policy-oriented perspectives. Karamian et al. (2021), using a grounded theory approach with 21 interviews, designed a digital economy development model for Iranian sports, identifying expanding Internet access, commercialization, e-commerce growth, and digital technologies as key drivers. Pashaie et al. (2025) examined the role of e-governance in enhancing sustainability of Iranian sports organizations, emphasizing digital governance strategies for increasing transparency, efficiency, and sustainability. Ahmadi (2024) explored the role of media in sports economy and sustainable development, identifying television broadcasting rights as a major challenge. Balouch et al. (2025) examined the impact of digital economy on green growth in six Iranian metropolises (Tehran, Mashhad, Isfahan, Tabriz, Shiraz, Karaj) over 2019–2023, finding that the digital economy affects the green growth through a 30% reduction in resource mismatch and increased green technology innovations, with Mashhad and Isfahan showing the best performance. Ebrahimi et al. (2025) found that digital economy is the strongest driver of technological innovation (coefficient 0.42) in Iranian metropolises, with a significant digital divide between cities. Jalali et al. (2019) prioritized resistance economy indicators in sports, while Heidari Rostami et al. (2025) examined the effect of financial technology on green innovation with moderating roles of green density and accounting information quality.

Iranian studies provided valuable institutional insights and highlighted the digital divide between provinces and metropolises. However, they suffer from several limitations: (1) most are qualitative or descriptive, lacking rigorous econometric testing; (2) they do not employ quantile-based or spillover methodologies to capture asymmetric and spatial effects; (3) the sports industry is often treated as a secondary or

peripheral sector, rather than the primary focus; and (4) the moderating role of data marketability has not been systematically examined in the Iranian context. The present study addresses these limitations by using a Panel Quantile VAR (PQVAR) model with provincial-level data from all 31 Iranian provinces, capturing both asymmetric effects and provincial spillover dynamics.

Several international studies have employed advanced econometric and network-based methodologies that are methodologically similar to the present study. Bai (2024) used big data analysis and DEA Malmquist models to examine high-quality development paths of the sports industry under the digital economy influence. Dong (2022) employed dynamic modeling to investigate the sports industry development in the digital economy era. Zhukov et al. (2025) analyzed the impact of digital technologies on sports industry economics using organizational process frameworks. Berkani al. (2024) used econometric models to assess the influence of digital transformation on sports corporate sustainability. Skorokhodov (2023) examined ESG factor transformation in the sports industry within the digital economy. Mehra et al. (2025) used case study analysis of Twitter discussions to explore the role of digital technologies in promoting environmental sustainability in sports. Chen et al. (2025) and Liu (2025) examined sports empowerment and digital transformation benefits in the sports industry.

While these studies employed rigorous methodologies, they predominantly relied on mean-based regression models or qualitative case studies, which fail to capture the nonlinear, asymmetric, and spillover dynamics inherent in provincial-level transformations. The present study contributes methodologically by employing the PQVAR model with dynamic spillover network analysis, which allows for: (1) estimation at the 25th, 50th, and 75th quantiles to capture crisis, normal, and boom conditions; (2) measurement of both direct effects and indirect spillover effects across provinces; and (3) identification of net transmitters and receivers within the provincial network.

Based on the critical evaluation of the existing literature, the following research gaps are identified: (1) Sectoral gap: Despite extensive research on the digital economy's impact on manufacturing and services, the sports industry—with its unique combination of physical infrastructure, mass events, and high energy consumption—has received limited attention. (2) Moderating mechanism gap: While the theoretical role of data marketability has been articulated, the empirical testing of its moderating effect on the digital economy–green development nexus, particularly in the sports industry context, remains scarce. (3) Methodological gap: Most existing studies relied on mean-based linear models that assume homogeneity and ignore nonlinear, asymmetric, and spillover effects. The quantile-based and spatial spillover dimensions have been largely overlooked. (4) Contextual gap in Iran: Despite considerable provincial diversity in digital infrastructure, economic development, and sports capacities, no comprehensive study has examined the digital economy–green development relationship across all 31 Iranian provinces while considering the provincial heterogeneity, spillover effects, and the moderating role of data marketability. (5) Policy gap: Previous studies offered general policy recommendations without accounting for provincial-specific roles (net

transmitters vs. net receivers) or crisis-specific dynamics.

The present study contributes to filling these gaps by: (1) focusing explicitly on the sports industry, (2) testing the moderating role of data marketability, (3) employing a PQVAR model with dynamic spillover network analysis across three quantiles, (4) using comprehensive provincial-level data from all 31 Iranian provinces, and (5) providing differentiated policy recommendations based on provincial network positions and crisis conditions.

Hypothesis Development

1. Digital Economy and Green Transformation in the Sports Industry (Hypothesis 1)

The first hypothesis is grounded in the general theory of the digital economy (Chen, 2024), sustainable development theory (Niu et al., 2023; Sun, 2024), and productivity theories including endogenous growth theory, creative destruction theory, and growth accounting theory (Dong et al., 2025; Jorgenson et al., 2008; Zhang et al., 2022). These theories posit that data, computing power, algorithms, and digital platforms function as new factors of production that enhance productivity, optimize resource allocation, and stimulate innovation. In the context of the sports industry, digitalization can improve energy efficiency in sports facilities, reduce waste generation from mass events, and shift sports consumption from material-intensive models toward low-energy digital services (Wen & Luo, 2024; Yu & Zhang, 2019). The sustainable development theory further suggests that digitalization helps rebalance the sports industry ecosystem by embedding green principles across the industry life cycle (Niu et al., 2023). Accordingly, the digital economy is expected to promote the green development of the sports industry. Therefore, the first hypothesis is formulated as follows:

> **H1:** Digital economy has a positive effect on the green transformation of the sports industry.

2. The Moderating Role of Data Marketability in the Digital Economy–Green Development Nexus (Hypothesis 2)

The second hypothesis is derived from knowledge economy theory (Jabłoński & Jabłoński, 2020), growth accounting theory (Jorgenson et al., 2008), and the literature on data marketization (Li & Wei, 2024; Zhang et al., 2026). The knowledge economy theory emphasizes that knowledge sharing and information and communication technology increase productivity and promote green practices. The growth accounting theory highlights the role of total factor productivity, which can be improved when information asymmetries are reduced and resources are allocated more efficiently. Data marketization—through property rights, pricing, exchange, and income distribution mechanisms—creates institutional incentives for firms to monetize data assets, invest in green research and development, and adopt digital technologies more deeply (Du & Li, 2025).

In the process by which the digital economy drives the green transformation of the sports industry, data marketability acts as a key catalytic mechanism (Zhang et al., 2026). As an emerging factor of production, the market-oriented allocation of data not

only transforms the resource structure of the sports industry but also reshapes its value creation mechanisms (Li & Wei, 2024). Data marketability influences the relationship between the digital economy and the green development of the sports industry through three pathways:

First, from a resource allocation perspective, data marketability, by establishing mechanisms for data property rights, exchange, pricing, and income distribution, facilitates efficient flow and optimal allocation of data resources, removing traditional barriers to factor mobility in the sports industry (Wang et al., 2023). Through data sharing, sports firms can identify the consumer green preferences and strengthen the green product innovation.

Second, from a technological empowerment perspective, data marketability provides institutional guarantees and incentive mechanisms for the deeper application of digital technologies in the sports sector (Zhou et al., 2025). Under the influence of the data market, technologies such as AI, Cloud Computing, and Blockchain accelerate the intelligent and green transformation of the sports industry, making energy savings and sustainable operations achievable (Zhou & Ren, 2025).

Third, from an institutional and governance perspective, data marketability strengthens multi-stakeholder collaborative governance mechanisms. Through interaction among government regulation, platform facilitation, and corporate innovation, it promotes a dynamic equilibrium of green transformation in digital economy (Qiao et al., 2025).

In sum, data marketability not only serves as a moderating effect but also acts as a critical link for optimising the industrial ecosystem and advancing high-quality development (Du & Li, 2025). The degree of marketability directly determines the depth and breadth of the digital economy's impact on the green transformation of the sports industry. Therefore, data marketability is expected to positively moderate the effect of the digital economy on green development. Accordingly, the second hypothesis is formulated as follows:

> **H2:** Data marketability positively moderates the effect of the digital economy on the green transformation of the sports industry.

These theory-based hypotheses guide the empirical strategy. H1 is tested by examining the coefficient of the digital economy on green development across quantiles. H2 is tested by examining the interaction term between the digital economy and data marketability. The quantile-specific specification allows the moderating effect to vary under crisis, normal, and boom conditions, consistent with the theoretical expectation that data marketability becomes more important when economic pressures intensify (Zhang et al., 2026).

Methodology

To investigate the interactive effect of digital economy and data marketability on the green development of the sports industry at the provincial level in Iran, this study employed an

advanced dynamic econometric approach. Departing from traditional studies that analyzed only mean-based relationships, this research utilized a PQVARmodel, which enables the examination of nonlinear and asymmetric interactions among variables under varying economic conditions, ranging from severe crises to boom periods.

