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The role of green industrial transformation in mitigating carbon emissions: Exploring the channels of technological innovation and environmental regulation

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ABSTRACT

The industrial sector is vital to economic progress, yet industrial pollution poses environmental and economic concerns. The purpose of the study was to investigate the influence of green industrial transformation in reducing Pakistan's carbon intensity between 1975 and 2020. Carbon emissions are considered an endogenous construct, while foreign direct investment (FDI) inflows, technological innovation, green industrial transformation, environmental legislation, and research and development (R&D) investment are possible mediators. The association between variables is assessed using the robust least-squares approach. Green industrial transformation is connected with lower carbon emissions, yet technical innovation, R&D investment, and inbound FDI raise a country's carbon emissions. The findings support the pollution haven hypothesis in a country. The causality estimates indicate that inward FDI contributes to environmental regulations; green industrial transformation directly relates to inbound FDI and R&D expenditures; and technological innovations correspond to inbound FDI, R&D expenditures, industrial ecofriendly progression, and environmental standards. According to the impulse response function, environmental policies are anticipated to have a differential effect on carbon emissions in 2023, 2024, 2028–2030, while they are likely to decrease in the years 2025–2027 and 2031 forward. Additionally, inward FDI and technology advancements would almost certainly result in a rise in carbon emissions over time. Green industrial transitions are projected to result in a ten-year reduction in carbon emissions. The variance decomposition analysis indicates that eco-friendly industrial adaptations would likely have the largest variance error shock on carbon emissions (11.747%), followed by inbound FDI, technological advancements, and regulatory changes, with R&D spending having a minimal impact over time. Pakistan's economy should foster a green industrial revolution to avoid pollution and increase environmental sustainability to meet its environmental goals.

1. Introduction

Climate change is a broad concept related to changes in the earth's climate on a local, regional, and global scale [1]. The reversal in the earth's climate is a consequence of human activity in industries, notably the burning of fossil fuels and the removal of trees from the land, which results in a massive rise in carbon emissions in the earth's atmosphere [2]. Climate change is caused by releasing greenhouse gasses such as methane and carbon. These gasses are produced by gasoline used in automobiles and coal, which generate heat in the atmosphere. The energy, transportation, industrial, and agricultural sectors are the primary polluters of the environment [3]. The industrial revolution began in 1750. Human activity in industries resulted in a rapid rise in the quantity of greenhouse gas (GHG) emissions in the atmosphere, slowing the heat loss from the planet and eventually causing warming [4–5]. While industrialization has historically been associated with wealth creation and improved living standards, it has a detrimental impact on the environment. It contributes to the acceleration of climate change [6]. It encompasses technical innovation and the social and economic revolutions that have created both new possibilities and new difficulties [7].

Abbreviations: ARDL, autoregressive distributed lag; CO2, carbon intensity; EREG, environmental regulation; FDI, foreign direct investment; GIT, green industrial transformation; GHG, greenhouse gas; GMM, generalized method of moments; R&D, research and development; RNDE, R&D expenditures; TINOV, technological innovation.

