Factors Affecting Green Innovation with an Emphasis on Digital Finance: A Case Study of OPEC Member Countries

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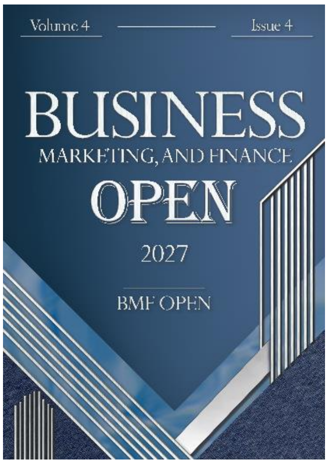

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Abstract: This study aimed to examine the factors affecting green innovation with emphasis on the role of digital finance in selected OPEC member countries during the period 2005–2024. This quantitative, applied, and ex post facto study was conducted using panel data from selected OPEC member countries, including Iran, Saudi Arabia, Iraq, Kuwait, the United Arab Emirates, and Venezuela. The data covered the period from 2005 to 2024 and were collected from secondary international sources, including the World Bank, World Development Indicators, International Monetary Fund databases, OECD-related innovation data, and other official statistical reports. The main dependent variable was green innovation, measured through environmentally related technologies or green patents. The key explanatory variable was digital financial services, while GDP per capita, gross national expenditure, research and development expenditure, and industry value added were used as control variables. Data were analyzed using descriptive screening, augmented Dickey–Fuller stationarity testing, Kolmogorov–Smirnov normality testing, variance inflation factor analysis, autocorrelation tests, Chow test, Hausman test, and fixed-effects panel regression. The inferential results showed that all variables were stationary at level according to the augmented Dickey–Fuller test, with probability values below 0.05. The Kolmogorov–Smirnov test confirmed the normal distribution of the variables, and VIF values ranging from 1.008 to 1.284 indicated no serious multicollinearity. First- and second-order autocorrelation tests were not significant, confirming the absence of serial correlation. The Chow test was significant ($p = 0.0009$), supporting the use of panel-data estimation, and the Hausman test was significant ($p = 0.0002$), confirming the superiority of the fixed-effects model. The model was statistically significant ($F = 11.440, p = 0.0000$), with $R^2 = 0.511$. Digital financial services ($\beta = 1.803, p = 0.0001$), GDP per capita ($\beta = 1.781, p = 0.0000$), gross national expenditure ($\beta = 1.899, p = 0.0003$), and industry value added ($\beta = 1.245, p = 0.0002$)had positive and significant effects. The results indicate that digital finance, economic development, national expenditure capacity, and industrial value added play significant roles in strengthening green innovation among selected OPEC member countries.

Keywords: Green innovation; digital finance; OPEC; panel data; fixed effects; sustainable development; green technology.

1. Introduction

Green innovation has become one of the most important strategic mechanisms through which resource-dependent economies can respond to the simultaneous pressures of environmental degradation, energy transition, technological competition, and sustainable development. In oil-exporting economies, especially countries whose fiscal revenues, industrial structures, and external trade patterns remain strongly connected to petroleum resources, the transition toward greener development cannot be understood merely as an environmental issue; rather, it is a multidimensional economic transformation involving finance, technology, institutional capacity, industrial upgrading, and the reconfiguration of national development models. The continuing centrality of energy in modern society shows that energy systems are deeply embedded in production, consumption, transportation, welfare, and geopolitical structures, and any shift toward sustainability requires coordinated changes in both technological systems and financial mechanisms [1]. For countries such as selected members of the Organization of the Petroleum Exporting Countries, the challenge is particularly complex because oil wealth has historically provided fiscal capacity and economic influence, while at the same time exposing these economies to carbon dependency, market volatility, delayed diversification, and structural dependence on natural resource rents [2]. Therefore, the study of green innovation in OPEC member countries requires attention not only to environmental technology but also to the financial and digital infrastructures that may enable or restrict the development and diffusion of such innovation.

The growing literature on sustainable development increasingly emphasizes that the conventional growth model based on intensive natural resource extraction is no longer sufficient for long-term economic resilience. The resource-finance nexus has been discussed through the lens of the resource curse and resource blessing debate, suggesting that natural resources may either obstruct or support development depending on the quality of financial systems, institutional structures, technological capabilities, and policy orientation [3]. In this framework, oil-exporting economies face a dual task: they must continue managing strategic energy resources while simultaneously investing in green technologies, cleaner production, renewable energy, and knowledge-based diversification. The experience of resource-dependent and emerging economies shows that financial development, green finance, and technological upgrading can transform natural resource advantages into broader sustainable development gains when they are aligned with responsible production, environmental regulation, and innovation systems [4]. This is especially relevant for OPEC economies, where resource abundance has often produced large public revenues but has not always translated into sufficient investment in research and development, digital infrastructure, or environmental innovation.

Digital finance has emerged as a major force in reshaping the relationship between finance and sustainability. By expanding access to financial services, reducing transaction costs, improving financial inclusion, supporting data-driven credit allocation, and enabling new forms of digital investment, digital finance can provide an important channel for financing green innovation. Recent studies on sustainable development suggest that digital and financial drivers can promote smarter growth by improving resource allocation and strengthening the capacity of economies to pursue green transformation [5]. Similarly, research on emerging economies highlights that FinTech, green finance, and natural resource dynamics interact in shaping environmental sustainability and sustainable development outcomes [6]. Digital finance may be especially important in oil-dependent countries because traditional financial systems may remain concentrated around state revenues, large public-sector projects, or hydrocarbon-related industries. In such settings, digital financial services can potentially broaden access to capital, support small and medium-sized enterprises, facilitate green entrepreneurship, and improve the efficiency of financial flows toward innovation-oriented activities.