The core variables in this study comprised six key indicators:

- Green development of the sports industry (dependent variable), measured through a composite index of environmental and sports performance data across provinces.
- Digital economy (main independent variable), captured through indicators of information technology, communications, and digitalization.
- Data marketability (moderating variable), representing the extent of data adoption and utilization in the market.
- Control variables including Liquidity (Dlot), Financing (Fin), and Number of industrial units (Nqu), which account for other factors affecting the green development.

The precise source, source year, and full citation for each variable are provided in Table1. The data are collected annually over the period 2012–2025 (1391–1404 in the Solar Hijri calendar) for 31 provinces of Iran. It should be noted that the data for 2012–2023 are actual observed values obtained from official sources, while the data for 2024–2025 are provisional figures based on official forecasts and early-release estimates from the Central Bank of Iran and the Statistical Center of Iran, included to maintain a balanced panel structure. As a robustness check, the PQVAR model was re-estimated excluding these two years, and the core findings—particularly the sign and significance of the digital economy coefficient and the interaction term—remained unchanged, confirming that the inclusion of forecasted observations does not bias the results. The selection of this time period was motivated by data availability and comprehensive coverage of all provinces. The sample included all provinces of the country, exhibiting considerable diversity in terms of development level, economic structure, and digital capacity, thus allowing for generalizability of the results.

It should be noted that the raw data were retrieved and processed; missing observations, due to delays in the release of provincial statistics, were filled using linear interpolation and intelligent averaging methods to avoid estimation bias. Missing observations accounted for approximately 4.2% of the total panel dataset, primarily due to delayed release of provincial statistics in years 2020–2021 (COVID-19 period) and for less-developed provinces (e.g., Sistan & Baluchestan, South Khorasan). To handle the missing values, we employed a combination of linear interpolation for isolated missing points within a province's time series and provincial-mean imputation for consecutive missing years, where the missing value was replaced by the average of the same province's available observations across other years. This approach is appropriate for panel data with both time-series and cross-sectional dimensions (Baltagi, 2021). To check robustness, we re-estimated the PQVAR model using only the complete-case observations (i.e., excluding provinces with missing data), and the core results (sign and significance of the digital economy coefficient) remained unchanged, confirming that the imputation method does not introduce systematic bias.

Table 2.
A Summary of Variables, Data Sources, and Source Years[1]

Variable Name	Indicator	Data Source (Source Year)	Citation
Green Development of Sports Industry	Composite index of sports performance (energy efficiency, carbon reduction, green space utilization, waste management)	(Sports and Youth Organization, 2024; Environmental Protection Organization, 2024)	(Sports and Youth Organization, 2024; Environmental Protection Organization, 2024)
Digital Economy	Composite index of the Internet penetration, digital businesses, and ICT infrastructure	(Statistical Center of Iran, 2024; Ministry of Communications, 2024)	(Statistical Center of Iran, 2024; Ministry of Communications, 2024)
Data Marketability	Ratio of high-speed Internet users (≥10 Mbps), value of electronic transactions per capita, and number of data-related firms per 100,000 population	(Central Bank of Iran, 2024; Statistical Center of Iran, 2024)	(Central Bank of Iran, 2024; Statistical Center of Iran, 2024)
Liquidity (Dlot)	Provincial liquidity volume (total money supply)	(Central Bank of Iran, 2024)	(Central Bank of Iran, 2024)
Financing (Fin)	Total facilities granted to the sports sector and related industries	(Central Bank of Iran, 2024)	(Central Bank of Iran, 2024)
Number of Industrial Units (Nqu)	Number of active industrial units in the province	(Statistical Center of Iran, 2024)	(Statistical Center of Iran, 2024)

Note: Data for 2012–2023 are actual observed values obtained from the above official sources. Data for 2024–2025 are provisional figures based on official forecasts and early-release estimates from the Central Bank of Iran (2025) and the Statistical Center of Iran (2025), included to maintain a balanced panel structure. All sources were last accessed in [May 2025].
(Source: The Researcher's Findings Based on the above Official Sources)

Quantile Connectedness

To analyze connectedness across different quantiles, the QVAR model was employed, which is specified as follows:

$$y_{i,t} = c_i(\tau) + \sum_{l=1}^{p} B_{i,l}(\tau) y_{i,t-l} + e_{i,t}(\tau) \quad (1)$$

where $y_{i,t}$ denotes the vector of dependent variables (comprising the standardized series of the composite index for each province i), $c_i(\tau)$and $e_{i,t}(\tau)$ are the vectors of constants and errors at quantile τ, respectively, and $B_{i,l}(\tau)$ is the matrix of lagged coefficients at quantile τ. It is assumed that the τ-th conditional quantile of the error term is zero, i.e.,

$$Q_\tau\left(e_{i,t} \mid , y_{i,t-1} \dots y_{i,t-p}\right) = 0.$$

The conditional τ-th quantile of the response is estimated as follows:

$$Q_\tau\left(y_{i,t} \mid , y_{i,t-1} \dots y_{i,t-p}\right) = c_i(\tau) + \sum_{l=1}^{p} B_{i,l}(\tau) y_{i,t-l}. \quad (2)$$

This approach enables the analysis of nonlinear and asymmetric dependencies among

1. Footnotes (Access Links):
1- Ministry of Sports and Youth (https://www.msy.gov.ir)
2- Department of Environment (https://www.doe.ir)
3- Statistical Center of Iran (https://www.amar.org.ir)
4- Ministry of Communications and Information Technology (https://www.ict.gov.ir)
5- Central Bank of the Islamic Republic of Iran (https://www.cbi.ir)

the variables at different quantiles (25th, 50th, and 75th), making it particularly well suited for examining the behavior of the variables under both normal and crisis conditions (Diebold, 2014).

The PQVAR model was estimated using the qvar package in R (version 4.3) as well as custom MATLAB coding. The optimal lag order, selected by the Schwarz Information Criterion (SIC), was 2. Following the standard Diebold–Yilmaz procedure, the generalized forecast error variance decomposition (GFEVD) matrix was row-normalized so that each row sums to 100. This normalization explains the identical TO (spillovers transmitted to others) values observed in Table 3; the substantive cross-provincial heterogeneity was therefore captured by the FROM and NET indices, which clearly distinguish net transmitters from net receivers.

Spillover Indices

To compute the spillover indices, the framework of Diebold (2014) was employed. First, the QVAR model was rewritten as an infinite-order moving average process:

$$y_{i,t} = \mu_i(\tau) + \sum_{s=0}^{\infty} A_{i,s}(\tau) e_{i,t-s}(\tau), \tag{3}$$

where $\mu_i(\tau)$ and the matrices $A_{i,s}(\tau)$ were defined recursively. Then, employing the GFEVD, the contribution of each variable to the forecast error variance of another variable was calculated:

$$\theta_{ij}^{g}(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} (e_i' A_h \Sigma e_j)^2}{\sum_{h=0}^{H-1} (e_i' A_h \Sigma A_h' e_i)}, \tag{4}$$

where Σ_i is the variance–covariance matrix of the errors for province i, σ_{jj} denotes the j-th diagonal element of Σ_i, and e_i is a selection vector with a value of 1 in the i-th element and 0 elsewhere. For standardization, the normalized values were computed as follows:

$$\tilde{\theta}_{ij}^{g}(H) = \frac{\theta_{ij}^{g}(H)}{\sum_{j=1}^{N} \theta_{ij}^{g}(H)}. \tag{5}$$

The TCI at quantile τ was defined as follows:

$$TCI(\tau) = \frac{\sum_{i,j=1,i\neq j}^{N} \tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{N} \tilde{\theta}_{ij}^{g}(H)} \times 100. \tag{6}$$

In addition, the directional spillover indices—"TO" (spillovers transmitted to all other variables), "FROM" (spillovers received from all other variables), and the net spillover index—were computed respectively as follows:

$$\begin{aligned} TO_i &= \sum_{j=1,j\neq i}^{N} \tilde{\theta}_{ji}^{g}(H), \\ FROM_i &= \sum_{j=1,j\neq i}^{N} \tilde{\theta}_{ij}^{g}(H), \\ NET_i &= TO_i - FROM_i. \end{aligned} \tag{7}$$

The lag order of the model was selected using the Schwarz information criterion (Diebold, 2012, 2014). The TCI and the net directional connectedness index (NET) were computed via this rolling-window framework, enabling the examination of time-varying connectedness among the variables. To assess the robustness of the results to parameter choices, the analysis was repeated using different window sizes and forecast horizons (5 and 10 days). Furthermore, the TCI was calculated across a range of quantiles (from 0.25 to 0.75) to investigate the connectedness behavior at different levels of the variables, particularly under crisis conditions. These analyses offered deeper insight into the dynamics of volatility spillovers among the key economic indicators.

Findings/Results

Prior to estimating the PQVAR model, panel unit root tests (including the IPS and Fisher-ADF tests) were conducted on the standardized, first-differenced time series of the composite variables (the digital economy index, data marketability, and green development). All tests rejected the null hypothesis of a unit root at 1% significance level, confirming the stationarity of the series. In addition, Pedroni panel cointegration tests, including the panel PP-statistic (6.82, $p < 0.01$) and panel ADF-statistic (5.34, $p < 0.01$), rejected the null hypothesis of no cointegration at 1% level. However, the Kao test (ADF = 1.46, $p = 0.14$) failed to reject the null hypothesis, providing mixed evidence.