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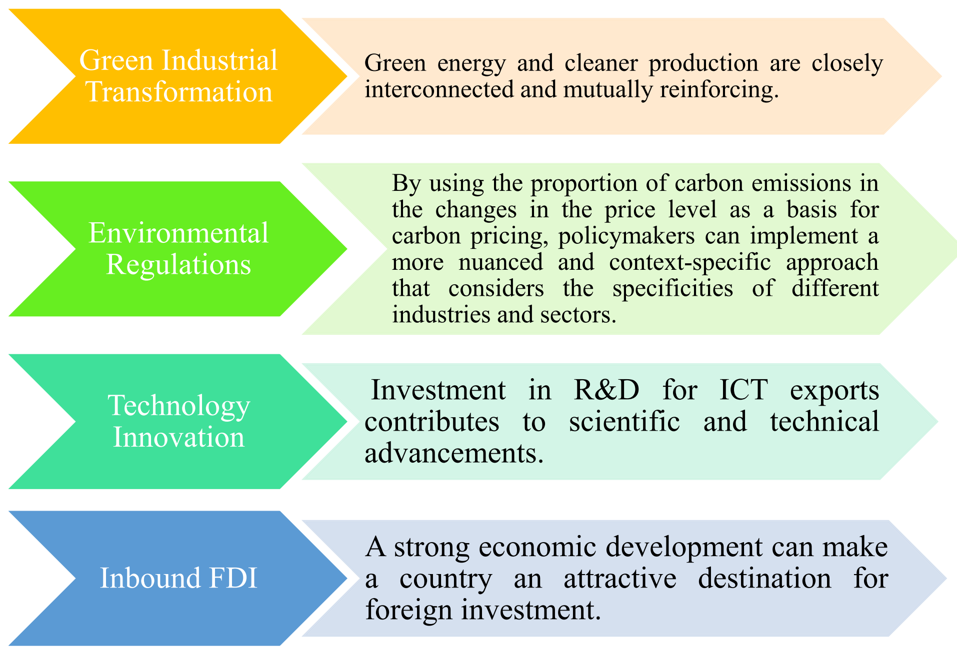

Fig. 1. An overview of factors that affect environmental quality. Source: Author's self extract.

The primary source of environmental deterioration is industrial pollution. It is the fundamental factor that transforms harsh climate into natural catastrophes. Not only does environmental pollution exacerbate natural disasters, but it also exacerbates secondary catastrophes that occur in the aftermath of catastrophic disasters [8–9]. The majority of industrial businesses are impacted by climate change due to increased carbon emissions in the environment, including steel, iron, cement production, and chemical and paper industries that are particularly energy-demanding [10]. Intensive production, waste, and an over-reliance on fossil fuels contribute to industrial emissions, but manufacturers are taking significant strides to reverse this trend. It focuses on enhancing the value chain, using more efficient production methods, and implementing the "reduce, reuse, recycle" philosophy, all of which contribute to the development of the manufacturing sector [11,12]. The green industrial transformation refers to the shift from a resource-intensive economy with high carbon emissions to a resource-efficient economy with low carbon emissions. It aims to promote sustainable development and economic growth. This process involves combining strategies such as renewable energy, circular economy, and decarbonization to create a sustainable and resilient industrial system [13]. The influential factors on environmental quality are illustrated in Fig. 1.

Pakistan has a very high and unacceptable degree of industrial pollution. Residents' health is primarily affected by the massive industrialization pollution [14]. Safe and clean drinking water is insufficient for consumption, and 70% of water in Lahore is contaminated and detrimental to human health due to industrial contamination [15]. Economic development and environmental deterioration are negatively connected [16]. Environmental deterioration has exacerbated the country's precarious predicament. Air pollution causes over 22,000 adult fatalities and 700 child deaths per year [17]. Industrial pollution is a big concern in Karachi, Pakistan's most polluted metropolis. Karachi confronts several difficulties related to air and water pollution. There are around 6000 enterprises in Karachi, yet none of them have a waste treatment facility. Karachi's industries degrade the environment and devastate its coastal regions, while the fishing, aviation, and agricultural sectors prepare for the danger of over ten million citizens [18]. Developing countries like Pakistan require financial support to overcome their socioeconomic challenges and make progress [19–20].

Climate change in Pakistan results from various consequences on the environment and people. As a consequence of climate change, Pakistan's climate has shifted significantly over the last several decades due to increased heat in some regions of the nation and the melting of glaciers, which threatens the country's majority of rivers. Pakistan was placed fifth in terms of harmful weather effects [21]. Pakistan's industries are chemicals, leather, textiles, fertilizer, paper, food, sugar, essential metals, cement, and car and engineering. In aggregate, these industrial operations generate enormous amounts of waste, gaseous pollutants, and smoke and dust emissions [22]. The COVID-19 pandemic has altered people's attitudes and behaviors towards consumption and production [23]. Democracy and the establishment have a role to play in addressing socioeconomic and geopolitical issues [24]. Pollution prevention is a more effective technique to combat pollution. "Source reduction" is a preventative strategy in which minimizing pollution results in less trash to dispose of and fewer obstacles to protecting the environment and public health [25].