The relevance of digital finance for green innovation also reflects the broader shift from conventional financial intermediation toward technology-enabled financial ecosystems. Digital payment systems, mobile banking, online investment platforms, digital credit, and data-driven financial services can reduce barriers for firms and individuals seeking to participate in innovation activities. In addition, digital financial development may complement green finance by making environmental investments more traceable, scalable, and accessible. Evidence from studies on finance, technology, and growth policies indicates that financial structures and technological capabilities play significant roles in sustainable mineral and natural gas management, demonstrating that sustainability transitions depend on the interaction between economic growth strategies, financial development, and technological progress [7]. In the same direction, studies of financial markets and minerals show that the connection between financial systems, mineral resources, energy transitions, and environmental sustainability has become increasingly important in global development debates [8]. These findings suggest that the financial architecture of resource-dependent economies is not merely a passive background condition but an active determinant of whether green innovation can expand.

The Middle East and North Africa region, where several OPEC members are located, has attracted increasing attention in relation to renewable energy consumption, financial development, and green innovation. Research on the MENA region suggests that green innovation and financial development can contribute to renewable energy consumption and provide a sustainability framework for economies facing energy transition pressures [9]. Similarly, African development studies indicate that financial development, energy transition, and digitalization can reinforce multidimensional gains when policy environments support sustainable transformation [10]. These insights are important because OPEC countries are geographically diverse and include economies from the Middle East, Africa, and Latin America, each with different levels of financial development, technological readiness, and institutional capacity. The diversity among OPEC members allows researchers to examine how digital finance and economic factors operate across heterogeneous oil-dependent contexts rather than within a single national or regional framework.

In oil-rich economies, the shift from hydrocarbon dependence to green innovation is also influenced by the broader politics of energy transition. The literature on power shifts in global energy systems emphasizes that energy transition is not only a technological process but also a redistribution of economic power, institutional authority, and development opportunities [11]. Just transition debates further show that countries in the Global South may face distinct obstacles in balancing climate commitments, development needs, employment concerns, and dependence on extractive industries [12]. This is directly relevant to OPEC economies, where decarbonization pressures may create fiscal and social challenges if green transformation is not accompanied by diversification, innovation, and inclusive financial systems. The experience of crises in oil-dependent systems also indicates that global energy instability can intensify the need for structural adaptation and more resilient development strategies [13]. Therefore, green innovation in OPEC countries must be understood as part of a broader transformation involving energy security, fiscal sustainability, industrial renewal, and environmental responsibility.

The COVID-19 pandemic and post-pandemic recovery debates further intensified the importance of green recovery, financial resilience, and sustainable investment. Studies on BRICS economies showed that the pandemic affected financial growth and created new guidelines for green recovery, emphasizing the need for economic recovery strategies that are environmentally sustainable rather than simply growth-restorative [14]. Energy transition has also been framed as a response to post-pandemic energy challenges, with scholars emphasizing that economies must develop more adaptive energy systems capable of addressing uncertainty, supply shocks, and sustainability pressures [15]. In the Gulf Cooperation Council context, post-pandemic recovery debates have highlighted the need for post-oil, sustainable, knowledge-based economies, showing that oil-rich countries increasingly recognize the limitations of hydrocarbon dependence and the importance of diversification through knowledge, technology, and innovation [16]. These perspectives support the argument that OPEC countries need to accelerate green innovation through financial and technological modernization.

Studies focusing on energy and economic development in oil-exporting or resource-rich contexts provide further justification for examining digital finance and green innovation together. Research on renewable energy development in the GCC region has emphasized both progress and persistent challenges, including institutional, economic, and technological barriers to expanding renewable energy systems [17]. A study of Saudi Arabia demonstrated the interconnections among energy, technology, and economic growth, suggesting that technological change and energy policy are deeply linked in resource-rich economies [18]. In African OPEC countries, spatiotemporal analysis of energy consumption and financial development has shown that financial systems and energy demand evolve together across time and space, making panel-based analysis particularly suitable for studying these relationships [19]. Likewise, research on OPEC++-participating countries has connected crude oil market functioning with sustainable development goals, showing that oil-market behavior and sustainability objectives must be studied in an integrated manner [20]. These studies collectively suggest that OPEC economies provide a highly relevant empirical setting for examining how finance, digitalization, and innovation interact in shaping environmental outcomes.

Green finance is also central to the transition from resource dependence to sustainability. Research on China has examined whether green finance can help shift the resource curse toward a resource blessing, suggesting that financial mechanisms can influence whether natural resource wealth becomes a developmental obstacle or a catalyst for sustainable transformation [21]. Studies on barriers to green finance and public spending have further shown that financial constraints, policy design, and institutional support affect the capacity of firms, especially small and medium-sized enterprises, to participate in green development [22]. Public-private partnerships may also function as instruments of sustainable development in oil-refining and related sectors by mobilizing investment, sharing risks, and improving project implementation capacity [23]. These findings are important for OPEC countries because green innovation often requires long-term investment, uncertain returns, and coordinated public-private financing, particularly where private financial markets are less diversified or where capital allocation remains shaped by hydrocarbon sectors.

The role of financial systems in supporting green transformation can also be understood through broader experiences of banking, investment, and social support models. The Malaysian economy, although not an OPEC case, provides comparative insights into how financial systems, Islamic finance, investment instruments, and social support frameworks can shape inclusive development and financial participation [24, 25]. Studies on Islamic finance and banking in Malaysia show that alternative financial structures can broaden the range of financing instruments and support more ethically oriented investment models [26, 27]. Related work on Islamic banking methods and investment instruments further demonstrates that financial innovation can be structured through diverse institutional and cultural frameworks, which is relevant for many Muslim-majority OPEC countries where Islamic finance may interact with digital finance and green investment [28, 29]. Moreover, social projects and support mechanisms in Malaysia highlight the importance of linking financial development with social objectives, an issue that is relevant for ensuring that digital finance and green innovation contribute to inclusive rather than narrowly concentrated development outcomes [30].