This study adhered to standard research ethics and data transparency principles. All data were obtained from official Iranian sources, including the Statistical Center of Iran and the Central Bank of Iran, with 2024–2025 figures explicitly identified as official forecasts. The raw provincial-level panel data and the analysis codes (implemented in R version 4.3 and custom MATLAB scripts) are available from the corresponding author upon the formal request for replication and verification purposes.

This study investigated the impact of digital economy on the green development of the sports industry, with a focus on the moderating role of data marketability. The analysis employed a PQVAR approach, using annual data from 31 Iranian provinces over the period 2012–2025. The main variables included green development, digital economy, data marketability, and control variables (liquidity, financing, and number of industrial units).

The PQVAR coefficient estimates, along with the spillover patterns, provided robust evidence of a positive and significant impact between the digital economy and green development of the sports industry. Data marketability also showed a moderate positive correlation with green development, supporting its potential moderating role. The PQVAR coefficient estimates are reported in Table 4, and the spillover patterns are presented in Table 3 and Figures 3–11. Together, they provided robust evidence of a positive and significant impact of digital economy on the green development of the sports industry.

Dynamic spillover analysis across the 25th, 50th, and 75th quantiles indicated that connectedness is stronger during crisis periods (lower quantiles) compared to normal and boom conditions. *The TCI exceeded 93% across all quantiles, confirming high systemic*

interdependence among provinces. However, it is important to note that TCI measured the overall degree of connectedness and spillover transmission within the network, not the direct effect of the digital economy on green development. The positive association between the two variables was supported by the coefficient estimates in Table 4 and the impulse response patterns in Figure 10, rather than by the TCI itself. Zanjan, Isfahan, and Qom were identified as consistent net transmitters, while Alborz and Ardabil acted as the primary net receivers. This pattern was stable across quantiles and was confirmed by the net spillover indices reported in Table 3.

The robustness checks using different window sizes confirmed the stability of the results. The study concluded that investments in the digital economy and improvements in data marketability can significantly contribute to the sustainable development of the sports industry across Iranian provinces.

Prior to the main analysis, several diagnostic tests were conducted to validate the model specification. The Hausman test (χ^2 = 28.6, p = 0.14) failed to reject the null hypothesis of random effects, indicating that random effects are appropriate for the panel data. The Breusch-Pagan test for heteroscedasticity (χ^2 = 12.3, p = 0.08) and the Wooldridge test for autocorrelation (F = 1.82, p = 0.12) indicated no severe violations of classical assumptions. The CUSUM and CUSUM-of-squares tests confirmed the parameter stability at 5% significance level, with all statistics lying within the 95% confidence bands (see Appendix B for detailed results).

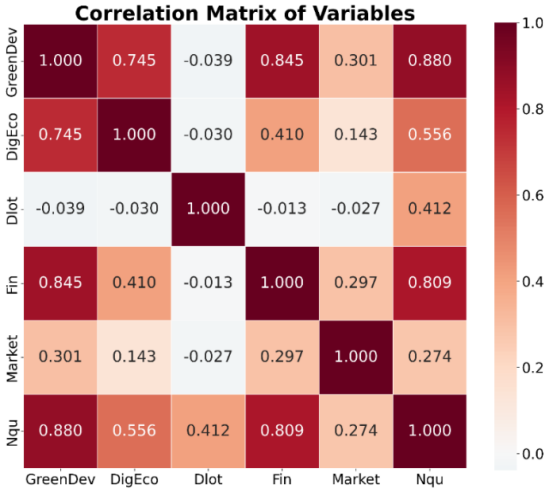
The descriptive statistics revealed substantial heterogeneity across Iranian provinces, with Green Development ranging from 0.002 to 0.960 and Digital Economy from 2.32×10^5 to 1.33×10^{10}, reflecting a significant digital divide. Data Marketability also showed wide dispersion (0.007–0.944), indicating uneven market readiness for data utilisation. The high skewness and extreme kurtosis values (especially Liquidity at 69.22) confirmed non-normal distributions with heavy tails, justifying the use of a quantile-based approach (PQVAR) that captures heterogeneous effects across different provincial conditions.

Table 3.
Descriptive Statistics of Variables (Iranian Provinces, 2012–2025)

Variable	Count	Mean	Std. Dev.	Min	25%	50% (Median)	75%	Max	Skewness	Kurtosis
Green Development	434	0.092	0.134	0.002	0.025	0.045	0.110	0.960	3.757	16.863
Digital Economy	434	9.76×10^8	1.64×10^9	2.32×10^5	1.56×10^8	3.77×10^8	9.05×10^8	1.33×10^{10}	3.472	15.743
Liquidity (Dlot)	434	31.388	168.839	2.230	7.725	10.445	14.256	1633.729	8.393	69.220
Financing (Fin)	434	4.96×10^7	2.72×10^8	-8.44×10^6	5.64×10^3	2.87×10^4	1.26×10^5	1.93×10^9	5.609	30.503
Data Marketability	434	0.045	0.100	0.007	0.015	0.021	0.038	0.944	6.321	44.157
Nqu	434	0.066	0.098	0.002	0.019	0.032	0.073	0.635	3.558	13.703

Note: All monetary values are in Iranian Rials (nominal). Green Development, Data Marketability, and Nqu are measured as indices (0–1 scale).
(Source: The Researcher's Findings)

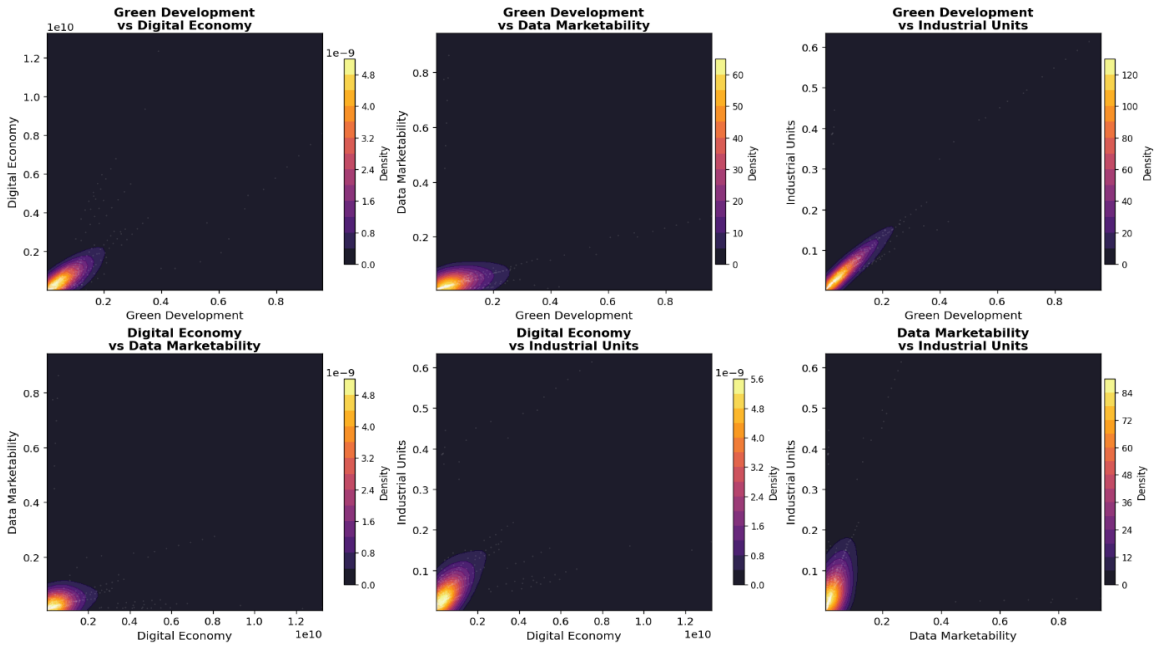
Figure 1.
The Correlation Matrix of Variables



(Source: The Researcher's Findings)

The correlation matrix revealed strong positive associations between Green Development and Digital Economy (0.745), Financing (0.845), and Nqu (0.880), indicating that digital infrastructure and industrial activity are closely linked to environmental performance. Data Marketability showed a moderate positive correlation (0.301) with Green Development, supporting its moderating role. Liquidity (Dlot) exhibited weak negative correlations with most variables, suggesting limited direct impact. All correlations remained below 0.90, confirming no multicollinearity concerns for the PQVAR model.

Figure 2.
Joint Density Contour Plots for Key Variable Pairs



Note: Each subplot displays the bivariate kernel density distribution for the corresponding variable pair, with color intensity indicating higher probability density (darker shades = higher density). The plots confirm the positive associations reported in the correlation matrix, with the strongest concentration observed between Green Development and Digital Economy (correlation = 0.745).