The environmental consequences of resource-based development also extend beyond national borders. Research on Russia’s trade with China and carbon dioxide emissions illustrates how trade, regional production structures, and resource flows can shape environmental outcomes in resource-intensive economies [31]. Such evidence is relevant for OPEC countries because oil exports, industrial value added, and international energy demand can influence both domestic emissions trajectories and incentives for green innovation. At the same time, responsible consumption and production of natural resources require a combination of green energy, green technology, and green finance, rather than isolated environmental policies [4]. Thus, green innovation should be viewed as a systemic outcome generated by the interaction of financial capacity, technological investment, industrial structure, and policy orientation.

Despite the growing body of literature on green finance, digitalization, renewable energy, and sustainable development, several gaps remain. First, many studies examine green innovation or digital finance in broad groups of emerging economies, while fewer studies focus specifically on OPEC member countries as oil-dependent economies with distinct structural characteristics. Second, existing research often emphasizes financial development or green finance in general, whereas the specific role of digital financial services in shaping green innovation remains less developed in the context of resource-dependent countries. Third, OPEC economies differ significantly in GDP per capita, industrial value added, research and development expenditure, and national expenditure patterns, making it necessary to use panel-data methods capable of accounting for heterogeneity across countries and over time. Finally, the period from 2005 to 2024 provides an analytically important window because it captures changes in digital finance, post-pandemic recovery pressures, energy transition debates, and the increasing global emphasis on environmental technologies.

Accordingly, the aim of this study is to examine the factors affecting green innovation with an emphasis on digital finance in selected OPEC member countries during the period 2005–2024.

2. Methodology

The present study was designed as a quantitative, applied, and ex post facto econometric investigation based on panel data. The main purpose of the research was to examine the factors affecting green innovation, with particular emphasis on the role of digital finance, among selected member countries of the Organization of the Petroleum Exporting Countries. The panel structure of the data made it possible to combine the cross-sectional dimension of countries with the time-series dimension of annual observations, thereby providing a stronger analytical framework for identifying dynamic relationships among economic, financial, technological, and environmental variables. The study covered the period from 2005 to 2024, which was selected to capture long-term changes in digital financial development, macroeconomic conditions, research and development activity, industrial value added, and green innovation performance. The use of panel data was especially appropriate because the countries under study differed substantially in their economic structures, levels of digital infrastructure, financial systems, industrial composition, and dependence on oil revenues.

The statistical population of the study consisted of OPEC member countries, and the analytical sample included Iran, Saudi Arabia, Iraq, Kuwait, the United Arab Emirates, and Venezuela. These countries were selected because they were among the oil-dependent economies that had a meaningful role in the global petroleum market and represented different geographical regions, including the Middle East and South America. Their inclusion allowed the study to examine green innovation in economies where natural resources, especially oil, have historically shaped development patterns, fiscal structures, industrial policies, and environmental challenges. Since the selected countries were characterized by considerable dependence on hydrocarbon revenues, they provided a suitable empirical context for investigating whether digital finance could support green innovation by improving access to financial services, facilitating investment in environmental technologies, and enhancing the efficiency of financial intermediation. Therefore, the units of analysis were country-year observations, and the final dataset was organized as a panel consisting of selected OPEC countries observed annually over the 2005–2024 period.

The data collection method was documentary and library-based, relying entirely on secondary data extracted from reputable international databases and official statistical reports. No questionnaire, interview, or human-subject instrument was used in this study. The required data were collected from sources such as the World Bank, World Development Indicators, the International Monetary Fund database, international innovation and technology databases, the Organization for Economic Cooperation and Development database, and other official reports published by recognized international organizations. After extraction, the data were classified by country and year, checked for consistency, and arranged in a panel format suitable for statistical and econometric analysis. The use of international databases increased the comparability of the variables across countries and reduced the risk of measurement inconsistency caused by differences in national reporting systems.

The dependent variable of the study was green innovation, represented by environmentally related technologies and measured by the number of such technologies, with the abbreviation GI. Digital finance was the main explanatory variable and was represented by digital financial services, abbreviated as DF, which was constructed by the researcher based on available indicators related to digital financial development. The control variables included gross domestic product per capita in current US dollars, abbreviated as $GDPpc$; gross national expenditure in current local currency units, abbreviated as GNE; research and development expenditure as a percentage of GDP, abbreviated as $R\&D$; and industry value added, including construction, in current US dollars, abbreviated as $IndVA$. These variables were selected because green innovation is not only affected by digital finance but also by the level of economic development, domestic expenditure capacity, scientific and technological investment, and the size of the industrial sector. Where necessary, the variables were transformed into natural logarithmic form to reduce scale differences, improve distributional properties, and allow the estimated coefficients to be interpreted in elasticity terms. Accordingly, the general logarithmic transformation was expressed as $\ln X_{it}$, where X_{it} denotes the value of a given variable for country i in year t.

The data analysis was conducted using descriptive statistics, correlation analysis, and advanced panel econometric methods. In the first stage, the data were screened and summarized through descriptive indicators in order to examine the central tendency, dispersion, minimum and maximum values, and general distribution of the variables. Correlation analysis was then used to assess the preliminary direction and strength of linear relationships among the variables. In this stage, the correlation coefficient was used to identify the degree and direction of association between variables, while the coefficient of determination was considered as an indicator of the proportion of variation in the dependent variable explained by the independent variables. Since the structure of the data was panel-based, the analysis proceeded beyond simple correlation and employed regression-based econometric models capable of capturing both country-specific and time-related variation.

Before estimating the main models, several diagnostic tests were conducted to determine the appropriate econometric strategy. Because panel data may suffer from cross-sectional dependence, especially when countries are connected through oil markets, financial flows, international shocks, technological diffusion, and global environmental pressures, the study first examined cross-sectional dependence using the Breusch–Pagan Lagrange Multiplier test, the scaled LM test, the Pesaran CD test, and the bias-corrected adjusted LM test. In addition, slope heterogeneity was assessed using slope heterogeneity tests such as the Pesaran–Yamagata test and the Blomquist–Westerlund approach. These tests were necessary because ignoring cross-sectional dependence and heterogeneous slopes may produce biased or misleading estimates in panel-data models. After evaluating these conditions, panel unit root tests robust to cross-sectional dependence were applied, including the cross-sectionally augmented IPS test and the cross-sectionally augmented Dickey–Fuller test. These tests helped determine whether the variables were stationary at level or became stationary after differencing. When the variables were integrated and long-run relationships were theoretically plausible, cointegration was examined using Westerlund panel cointegration tests, including G_t, G_a, P_t, and P_a, which are based on an error-correction framework and are suitable for panel settings affected by cross-sectional dependence.