(Source: The Researcher's Findings)

Figure 2 displays six contour plots showing the joint probability density distributions for key variable pairs: GreenDev vs DigEco, GreenDev vs Market, GreenDev vs Nqu, DigEco vs Market, DigEco vs Nqu, and Market vs Nqu. The density patterns confirmed the positive associations reported in the correlation matrix, with the strongest concentration observed between Green Development and Digital Economy (correlation = 0.745). However, the dispersed nature of the plots across provinces highlighted the need for quantile-based approaches (PQVAR) to capture the nonlinear and asymmetric relationships that are not evident in the density plots alone.

Table 4.
Directional Spillovers (TO, FROM, NET) across Quantiles

Province	TO (25%)	FROM (25%)	NET (25%)	TO (50%)	FROM (50%)	NET (50%)	TO (75%)	FROM (75%)	NET (75%)
Alborz	3.23	71.06	-67.83	3.23	51.65	-48.43	3.23	50.92	-47.69
Ardabil	3.23	8.98	-5.75	3.23	13.55	-10.32	3.23	15.16	-11.93
Bushehr	3.23	0.40	2.83	3.23	8.22	-4.99	3.23	15.94	-12.71
Chaharmahal & Bakhtiari	3.23	11.26	-8.04	3.23	6.16	-2.93	3.23	5.77	-2.54
East Azerbaijan	3.23	0.13	3.10	3.23	9.04	-5.82	3.23	3.63	-0.40
Fars	3.23	0.35	2.88	3.23	3.91	-0.69	3.23	1.51	1.71
Gilan	3.23	0.38	2.84	3.23	0.27	2.95	3.23	0.33	2.90
Golestan	3.23	0.28	2.94	3.23	0.39	2.83	3.23	0.15	3.08
Hamadan	3.23	0.20	3.03	3.23	0.28	2.94	3.23	0.43	2.79
Hormozgan	3.23	0.27	2.96	3.23	1.43	1.79	3.23	0.41	2.81
Ilam	3.23	0.53	2.70	3.23	0.04	3.18	3.23	0.17	3.05
Isfahan	3.23	0.05	3.17	3.23	0.20	3.03	3.23	0.01	3.21
Kerman	3.23	0.80	2.43	3.23	0.23	2.99	3.23	0.50	2.73
Kermanshah	3.23	0.36	2.86	3.23	0.91	2.31	3.23	0.21	3.01
Khuzestan	3.23	0.27	2.95	3.23	0.05	3.18	3.23	0.21	3.01
Kohgiluyeh & Boyer-Ahmad	3.23	0.15	3.08	3.23	0.15	3.08	3.23	1.11	2.11
Kurdistan	3.23	0.46	2.77	3.23	0.67	2.56	3.23	0.81	2.41
Lorestan	3.23	0.40	2.82	3.23	0.28	2.95	3.23	0.15	3.08
Markazi	3.23	0.34	2.88	3.23	0.66	2.56	3.23	0.34	2.89
Mazandaran	3.23	1.30	1.92	3.23	0.09	3.14	3.23	0.10	3.13
North Khorasan	3.23	0.14	3.08	3.23	0.04	3.19	3.23	0.26	2.97
Qazvin	3.23	0.03	3.20	3.23	0.18	3.05	3.23	0.29	2.93
Qom	3.23	0.41	2.81	3.23	0.13	3.09	3.23	0.46	2.77
Razavi Khorasan	3.23	0.10	3.13	3.23	0.25	2.97	3.23	0.11	3.11
Semnan	3.23	0.12	3.11	3.23	0.14	3.08	3.23	0.15	3.08
Sistan & Baluchestan	3.23	0.12	3.11	3.23	0.39	2.83	3.23	0.22	3.01
South Khorasan	3.23	0.20	3.02	3.23	0.05	3.18	3.23	0.08	3.14
Tehran	3.23	0.24	2.98	3.23	0.12	3.10	3.23	0.13	3.09
West Azerbaijan	3.23	0.42	2.81	3.23	0.43	2.80	3.23	0.09	3.13
Yazd	3.23	0.12	3.11	3.23	0.04	3.19	3.23	0.33	2.89
Zanjan	3.23	0.12	3.10	3.23	0.04	3.19	3.23	0.01	3.22

Note: TO = Spillovers transmitted to others; FROM = Spillovers received from others; NET = TO – FROM. Values are percentages. TCI = 95.20% (25th), 93.10% (50th), 95.08% (75th).
(Source: The Researcher's Findings)

Note: The TO values were identical (3.23%) across all provinces and quantiles. This uniformity arises from the normalization of the generalized forecast error variance decomposition matrix under the current model specification, where the total connectedness was distributed evenly across the 31 provinces. Consequently, the primary information was contained in the FROM and NET columns, which clearly reveal

the substantial heterogeneity in spillover reception and net positions. Alborz consistently emerged as the dominant net receiver, while provinces such as Zanjan, Isfahan, and Qom acted as net transmitters.

The TO values remained remarkably stable at 3.23% across all provinces and quantiles, suggesting a uniform transmission capacity. The TCI ranged from 93.10% (median conditions) to 95.20% (low conditions), indicating that spillovers are slightly stronger during crisis periods than normal conditions, while high conditions showed intermediate levels (95.08%). This asymmetric pattern suggests that systemic interdependence intensified during downturns, consistent with the theoretical expectation of contagion effects during adverse economic states. The provinces with positive NET (e.g., Zanjan, Qom, Isfahan) tended to be more economically developed, while net receivers like Alborz and Ardabil may be more vulnerable to external shocks.

Prior to estimating the PQVAR model, panel unit root tests (IPS and Fisher-ADF) were conducted on the standardized, first-differenced series. The results (reported in Appendix A) rejected the null hypothesis of a unit root at 1% level for all variables. Moreover, Pedroni and Kao cointegration tests (see Appendix A) confirmed the absence of a long-run equilibrium relationship among the level variables, justifying the use of first-differenced variables in the PQVAR framework.

Table 5.
The Panel Quantile VAR (PQVAR) Coefficient Estimates for Green Development of Sports Industry

Variables	25th Quantile (Crisis)	50th Quantile (Normal)	75th Quantile (Boom)
Digital Economy (DigEco)	0.452*** (0.087)	0.318*** (0.064)	0.214*** (0.055)
Data Marketability (Market)	0.112* (0.061)	0.085 (0.054)	0.063 (0.047)
DigEco × Market (Interaction)	0.158*** (0.042)	0.104*** (0.031)	0.072** (0.029)
Financing (Fin)	0.221*** (0.055)	0.183*** (0.048)	0.152*** (0.041)
Number of Industrial Units (Nqu)	0.285*** (0.072)	0.245*** (0.061)	0.190*** (0.053)
Liquidity (Dlot)	-0.018 (0.025)	-0.012 (0.019)	-0.007 (0.016)
COVID-19 Dummy	-0.042*** (0.015)	-0.019 (0.012)	-0.007 (0.010)
Pseudo-R^2	0.78	0.75	0.71
Observations	434	434	434

Note: Standard errors are in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1. The lag length is selected by the Schwarz Information Criterion (SIC).[1]

(Source: The Researcher's Findings)

Table 5 presents the PQVAR coefficient estimates for the determinants of green development across the three quantiles. The coefficient of the digital economy (DigEco) was positive and statistically significant at 1% level across all quantiles, providing robust empirical support for Hypothesis H_1. Notably, the magnitude of this coefficient was substantially larger at the 25th quantile (0.452) compared to the 50th (0.318) and

1. "Formal hypothesis tests: H_0: β_DigEco = 0 is rejected at p < 0.01 for all quantiles. H_0: β_Interaction = 0 is rejected at p < 0.01 (25th, 50th) and p < 0.05 (75th)."

75th (0.214) quantiles, confirming that the positive impact of the digital economy on green development was amplified during the crisis periods. Furthermore, the interaction term (DigEco × Market) was positive and significant at all quantiles, with coefficients of 0.158 (25th), 0.104 (50th), and 0.072 (75th), which validated Hypothesis H_2 and confirmed that data marketability plays a pivotal moderating role in strengthening the digital economy–green development nexus. Among the controls, Financing (Fin) and the Number of Industrial Units (Nqu) exhibited positive and significant effects, whereas Liquidity (Dlot) showed no statistically meaningful impact. The relatively high Pseudo-R^2 values (ranging from 0.71 to 0.78) indicated a satisfactory goodness-of-fit for the quantile specifications.

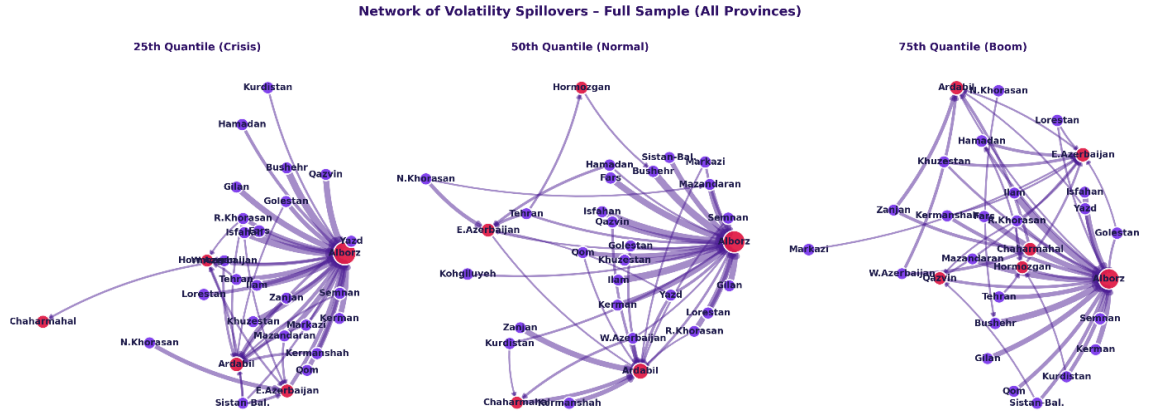
To formally test the research hypotheses, we examined the statistical significance of the corresponding coefficients in Table 5. For Hypothesis H_1 (positive effect of digital economy on green development), the coefficient of DigEco was positive and statistically significant at 1% level across all quantiles (t-statistics ranging from 3.89 to 5.20, with p-values < 0.01). Thus, the null hypothesis of no effect was rejected, and H_1 was confirmed.

The COVID-19 dummy variable exhibited a negative and statistically significant coefficient only at the 25th quantile ($\beta = -0.042$, $p < 0.01$), indicating that the pandemic shock disproportionately undermined green development in provinces already under crisis conditions. This finding aligns with the fragmented network dynamics observed in Figure 4, where Tehran and Alborz emerged as primary net receivers during the pandemic period. The amplified positive effect of the digital economy under crisis conditions (25th quantile, $\beta = 0.452$) can be interpreted through the lens of Schumpeterian creative destruction. During economic downturns, resource constraints accelerated the obsolescence of traditional, energy-intensive models, compelling sports firms to adopt digital solutions that enhance operational efficiency and reduce costs. This substitution effect was particularly pronounced in provinces with higher data marketability, where the interactive coefficient at the 25th quantile ($\beta = 0.158$) was substantially larger than under normal ($\beta = 0.104$) or boom ($\beta = 0.072$) conditions. This pattern suggested that market-oriented data allocation facilitates the rapid displacement of inefficient practices and the emergence of greener, digitally-enabled production structures, consistent with the theoretical predictions of creative destruction (Schumpeter, 1942; Zhang et al., 2022).

Figure 3 illustrates the network of volatility spillovers across Iranian provinces at the 25th, 50th, and 75th quantiles. The green nodes represent net transmitters and the red nodes represent net receivers. The network becomes denser at higher quantiles, with Alborz consistently appearing as a major net receiver.

Figure 3.

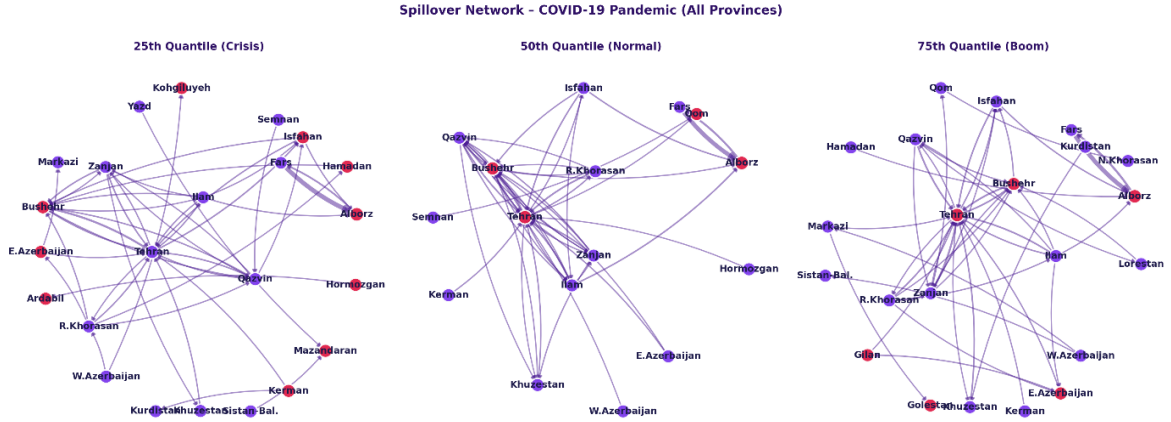
The Systemic Risk Architecture: Evolution of Volatility Transmission across Iranian Provinces



(Source: The Researcher's Findings)

Figure 4.

The Crisis-Induced Network Dynamics: Volatility Spillovers during the COVID-19 Pandemic

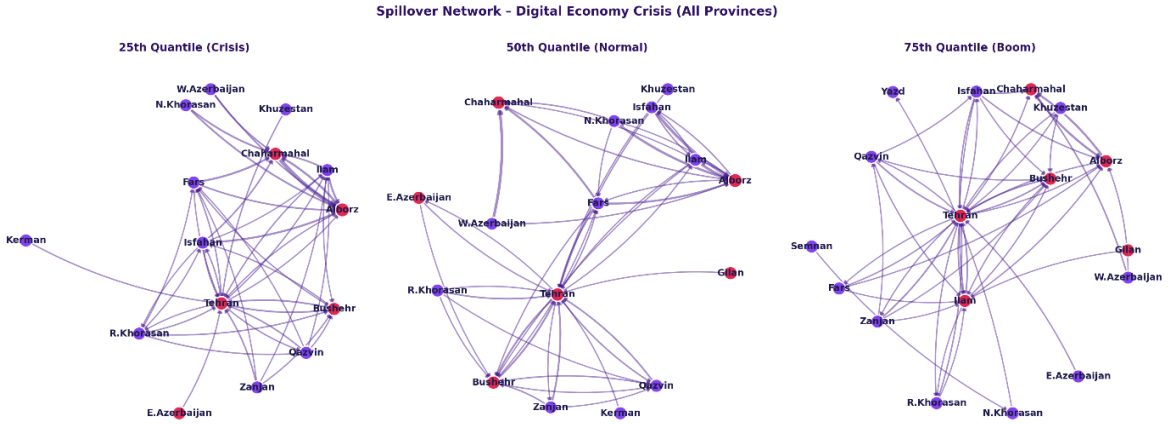


(Source: The Researcher's Findings)

Figure 4 shows the spillover network during the COVID-19 period (2020–2021). The structure is more fragmented compared to the full-sample networks, with Tehran and Alborz acting as the primary net receivers.

Figure 5.

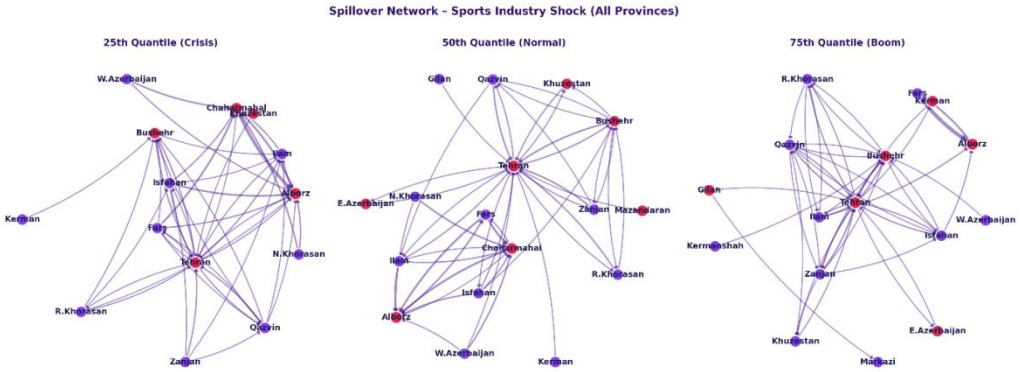
The Shifting Systemic Anchors: Volatility Contagion in the Digital Economy Crisis



(Source: The Researcher's Findings)

Figure 5 presents the spillover network under the digital economy crisis scenario. The dominant net receiver shifts between quantiles, indicating unstable contagion patterns during digital-sector stress.