For the baseline panel specification, pooled, fixed-effects, and random-effects estimations were considered. The Chow or Limer F-test was used to determine whether a pooled model without individual effects was appropriate or whether a fixed-effects model should be preferred. The null hypothesis in this test was that the pooled model was adequate, while the alternative hypothesis supported the presence of fixed effects. If the probability value of the test statistic was below 0.05, the null hypothesis was rejected and the fixed-effects model was considered more appropriate. Afterward, when fixed and random effects were both possible, the Hausman test was used to select between them. In the Hausman test, the null hypothesis supported the random-effects model, while the alternative hypothesis supported the fixed-effects model. The selection of the final baseline model was therefore based on the combined results of these panel specification tests. The general static panel regression model of the study was expressed as follows:

$$\ln GI_{it} = \alpha + \beta_1 \ln DF_{it} + \beta_2 \ln GDPpc_{it} + \beta_3 \ln GNE_{it} + \beta_4 \ln R\&D_{it} + \beta_5 \ln IndVA_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

In this equation, GI_{it}denotes green innovation for country $i$in year t, DF_{it}denotes digital finance, $GDPpc_{it}$represents GDP per capita, GNE_{it}represents gross national expenditure, $R\&D_{it}$represents research and development expenditure as a percentage of GDP, and $IndVA_{it}$represents industry value added. The term $\mu_i$captures unobserved country-specific effects, $\lambda_t$captures time-specific effects when included, and ε_{it}represents the random error term. The coefficients $\beta_1$to $\beta_5$indicate the estimated effects of the explanatory variables on green innovation. In particular, $\beta_1$was the main coefficient of interest because it measured the effect of digital finance on green innovation after controlling for macroeconomic, technological, and industrial factors.

Because green innovation may be dynamic and influenced by its past values, the study also used dynamic panel data estimation. The dynamic model allowed the lagged dependent variable to enter the regression equation and helped address persistence in green innovation over time. Since explanatory variables such as digital finance, industrial development, and research and development may be endogenous, the system generalized method of moments estimator was used as the preferred dynamic panel estimator. This approach combines equations in first differences and equations in levels, using lagged levels as instruments for differenced equations and lagged differences as instruments for level equations. The dynamic panel model was specified as follows:

$$\ln GI_{it} = \alpha_0 + \rho \ln GI_{i,t-1} + \beta_1 \ln DF_{it} + \beta_2 \ln GDPpc_{it} + \beta_3 \ln GNE_{it} + \beta_4 \ln R\&D_{it} + \beta_5 \ln IndVA_{it} + \mu_i + \varepsilon_{it}$$

In this model, $\ln GI_{i,t-1}$represents the lagged value of green innovation, and ρcaptures the persistence of green innovation over time. The system GMM method was selected because it is suitable for models with endogenous regressors, omitted-variable bias, unobserved country heterogeneity, measurement error, and dynamic relationships. The validity of instruments was examined through overidentification tests, and serial correlation in the differenced residuals was assessed using autocorrelation diagnostics. The absence of second-order serial correlation and the validity of instruments were considered essential conditions for the reliability of the dynamic panel estimates.

To examine whether the effects of digital finance and other explanatory variables differed across the distribution of green innovation, the study further employed the method of moments quantile regression with fixed effects. This method was appropriate because the effect of digital finance may not be identical for countries with low, medium, and high levels of green innovation. Unlike conventional mean-based regression methods, quantile regression made it possible to estimate heterogeneous effects at different conditional quantiles of the dependent variable. The location-scale form of the model was expressed as follows:

$$Y_{it} = \alpha_i + X'_{it}\beta + (\delta_i + Z'_{it}\gamma)U_{it}$$

In this equation, Y_{it}represents the logarithm of green innovation, $X_{it}$is the vector of explanatory variables, $\alpha_i$captures individual fixed effects, $Z_{it}$is a vector of known differentiable transformations of X_{it}, $\beta$and $\gamma$are parameters to be estimated, and $U_{it}$is the disturbance term normalized according to the moment conditions of the method. The conditional quantile function was specified as follows:

$$Q_Y(\tau \mid X_{it}) = \alpha_i + \delta_i q(\tau) + X'_{it}\beta + Z'_{it}\gamma q(\tau)$$

Here, $Q_Y(\tau \mid X_{it})$denotes the conditional quantile of green innovation at quantile τ, and $q(\tau)$represents the τ-th quantile of the unobserved component. This specification allowed the study to identify whether digital finance had stronger or weaker effects at lower, middle, or upper levels of green innovation. The quantile results therefore complemented the baseline and dynamic panel estimations by providing a more distribution-sensitive interpretation of the relationship between digital finance and green innovation.

The statistical significance of the estimated models and coefficients was evaluated using conventional inferential tests. The overall significance of the regression models was assessed through the F-statistic, which was calculated as follows:

$$F = \frac{R^2/(K-1)}{(1-R^2)/(n-K)}$$

In this formula, R^2denotes the coefficient of determination, Krepresents the number of parameters, and $n$represents the number of observations. If the calculated F-statistic exceeded the critical value at the selected significance level, the model was considered statistically significant. The significance of individual coefficients was examined using the t-statistic, calculated as follows:

$$t = \frac{\hat{\beta}}{SE(\hat{\beta})}$$

The residual variance was calculated as follows:

$$\hat{\sigma}^2 = \frac{\sum e^2}{n-k}$$

In these equations, $\hat{\beta}$is the estimated coefficient, $SE(\hat{\beta})$is the standard error of the estimated coefficient, $e^2$is the squared residual, $n$is the number of observations, and $k$is the number of estimated parameters. The calculated t-statistics were compared with critical values at the 90%, 95%, and 99%confidence levels. A coefficient was considered statistically significant when the absolute value of its t-statistic exceeded the relevant critical value or when its probability value was below the chosen significance level. Autocorrelation was also examined because correlated error terms may distort standard errors and lead to incorrect statistical inference. Overall, the combined use of baseline panel models, diagnostic tests, system GMM estimation, and method of moments quantile regression provided a comprehensive analytical framework for evaluating the determinants of green innovation in selected OPEC member countries, with special emphasis on the role of digital finance.