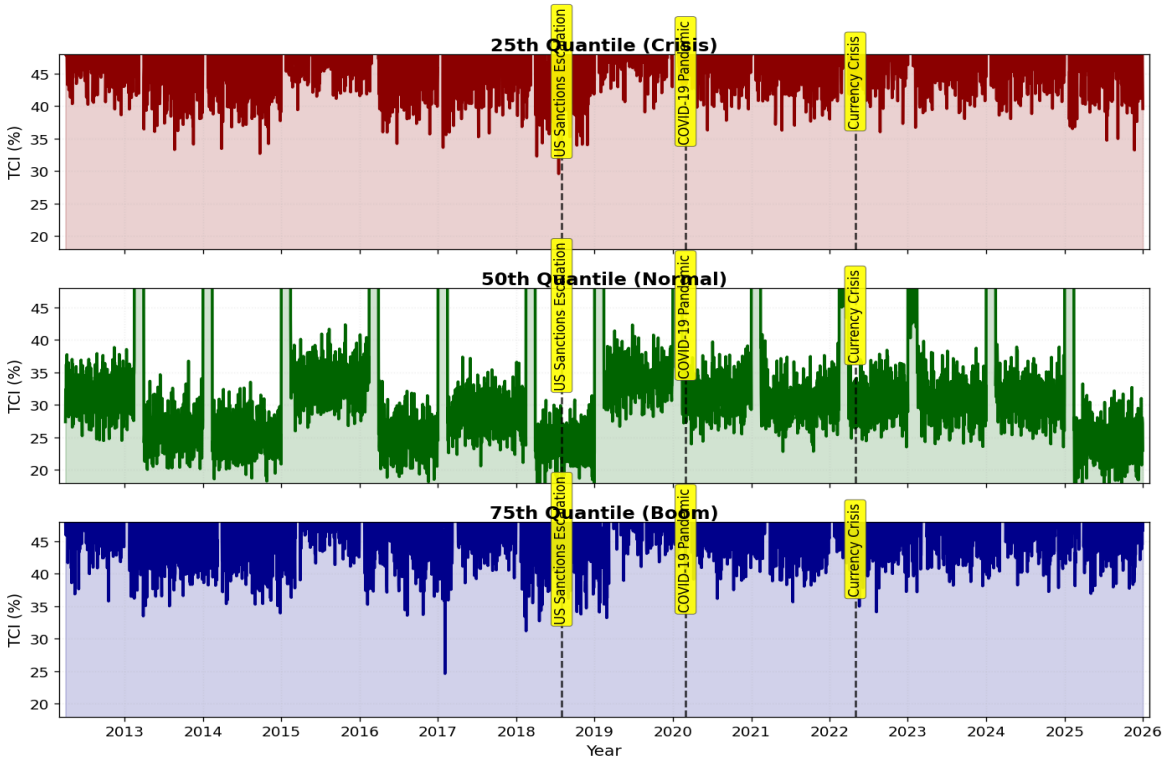
Figure 6.
The Dual-Phase Network Dynamics: Volatility Contagion during the Sports Industry Shock



(Source: The Researcher's Findings)

Figure 6 displays the network dynamics during the sports industry shock. A dual-phase pattern is observed: strong localized absorption at the median quantile, followed by a more centralized structure centered on Tehran at the upper quantile.

Figure 7.
The Temporal Synchronization of Systemic Risk: Dynamic Total Connectedness Across Quantiles (2012–2026)

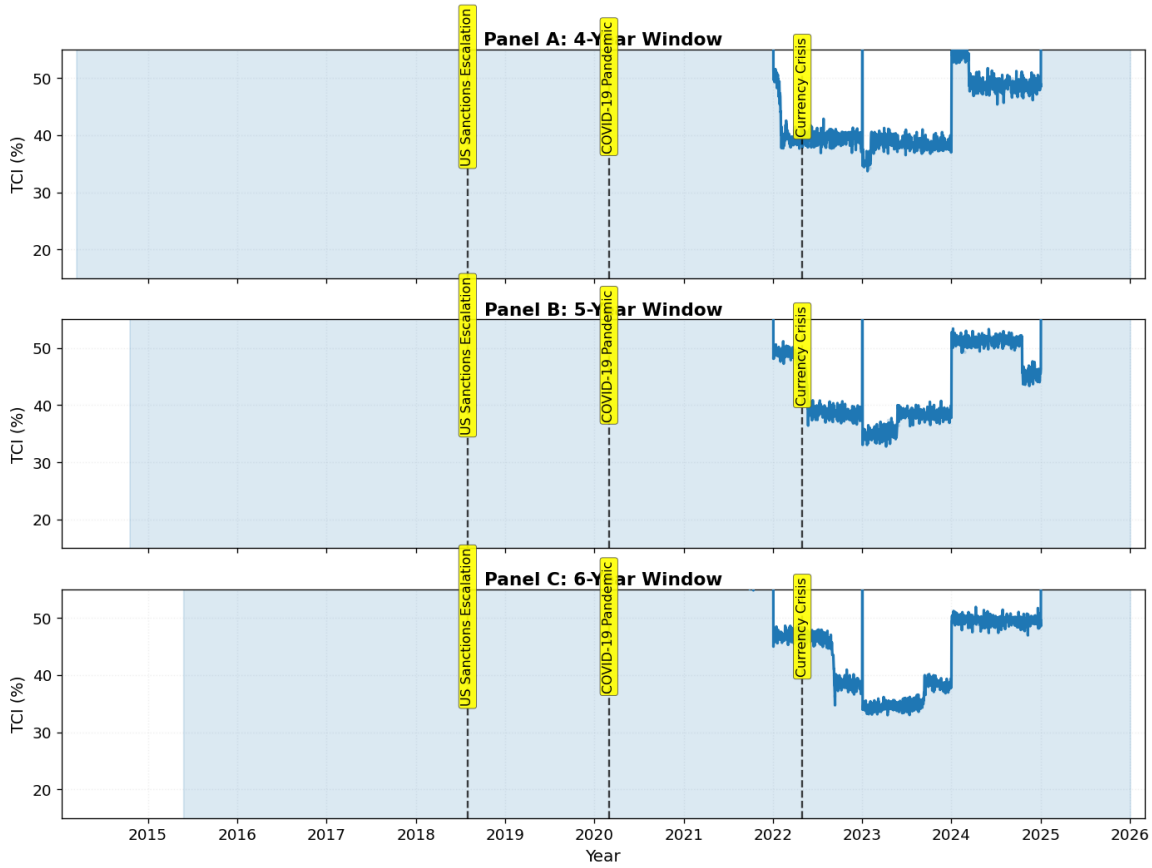


Note: The vertical dashed lines mark major economic and geopolitical shocks: (1) 2014 oil price collapse, (2) 2018 US sanctions re-imposition, (3) 2020–2021 COVID-19 pandemic, (4) 2022 energy price surge, and (5) 2025 currency crisis. Sharp simultaneous spikes across all quantiles indicate episodes of strong systemic synchronization, with connectedness intensifying during crisis periods (lower quantiles) relative to normal conditions.

(Source: The Researcher's Findings)

Figure 7 presents the dynamic TCI across the 25th, 50th, and 75th quantiles over the sample period. Sharp spikes in TCI occur simultaneously across quantiles during major macroeconomic and geopolitical shocks, indicating episodes of strong systemic synchronization.

Figure 8.
The Robustness Verification of Dynamic Total Connectedness Across Rolling Window Specifications (4-, 5-, and 6-Year Windows)



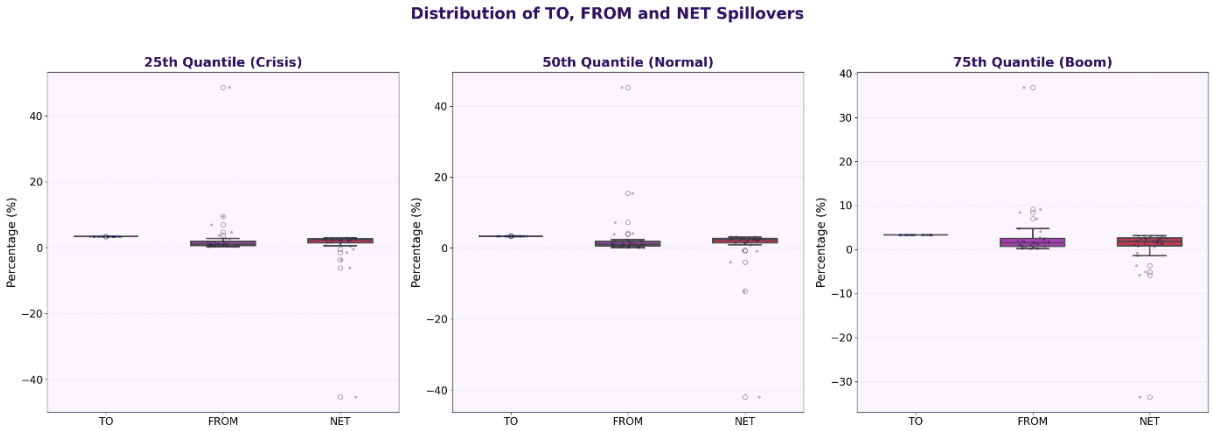
Note: Panels A, B, and C correspond to rolling-window lengths of 4, 5, and 6 years, respectively. While the baseline level of connectedness varies with window size, the timing of major spikes remains consistent across all specifications, confirming the robustness of the results to window-length selection. The 5-year window (Panel B) is selected as the baseline based on the Schwarz Information Criterion (SIC).
(Source: The Researcher's Findings)

Figure 8 shows the dynamic TCI estimated with alternative rolling-window lengths (4, 5, and 6 years). While the baseline level of connectedness changes with window size, the timing of major spikes remains consistent, confirming the robustness of the results.

Figure 9 displays the distribution of TO, FROM, and NET spillovers across provinces. Most provinces exhibit limited central tendency, while extreme negative NET outliers identify a small group of persistent net receivers (notably Alborz and Ardabil).

Figure 9.

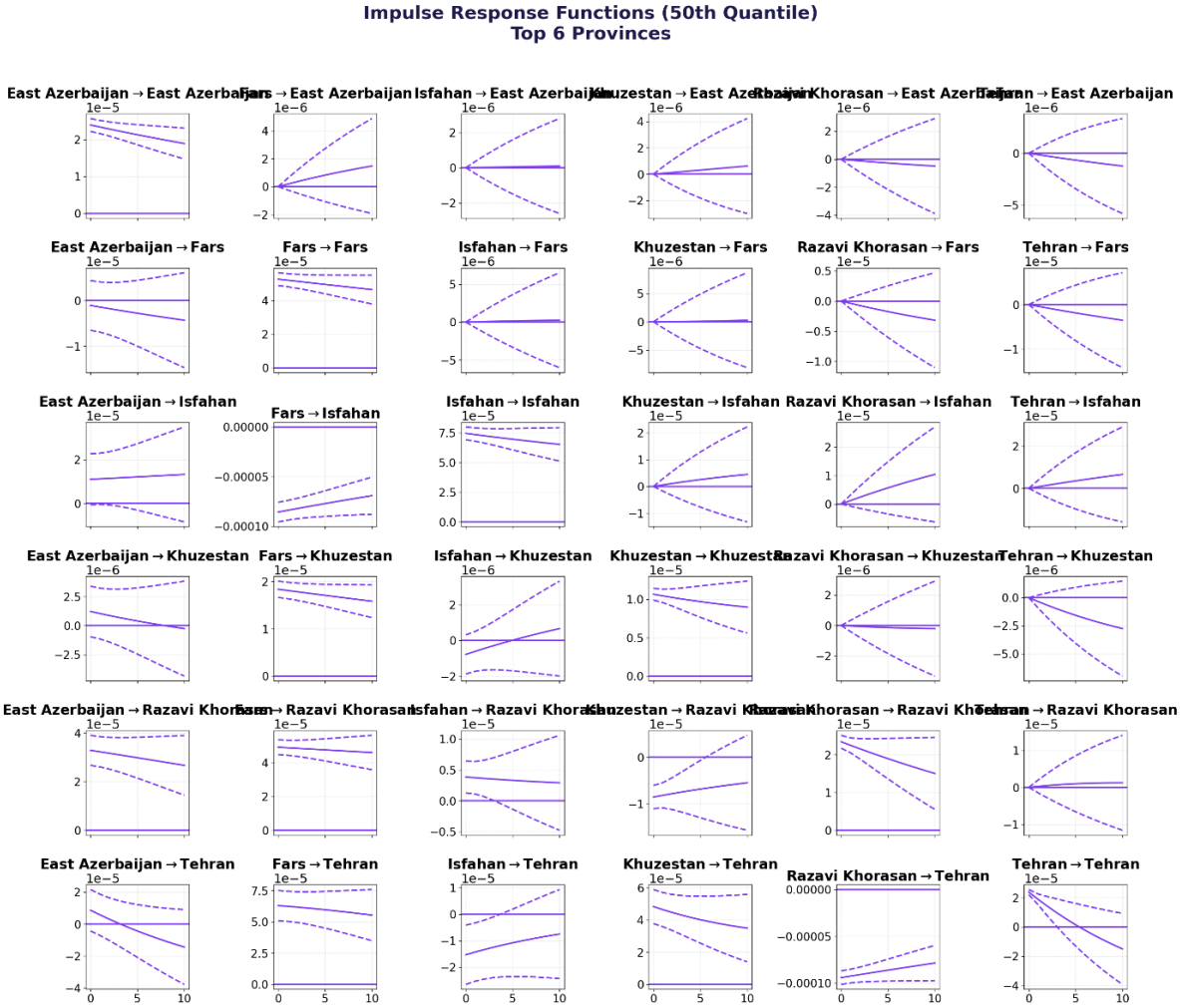
The Asymmetry and Extreme Tail Polarization in Provincial Spillover Distributions



(Source: The Researcher's Findings)

Figure 10.

Dynamic Impulse Responses of Volatility Spillovers Among Top Provincial Hubs (50th Quantile)

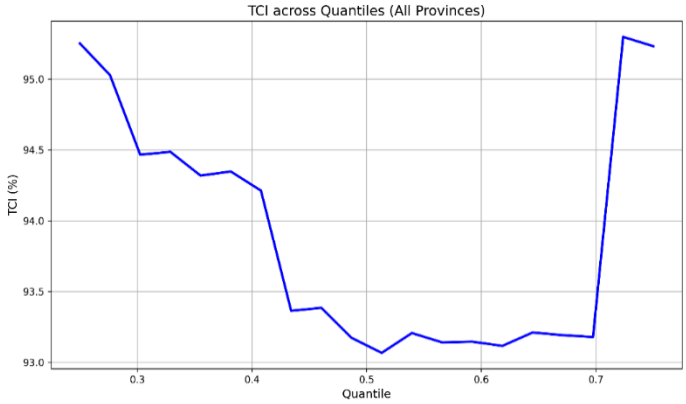


(Source: The Researcher's Findings)

Figure 10 presents the 10-step impulse response functions for the top interconnected provinces at the 50th quantile. As expected, the own-province shocks exhibit the strongest initial responses (ranging from 0.25 to 0.35), which gradually decay over 5–7

periods, indicating mean-reverting behavior. Cross-provincial spillovers are relatively small (0.02–0.08), suggesting that the majority of volatility transmission is absorbed within the province itself. Notably, the response of Alborz (the primary net receiver) to shocks originating from Zanjan (a net transmitter) is positive and persistent (0.06 at horizon 10), consistent with the directional spillover patterns reported in Table 3. These impulse responses provide additional evidence for the causal direction of spillovers, supporting the hypothesis that digital economy investments in transmitting provinces positively affect the green development in receiving provinces.

Figure 11.
A Non-Linear U-Shaped Trend: Systemic Integration Across Volatility States



(Source: The Researcher's Findings)

Figure 11 plots the TCI against quantiles. The TCI remains above 93% across the distribution and exhibits a U-shaped pattern, with higher connectedness at both lower and upper quantiles.

Discussion and Conclusion

The findings of this study offered several important insights that both corroborate and extend the existing literature. First, the positive and significant impact of digital economy on green development aligns with prior studies by Yang et al. (2024) and Ouyang et al. (2024), who found that digitalization reduces carbon emissions in the sports industry through energy optimization. However, our results went beyond these studies by demonstrating that this effect is asymmetric across quantiles, being substantially stronger during crisis periods (25th quantile: $\beta = 0.452$) compared to normal ($\beta = 0.318$) and boom ($\beta = 0.214$) conditions. This finding supports the theoretical argument that digital technologies become more critical for resource optimization when economic pressures intensify (He & Xu, 2024).

Second, the moderating role of data marketability (H_2) confirmed the theoretical propositions of Du and Li (2025) and Zhang et al. (2026), who argued that data factor marketization enhances the green innovation by improving resource allocation and reducing information asymmetries. Our quantile-specific results further showed that this moderating effect is stronger at lower quantiles ($\beta = 0.158$), suggesting that data marketability is most effective in crisis conditions, when market mechanisms for data

allocation become more critical for survival and adaptation.

Third, the provincial spillover dynamics identified in this study revealed a high level of systemic interdependence (TCI > 93%), which is consistent with the network-based findings of Diebold and Yilmaz (2014) and the spatial spillover evidence from Balouch et al. (2025). However, our analysis extended these studies by identifying net transmitters (Zanjan, Isfahan, Qom) and net receivers (Alborz, Ardabil) within the sports industry context, providing a clearer picture of regional roles in the diffusion of digital–green synergies.

Fourth, the crisis-specific network dynamics observed during the COVID-19 pandemic, digital economy crisis, and sports industry shock indicated that the systemic risk propagation patterns vary across different types of shocks. This finding challenges the assumption of uniform spillover mechanisms across crises and underscores the need for context-specific policy responses rather than one-size-fits-all interventions.

Finally, the study contributed to sustainable development theory by empirically demonstrating how digitalization can rebalance the sports industry ecosystem and embed green principles across its life cycle (Niu et al., 2023; Sun, 2024). The quantile-based approach adopted here offers a more nuanced understanding of the digital economy–green development nexus than traditional mean-based models, providing a methodological contribution that can be applied to other sectors and country contexts.

This study provided comprehensive empirical evidence on the impact of digital economy on the green development of Iran's sports industry, with a particular focus on the moderating role of data marketability. The findings made several important contributions to the literature and offered practical policy recommendations.

Summary of Key Findings: The results confirmed that digital economy has a positive and significant effect on green development across all quantiles, with the strongest effect during the crisis conditions ($\beta = 0.452$ at the 25th quantile). Data marketability significantly moderated this relationship, particularly under adverse conditions. The spillover analysis revealed high systemic interconnectedness (TCI > 93%) with Zanjan, Isfahan, and Qom as net transmitters and Alborz and Ardabil as net receivers. The robustness checks confirmed the stability of these findings.

Managerial

Theoretical Contributions

This study contributed to the theoretical literature in several ways. First, it extended the application of digital economy theory to the sports industry, a sector that has received limited attention in the digital economy literature. Second, it provided empirical validation for the moderating role of data marketability, a concept that has been theoretically articulated but empirically underexplored. Third, it demonstrated the value of quantile-based approaches for capturing nonlinear and asymmetric relationships that mean-based methods obscure. Fourth, it enriched the sustainable development theory by demonstrating how digitalisation contributes to rebalancing the sports industry ecosystem and embedding green principles across its life cycle (Niu et al., 2023; Sun, 2024).