3. Findings and Results

The findings of the study are presented in accordance with the sequence of descriptive statistics, preliminary diagnostic tests, panel-model selection tests, model fit indices, and regression coefficients. The analysis was conducted for selected OPEC member countries over the period 2005–2024. The main variables included green innovation, digital financial services, GDP per capita, gross national expenditure, research and development expenditure, and industry value added. Before testing the research hypotheses, the stationarity of the variables, normality of distribution, multicollinearity, autocorrelation, and the appropriate panel-data specification were examined.

Table 1. Descriptive Statistics of the Research Variables

Research variables	Unit of measurement	Mean	Median	Minimum	Maximum	Standard deviation	Skewness	Kurtosis
Green innovation (GI)	Number of green patents	145	132	15	420	92	0.85	2.90
Digital financial services (DF)	Index, 0 to 1	0.48	0.46	0.12	0.89	0.18	0.40	2.25
GDP per capita (GDPpc)	US dollars	19,850	17,400	2,100	43,800	12,650	0.72	2.60
Gross national expenditure (GNE)	Local currency unit	545,000,000,000	490,000,000,000	82,000,000,000	1,450,000,000,000	310,000,000,000	0.95	3.10
Research and development expenditure (R&D)	Percentage of GDP	0.72	0.60	0.05	1.90	0.55	0.68	2.40
Industry value added (IndVA)	US dollars	265,000,000,000	230,000,000,000	45,000,000,000	720,000,000,000	185,000,000,000	0.88	2.75

As shown in Table 1, the mean value of green innovation was 145 green patents, with a minimum of 15 and a maximum of 420. This wide range indicates a considerable difference in the level of environmentally oriented innovative activity among the selected OPEC countries. The mean value of digital financial services was 0.48, and its standard deviation was 0.18, showing a moderate degree of dispersion in the level of digital financial development across the sample. GDP per capita had a mean value of 19,850 US dollars, while the large gap between its minimum and maximum values indicates substantial heterogeneity in the level of economic development among the selected countries.

The descriptive results also show very large values for gross national expenditure and industry value added, which is consistent with the economic structure of the selected OPEC countries and their strong dependence on natural resources, industrial activity, and oil-related sectors. The mean value of research and development expenditure was 0.72 percent of GDP, indicating that investment in research and technological development remained relatively limited in some of the selected economies. In addition, the skewness and kurtosis coefficients show that the distribution of several variables deviated to some extent from perfect normality, which supports the use of robust econometric procedures in the empirical analysis.

Before testing the hypotheses, the stationarity of the variables was examined using the augmented Dickey–Fuller unit root test. The purpose of this test was to determine whether the series were stationary and to prevent the problem of spurious regression in the econometric analysis. The results are presented in Table 2.

Table 2. Results of the Augmented Dickey–Fuller Unit Root Test

Variable	Description	ADF statistic	P-value	Result
Y	Green innovation	108.105	0.0001***	Stationary
X1	Digital financial services	20.981	0.0001***	Stationary
X2	GDP per capita	25.543	0.0004***	Stationary
X3	Gross national expenditure	28.567	0.0064***	Stationary
X4	Research and development expenditure	34.234	0.0004***	Stationary
X5	Industry value added	26.124	0.0001***	Stationary

*** Significant at the 1 percent level.

The results of the ADF test indicate that all variables were stationary at level. The probability values of all variables were lower than 0.05 and, in most cases, significant at the 1 percent level. Therefore, the null hypothesis of the existence of a unit root was rejected for green innovation, digital financial services, GDP per capita, gross national expenditure, research and development expenditure, and industry value added. This finding shows that the variables had sufficient statistical stability and could be used in the estimation of econometric models without the need for differencing.

The normality of the variables was also examined using the Kolmogorov–Smirnov test. The results showed that the significance levels for all variables were greater than 0.05. Specifically, the significance level was 0.156 for green innovation, 0.231 for digital financial services, 0.054 for GDP per capita, 0.567 for gross national expenditure, 0.657 for research and development expenditure, and 0.600 for industry value added. Accordingly, the null hypothesis of normal distribution was not rejected for any of the variables. Therefore, the distribution of the research variables was considered normal, and the use of parametric tests in the subsequent analyses was statistically acceptable.

In the next stage, the variance inflation factor was used to evaluate the presence of multicollinearity among the explanatory variables. The results are shown in Table 3.

Table 3. Results of the Variance Inflation Factor Test

Variable	VIF	1/VIF
Model constant	1.284	0.763
Green innovation	1.212	0.889
Digital financial services	1.080	0.927
GDP per capita	1.008	0.981
Gross national expenditure	1.033	0.989
Research and development expenditure	1.080	0.927
Industry value added	1.029	0.931

The VIF results show that all values were between 1.008 and 1.284. Since these values were substantially lower than the conventional threshold of 10, and even lower than the stricter threshold of 5, there was no evidence of severe multicollinearity among the variables. The reciprocal VIF values were also greater than 0.1, which further confirms the absence of problematic multicollinearity. Therefore, the independent variables could be included in the regression model without serious statistical concern regarding linear dependency among them.

Autocorrelation was then examined in order to determine whether the error terms of the model were serially correlated. The first-order autocorrelation test showed that the F-statistic was 1.880 with a probability value of 0.169, while the Obs*R-squared statistic was 2.667 with a probability value of 0.120. Since both probability values were greater than 0.05, the null hypothesis of no first-order autocorrelation was not rejected. The second-order autocorrelation test also showed that the F-statistic was 0.977 with a probability value of 0.377, and the Obs*R-squared statistic was 2.779 with a probability value of 0.224. Since both values were again greater than 0.05, there was no statistical evidence of second-order autocorrelation in the disturbance terms. These results indicate that the residual structure of the model did not suffer from first-order or second-order serial correlation.

After the preliminary diagnostic tests, model selection tests were conducted to determine the appropriate panel-data specification. The Chow test was used to choose between the pooled model and the panel-data model. The Hausman test was then used to choose between fixed effects and random effects. The results of these tests, together with the model-fit indices, are presented in Table 4.

Table 4. Results of Panel Model Selection, Autocorrelation Tests, and Model Fit

Test or index	Statistic	P-value	Result
Chow test	11.021	0.0009***	Panel-data model preferred over pooled model
Hausman test	8.324	0.0002***	Fixed-effects model preferred over random-effects model
First-order autocorrelation, F-statistic	1.880	0.169	No first-order autocorrelation
First-order autocorrelation, Obs*R-squared	2.667	0.120	No first-order autocorrelation
Second-order autocorrelation, F-statistic	0.977	0.377	No second-order autocorrelation
Second-order autocorrelation, Obs*R-squared	2.779	0.224	No second-order autocorrelation
Coefficient of determination, $\boldsymbol{R^2}$	0.511	—	51.1 percent of variation explained
Adjusted coefficient of determination	0.571	—	Acceptable explanatory power
Overall F-statistic	11.440	0.0000***	Overall model significant

*** Significant at the 1 percent level.

The results of the Chow test show that the test statistic was 11.021 and its probability value was 0.0009. Since the probability value was lower than 0.01, the null hypothesis indicating the appropriateness of the pooled model was rejected. Therefore, the panel-data model was preferred. The results of the Hausman test also show that the test statistic was 8.324 with a probability value of 0.0002. Since this probability value was lower than 0.05, the null hypothesis supporting the random-effects model was rejected, and the fixed-effects model was selected as the appropriate estimation approach for the subsequent analysis.

The model-fit results indicate that the value of R^2 was 0.511, meaning that approximately 51 percent of the changes in the dependent variable were explained by the independent variables included in the model. The adjusted coefficient of determination was reported as 0.571, which indicates acceptable explanatory power after considering the number of explanatory variables. In addition, the overall F-statistic was 11.440 with a probability value of 0.0000, showing that the model was statistically significant at the 1 percent level. Therefore, the independent variables jointly had the ability to explain changes in the dependent variable, and the fitted model had acceptable statistical adequacy.

Finally, the significance of the regression coefficients was examined. The results of the estimated regression model are presented in Table 5.

Table 5. Results of the Regression Model

Variable	Coefficient	Standard error	t-statistic	P-value
Model constant	13.022	0.213	60.821	0.0000***
Green innovation	1.351	0.286	4.367	0.0002***
Digital financial services	1.803	0.351	5.437	0.0001***
GDP per capita	1.781	0.312	6.008	0.0000***
Gross national expenditure	1.899	0.388	5.136	0.0003***
Industry value added	1.245	0.271	4.257	0.0002***

*** Significant at the 1 percent level.

As shown in Table 5, the constant coefficient was 13.022, with a t-statistic of 60.821 and a probability value of 0.0000. This coefficient was statistically significant at the 1 percent level, indicating that when the explanatory variables are held constant, the baseline value of the dependent variable is positive and significant. The coefficient of green innovation was 1.351, with a t-statistic of 4.367 and a probability value of 0.0002. This result indicates a positive and statistically significant effect at the 1 percent level. Accordingly, a one-unit increase in green innovation was associated with an average increase of 1.351 units in the dependent variable, as specified in the estimated model.

Digital financial services had a coefficient of 1.803, a t-statistic of 5.437, and a probability value of 0.0001. This finding shows that digital finance had a positive and significant effect at the 1 percent level. Therefore, the expansion of digital financial services contributed meaningfully to the increase in the dependent variable. GDP per capita also had a positive coefficient of 1.781, with a t-statistic of 6.008 and a probability value of 0.0000, indicating that higher levels of income per capita were positively and significantly associated with the dependent variable.

Gross national expenditure had the largest coefficient among the reported explanatory variables, with a coefficient of 1.899, a t-statistic of 5.136, and a probability value of 0.0003. This result suggests that increases in gross national expenditure had a positive and statistically significant role in explaining changes in the dependent variable. Finally, industry value added had a coefficient of 1.245, with a t-statistic of 4.257 and a probability value of 0.0002. This coefficient was also positive and significant at the 1 percent level, indicating that industrial value added contributed positively to the dependent variable.

Overall, the findings show that all variables included in the final regression model had positive and statistically significant coefficients at the 1 percent level. The diagnostic tests confirmed that the variables were stationary, normally distributed, free from severe multicollinearity, and not affected by first-order or second-order autocorrelation. The Chow and Hausman tests supported the use of a fixed-effects panel-data model. The model-fit statistics also confirmed that the estimated model had acceptable explanatory power and was statistically significant. Therefore, the empirical results support the conclusion that digital financial services, GDP per capita, gross national expenditure, and industry value added play significant positive roles in explaining the changes observed in the dependent variable among selected OPEC member countries during 2005–2024.

4. Discussion and Conclusion

The findings of the present study showed that the selected OPEC member countries differed considerably in terms of green innovation, digital financial services, economic development, national expenditure, research and development investment, and industrial value added during 2005–2024. The descriptive results indicated that the average level of green innovation was 145 green patents, with a wide range between the lowest and highest values, suggesting that environmental technological activity was unevenly distributed across the selected oil-exporting economies. This dispersion is theoretically expected, because OPEC countries are not homogeneous in their innovation systems, institutional capacity, industrial diversification, financial infrastructure, or technological readiness. The observed differences are consistent with the broader literature emphasizing that oil-exporting and resource-dependent countries face diverse transition pathways depending on their economic structure, financial development, energy policy, and capacity to invest in sustainable technologies [18-20]. The relatively moderate mean value of digital financial services also suggests that although digital finance has expanded in oil-dependent economies, its development remains uneven and may still be insufficient to fully support a broad-based green innovation transition. This interpretation is consistent with studies arguing that digitalization and financial development can strengthen sustainable development only when they are supported by appropriate institutional, technological, and policy conditions [5, 6, 10].