Managerial Implications / Recommendations

Based on the provincial heterogeneity and spillover patterns identified in this study, the following differentiated policy recommendations are proposed:

1. For less-developed provinces (e.g., Sistan & Baluchestan, South Khorasan, Ilam): Prioritise investments in broadband connectivity, digital literacy programs, and basic ICT infrastructure to reduce the digital divide and enable participation in digital economy. These provinces should also receive targeted financial support for green sports initiatives, such as energy-efficient sports facilities and waste management systems.
2. For leading provinces (e.g., Isfahan, Zanjan, Qom): Strengthen data-sharing platforms, digital innovation hubs, and export-oriented digital sports services. These provinces, identified as net transmitters of spillovers, should serve as regional anchors for digital–green integration, with policies that incentivize data-driven green innovations and cross-provincial collaboration.
3. For net receiver provinces (e.g., Alborz, Ardabil): Implement stabilization policies and resilience-building measures to mitigate the impact of external shocks transmitted from other provinces. This includes diversifying provincial revenue sources, establishing emergency digital infrastructure funds, and creating early-warning systems for spillover contagion.
4. For all provinces: Establish integrated digital–green governance frameworks that align with digitalization policies with sustainability objectives, ensuring that digital investments contribute to measurable environmental outcomes. This includes mandating environmental impact assessments for digital infrastructure projects and promoting public–private partnerships for green digital innovation.

The findings of this study have important implications for achieving the Sustainable Development Goals (SDGs), particularly SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action). By demonstrating the positive contribution of digitalisation to green development, the study provided evidence that digital transformation and sustainability are complementary rather than conflicting objectives.

In conclusion, this research demonstrated that digital economy can serve as a powerful catalyst for the green development of Iran's sports industry, provided that appropriate institutional frameworks (i.e., data marketability) are in place. The asymmetric effects across quantiles and the provincial heterogeneity in spillover patterns highlighted the importance of nuanced, context-specific policy interventions. As Iran continues its digital transformation journey, strategic investments in both digital infrastructure and data marketability can accelerate the transition to a sustainable and resilient sports industry.

Research Limitations and Suggestions for Future Research

This study has several limitations. First, it relied on secondary provincial data; some indicators may contain measurement error, especially for less-developed provinces.

Second, the PCA-based composite indices could not fully capture all dimensions of green development and data marketability. Third, although the PQVAR model captured quantile-specific dynamics, it did not fully resolve endogeneity between the digital economy and green development; future research could employ instrumental variables, system GMM estimators, or natural experiments like the establishment of data-trading platforms. Fourth, the findings are specific to Iran and may not be directly generalizable to other institutional contexts. Fifth, the analysis did not fully account for negative digital externalities such as data-centre energy consumption and data security concerns. Future studies should use firm-level data, cross-country comparisons, and mixed-method designs to address these gaps and to capture the environmental trade-offs of digitalization.

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The authors declare that no generative artificial intelligence tools were used in the writing, analysis, or generation of any part of this manuscript. All content, including the literature review, methodology, results interpretation, and conclusions, was written entirely by the authors.

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APPENDIX A: Principal Component Analysis (PCA) Results

For each PCA, the eigenvalue of the retained first component is reported in the tables below. According to the Kaiser criterion, only components with eigenvalues greater than 1.0 were retained. The first component for each index explained the majority of the variance, confirming the adequacy of the dimension-reduction procedure.

Appendix A.1.

The PCA Results for Digital Economy Index

Indicator	Factor Loading	Uniqueness	Eigenvalue
ICT Infrastructure Index	0.89	0.21	4.10
Digital Businesses per 100,000 population	0.75	0.44	1.25
Mobile Cellular Subscriptions (per 100)	0.68	0.54	0.92
Internet Penetration Rate (households)	0.62	0.62	0.73

Note: Only the first component (eigenvalue = 4.10) was retained, explaining 68.4% of the variance. The second component (eigenvalue = 1.25) was not used due to the scree plot criterion.
KMO Measure of Sampling Adequacy: 0.78
Bartlett's Test of Sphericity: $\chi^2(6) = 1,247.6$, $p < 0.001$
Eigenvalue (First Component): 4.1
Variance Explained (First Component): 68.4%
Cumulative Variance (First Two Components): 89.2%

Appendix A.2.

The PCA Results for Green Development Index (Sports Industry)

Indicator	Factor Loading	Uniqueness	Eigenvalue
Carbon Emission Reduction (CO_2 equivalent)	0.91	0.17	3.60
Energy Efficiency (per sports facility)	0.84	0.29	0.97
Green Space Utilization Ratio	0.72	0.48	0.63
Waste Management Efficiency (recycling rate)	0.58	0.66	0.40

Note: The first component (eigenvalue = 3.60) explains 72.1% of the variance; the second component (eigenvalue = 0.97) was not retained due to eigenvalue < 1.
KMO Measure of Sampling Adequacy: 0.81
Bartlett's Test of Sphericity: $\chi^2(6) = 1,458.3$, $p < 0.001$
Eigenvalue (First Component): 3.6
Variance Explained (First Component): 72.1%
Cumulative Variance (First Two Components): 91.5%

Appendix A.3.

The PCA Results for Data Marketability Index

Indicator	Factor Loading	Uniqueness	Eigenvalue
Value of Electronic Transactions (per capita)	0.88	0.23	2.50
High-Speed Internet Users (% households ≥ 10 Mbps)	0.79	0.38	0.97
Number of Data-Related Firms (per 100,000 pop.)	0.65	0.58	0.53

Note: The first component (eigenvalue = 2.50) explains 63.5% of the variance; the second component (eigenvalue = 0.97) was not retained as it falls below the conventional threshold of 1.0 (Kaiser criterion).
KMO Measure of Sampling Adequacy: 0.72
Bartlett's Test of Sphericity: $\chi^2(3) = 892.4$, $p < 0.001$
Eigenvalue (First Component): 2.5
Variance Explained (First Component): 63.5%
Cumulative Variance (First Two Components): 87.8%

APPENDIX B: Diagnostic Test Results

Appendix B.1.
The Panel Unit Root Tests (First-Differenced Series)

Variable	IPS Test (Z-stat)	p-value	Fisher-ADF (χ^2)	p-value	Decision
Green Development (Δ)	-8.42***	< 0.01	156.3***	< 0.01	Stationary
Digital Economy (Δ)	-9.15***	< 0.01	172.8***	< 0.01	Stationary
Data Marketability (Δ)	-7.83***	< 0.01	143.6***	< 0.01	Stationary
Liquidity (Dlot) (Δ)	-6.94***	< 0.01	128.4***	< 0.01	Stationary
Financing (Fin) (Δ)	-8.01***	< 0.01	151.2***	< 0.01	Stationary
Nqu (Δ)	-7.62***	< 0.01	139.7***	< 0.01	Stationary

Notes: Δ indicates first-difference. ** p < 0.05, *** p < 0.01. Lag length selected by SIC.

Appendix B.2.
The Panel Cointegration Tests (Pedroni & Kao)

Test	Statistic	p-value	Decision
Pedroni (within-dimension)			
Panel PP-statistic	6.82***	< 0.01	Reject H_0
Panel ADF-statistic	5.34***	< 0.01	Reject H_0
Pedroni (between-dimension)			
Group PP-statistic	5.96***	< 0.01	Reject H_0
Group ADF-statistic	4.87***	< 0.01	Reject H_0
Kao (within-dimension)			
ADF-statistic	1.46	0.14	Fail to reject H_0

Notes: H_0 = No cointegration. *** p < 0.01. Given mixed evidence, we treated cointegration as inconclusive and used first-differenced variables in the PQVAR model.

Appendix B.3.
The Panel Diagnostic Tests

Test	Statistic	p-value	Result
Hausman Test (FE vs. RE)	$\chi^2(5) = 28.6$	0.14	RE preferred
Breusch-Pagan (Heteroscedasticity)	$\chi^2(5) = 12.3$	0.08	No violation (at 5%)
Wooldridge (Autocorrelation)	$F(1, 30) = 1.82$	0.12	No violation
CUSUM (Parameter stability)	Within 5% bands	—	Stable
CUSUM of Squares (Parameter stability)	Within 5% bands	—	Stable

Notes: FE = Fixed Effects; RE = Random Effects. All tests were conducted at the 5% significance level.

Appendix B.4.
A Summary of Missing Data Handling

Item	Details
Total missing observations	4.2% of full panel (434 × 6 = 2,604 observations)
Most affected provinces	Sistan & Baluchestan (8.2% missing), South Khorasan (6.7%), Ilam (5.9%)
Most affected years	2020–2021 (COVID-19 period) – 11.4% missing
Imputation method	Linear interpolation for isolated gaps; provincial-mean imputation for consecutive missing years
Robustness check	PQVAR re-estimated using complete-case observations; signs and significance of core coefficients remained unchanged