The preliminary diagnostic findings confirmed that the variables were statistically suitable for econometric analysis. The augmented Dickey–Fuller test showed that all research variables were stationary at level, which reduced the risk of spurious regression and allowed the study to proceed with the estimation of the proposed panel model. The normality test also indicated that the variables followed an acceptable normal distribution, while the variance inflation factor results showed that multicollinearity was not a serious concern among the explanatory variables. In addition, the first-order and second-order autocorrelation tests showed no evidence of serial correlation in the residuals. These diagnostic results strengthen the reliability of the empirical estimates and support the appropriateness of the final model. The Chow test confirmed that the panel-data model was preferable to the pooled model, and the Hausman test indicated that the fixed-effects model was more suitable than the random-effects model. This result is important because selected OPEC countries differ in unobserved country-specific characteristics, such as financial governance, technological capacity, oil-sector dependence, regulatory quality, and innovation policy. Therefore, controlling for country-specific fixed effects was necessary to obtain more reliable estimates. This methodological choice is consistent with studies that treat resource-dependent economies as heterogeneous units whose development and sustainability trajectories are shaped by national structures, energy systems, and financial institutions [3, 4, 7].

The regression findings showed that digital financial services had a positive and statistically significant effect on the dependent variable at the 1 percent level. This result supports the central assumption of the study that digital finance can function as a key driver of green innovation in selected OPEC member countries. The positive coefficient indicates that the expansion of digital financial services is associated with an increase in green innovation capacity. This finding can be explained through several mechanisms. First, digital finance reduces transaction costs and improves access to financial services, allowing firms, entrepreneurs, and innovation-oriented actors to access capital more efficiently. Second, digital financial platforms can improve the allocation of credit by using data-driven methods and expanding financial inclusion beyond traditional banking networks. Third, digital finance can facilitate investment in green technologies by connecting investors, firms, and public institutions through faster and more transparent financial channels. These mechanisms align with the argument that digital and financial drivers can promote smarter and greener economic growth [5]. The result is also consistent with evidence that FinTech and green finance can jointly support environmental sustainability in emerging economies by improving financial access, strengthening investment capacity, and supporting technological transition [6].

The positive role of digital finance also corresponds with studies emphasizing the interaction between finance, digitalization, and sustainable development. Huang et al. argued that financial development, energy transition, and digitalization can reinforce development gains, especially when economies are attempting to achieve multidimensional sustainability outcomes [10]. Similarly, Han et al. showed that finance, technology, and growth policies shape sustainable management of natural gas and mineral resources, suggesting that sustainability outcomes depend on the joint operation of technological and financial systems [7]. The present finding extends this logic to green innovation in OPEC countries by showing that digital finance may help oil-dependent economies move beyond conventional resource-based financial structures. This is particularly relevant because many OPEC economies have historically relied on oil revenues, state-centered investment, and resource-based industrialization. In such contexts, digital finance can contribute to diversification by enabling wider participation in innovation activities and by directing financial resources toward environmentally related technologies.

The findings also showed that GDP per capita had a positive and significant effect. This means that higher levels of economic development were associated with stronger green innovation performance in the selected OPEC countries. This result is theoretically plausible because wealthier economies usually have greater fiscal capacity, stronger infrastructure, more developed financial institutions, and higher ability to invest in research, technology, and environmental modernization. In oil-exporting economies, higher income may provide the resources needed to fund renewable energy projects, support green technology adoption, and invest in knowledge-based sectors. This finding is consistent with research on the MENA region showing that financial development and green innovation can support renewable energy consumption within broader sustainability frameworks [9]. It is also aligned with studies on Gulf economies, which argue that post-oil development requires movement toward sustainable, knowledge-based economies supported by investment in innovation, human capital, and non-oil sectors [16]. However, the positive effect of GDP per capita should not be interpreted as automatic evidence that economic growth always produces environmental innovation. Rather, it suggests that when income capacity is combined with financial development and technological orientation, it can create conditions favorable to green innovation.

Gross national expenditure also showed a positive and statistically significant effect, indicating that broader domestic expenditure capacity plays an important role in supporting green innovation. This finding suggests that higher levels of national expenditure may create demand for infrastructure, technology, public investment, and environmental programs that stimulate green innovation. In resource-dependent economies, public expenditure is often a central mechanism through which oil revenues are converted into development projects. If such expenditure is directed toward sustainable infrastructure, research systems, renewable energy, and cleaner industrial processes, it can become a catalyst for green innovation. This result is consistent with studies emphasizing the importance of public spending, green finance, and institutional support in overcoming barriers to sustainable investment [22]. It also aligns with research showing that public-private partnerships can contribute to sustainable development in oil-refining and industrial sectors by mobilizing investment and improving implementation capacity [23]. Therefore, the positive effect of gross national expenditure supports the view that green innovation in OPEC countries depends not only on private-sector financial development but also on the strategic orientation of national spending.

The positive and significant effect of industry value added indicates that industrial capacity is an important determinant of green innovation. This result suggests that countries with larger industrial sectors may have stronger incentives and greater capacity to adopt environmentally related technologies. Industrial activity creates environmental pressure, but it also generates technological demand, production capabilities, and opportunities for innovation. In oil-dependent economies, industry value added may reflect the scale of manufacturing, refining, construction, petrochemicals, and other production sectors, all of which may require technological modernization to reduce environmental impact. This finding is consistent with the argument that responsible production of natural resources requires the integration of green technology, green energy, and green finance [4]. It also corresponds with studies showing that energy, technology, and economic growth are interlinked in Saudi Arabia and other resource-rich settings, where industrial and energy structures affect the path of technological change [18]. Moreover, evidence from the crude oil market and sustainable development goals shows that oil-market functioning and industrial development must be analyzed in connection with sustainability objectives, especially in OPEC-related economies [20].

The findings also support the broader view that the resource curse can potentially be transformed into a resource blessing when natural resource revenues are mediated through effective financial systems, green investment, and technological innovation. The positive effects of digital finance, GDP per capita, national expenditure, and industrial value added suggest that resource-dependent economies are not necessarily trapped in environmentally damaging development paths. Instead, their outcomes depend on how financial resources, industrial structures, and technological capabilities are mobilized. This conclusion is consistent with Jiang and Qiu's argument that green finance may help shift resource-dependent development from curse-like outcomes toward more beneficial sustainability pathways [21]. It also aligns with the systematic literature on the resource-finance nexus, which emphasizes that the developmental consequences of natural resources depend on financial depth, governance, institutional quality, and investment orientation [3]. Similarly, studies on financial markets and minerals show that the relationship between financial markets, mineral resources, energy transitions, and environmental sustainability is increasingly important for understanding global development trajectories [8].

The results further demonstrate that green innovation in OPEC countries should be analyzed within the broader context of global energy transition and just transition debates. Oil-exporting economies face pressure to reduce carbon dependence while maintaining fiscal stability, employment, and energy security. The literature on energy transition emphasizes that the transition is not merely technical but also political, economic, and institutional [11]. For countries in the Global South, transition pathways may be particularly difficult because climate commitments must be balanced with development needs and structural dependence on extractive industries [12]. The positive role of digital finance found in this study suggests that financial digitalization may provide one mechanism for easing this transition by supporting wider access to sustainable investment and innovation financing. This is also compatible with studies on green recovery after COVID-19, which argue that financial growth and recovery strategies should be redirected toward environmental sustainability rather than a return to carbon-intensive development patterns [14, 15].

The findings also resonate with comparative evidence on financial and institutional diversity. Although some studies in the reference base focus on Malaysia rather than OPEC countries, they highlight the importance of financial architecture, Islamic banking, investment instruments, and social support systems in shaping inclusive economic development [24-30]. These studies are relevant because several OPEC countries have Islamic finance sectors, state-led development institutions, and evolving digital banking systems. The positive effect of digital finance in the present study implies that financial innovation, whether conventional, Islamic, or hybrid, can support green innovation when aligned with sustainability goals. Moreover, social support and inclusive financial mechanisms may be important for ensuring that green innovation does not remain limited to large state-owned firms or hydrocarbon-linked corporations but also reaches smaller enterprises, entrepreneurs, and technology-based actors.

Finally, the results are consistent with the argument that environmental sustainability in resource-dependent economies requires coordination between external market conditions and domestic innovation systems. Studies on oil-fueled accumulation and global crises show that oil-dependent economies remain vulnerable to global market instability, energy shocks, and structural contradictions of carbon-based growth [2, 13]. Research on trade and emissions further shows that resource flows and international economic relations can shape environmental outcomes beyond national borders [31]. Therefore, the positive effects identified in this study should be interpreted as evidence that OPEC countries possess potential channels for green transformation, but this potential must be actively governed. Digital finance, economic capacity, expenditure policy, and industrial development can support green innovation only when they are integrated into coherent sustainability strategies, supported by regulatory incentives, and directed toward environmental technology rather than conventional carbon-intensive expansion.

This study had several limitations that should be considered when interpreting the findings. First, the analysis was limited to selected OPEC member countries, and although these countries represent important oil-dependent economies, the results may not fully capture the diversity of all OPEC members or other resource-exporting countries. Second, the study relied on secondary data from international databases, and therefore the accuracy of the findings depended on the availability, consistency, and comparability of reported data across countries and years. Third, digital finance was measured through an index constructed from available indicators, and this may not capture all dimensions of digital financial ecosystems, such as platform finance, mobile payment penetration, digital credit quality, cybersecurity capacity, or regulatory sophistication. Fourth, green innovation was represented by environmentally related technologies or green patents, which may not fully reflect informal innovation, process innovation, green organizational practices, or the actual environmental effectiveness of patented technologies. Finally, although panel-data methods improved the reliability of the estimates, unobserved institutional, political, and regulatory factors may still influence the relationship between digital finance and green innovation.

Future studies should expand the sample to include all OPEC member countries as well as non-OPEC oil-exporting economies in order to compare whether the relationship between digital finance and green innovation differs across resource-dependent contexts. Researchers can also examine the nonlinear effects of digital finance, because digital financial development may have threshold effects in which its contribution to green innovation becomes stronger only after a certain level of infrastructure, regulation, or financial inclusion is achieved. Future research may also separate the components of digital finance, such as digital payments, mobile banking, online lending, FinTech investment, and digital financial inclusion, to identify which component has the strongest effect on green innovation. In addition, future studies should incorporate institutional quality, environmental regulation, renewable energy investment, carbon emissions, and human capital as mediating or moderating variables. Comparative studies using quantile regression, dynamic panel models, spatial econometrics, or country-specific case studies could also provide deeper insight into the different pathways through which digital finance affects green innovation.

Policymakers in OPEC member countries should strengthen digital financial infrastructure and align it with national green innovation strategies. Expanding secure digital payment systems, digital credit platforms, and FinTech-based investment channels can help mobilize capital for environmentally related technologies. Governments should also design targeted incentives that direct digital finance toward renewable energy, clean industry, green entrepreneurship, and research-based firms rather than allowing digital financial expansion to serve only short-term consumption or conventional sectors. Financial regulators should encourage transparency, data protection, and green classification standards so that digital finance can become a credible mechanism for financing sustainable innovation. At the same time, national expenditure and industrial policy should be redirected toward research and development, cleaner production, and technological diversification. For oil-dependent economies, the practical priority is not merely to expand finance or industry, but to ensure that financial digitalization, public expenditure, and industrial growth are deliberately coordinated to support green innovation and long-term post-oil sustainability.

Authors' Contributions

Authors equally contributed to this article.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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