1.2. Pakistan's industrial shift to a greener economy

Industrial structure transformation is critical for demonstrating a good shift toward progress via advanced industrial processes. Industrialization enables nations to make the most use of their natural resources, and the number of produced commodities contributes more to economic growth [26]. Industrial green transformation is critical in Pakistan to mitigate the destructive effects of industrial pollution on the environment and society and ensure the industrial sector's long-term viability [27–29]. Pakistan requires superior technology and development to accelerate the industrial transition toward lower carbon intensity and economic prosperity [30]. Because the industrial sector contributes to agricultural goods in Pakistan, people are increasingly concerned with the growth of manufacturing sectors via worldwide advancements in technology and environmental protection from climate change [31]. Green transformation of industries is necessary to meet the government's environmental goals while also achieving good economic growth and development [32].

Pakistan has developed a plan for environmental stability connected to the Sustainable Development Goals (SDGs), climate action, and land life. Pakistan intends to plant 10 billion trees over five years (2018–2023) and complete 1 billion trees Tsunami Afforestation in KPK from 2014 to 2019, which measures to mitigate emissions [33]. Because the development of a green economy promotes sustainable economic development, the government of Pakistan is accelerating its growth to achieve a green economy by safeguarding social values, public rights, and a livable environment through tax reforms and the enforcement of environmental laws. Carbon emissions in Pakistan reached a record 217 million tonnes in 2020, after a rate reduction of -0.43% [34]. Pakistan's goal for a healthy environment is to decrease net carbon emissions by more than 55% by 2030 and achieve carbon neutrality by 2050 [35]. There is an excellent opportunity to achieve Pakistan's social, environmental, and economic goals via industrial growth. Punjab's growth plan 2018 in Pakistan advocated that development be fueled by the private sector, a welcoming climate, investments, an emphasis on exports, a rise in jobs, and a healthy environment. Around 40% of Pakistan's industrial workforce is employed in the textile industry, which contributes 8% to the country's total GDP. About 354,000 tonnes of CO_2 emissions were reduced during five years. They contribute to private finances and participate in achieving Pakistan's SDGs. Pakistan's economy spurs action on climate change as part of the Paris accord [36]. America, Japan, and Russia actively promote industrialization on a massive scale. Pakistan is ranked 41st in the world in terms of industrial production. Pakistan's most prominent industries include cotton textile and clothing manufacture, which accounts for a significant portion of exports [37]. Green growth strategies are critical in Pakistan for addressing environmental issues that have a detrimental influence on the country's sustainable development pattern. Sustainable green development creates employment and income possibilities while minimizing environmental deterioration [38].

Based on the debate above, the following research questions evolved, i.e., to what degree is green industrial transformation advantageous in carbon emissions reduction? The utilization of cleaner energy and sustainable production technologies would be beneficial to reducing carbon intensity; consequently, it is vital to move towards sustainable production and consumption and realize green energy sources to enhance environmental quality in a nation. The second question is to what effect does technological innovation have on carbon emissions reduction? Sustainable technology advances give a pathway to attain green development objectives. However, it should conform to its environmental standards to continue economic output. Hence, the third research issue is connected to the environmental regulations that help minimize carbon intensity, i.e., how does environmental regulation relate to carbon emissions? The incentive-based environmental legislation and carbon price control measures would enhance environmental quality. The last research question is: does a country's pollution haven hypothesis hold? The inward FDI is the crucial factor that raises carbon output in the ease of environmental legislations, so it followed the pollution haven hypothesis. The research assessed the given hypothesis that helps comprehend the country's environmental policies towards reducing carbon emissions at a large scale. Based on the importance of the study matter, the following goals are established for research:

(i) To assess the influence of Pakistan's industrial transformation on the carbon intensity of the atmosphere.
(ii) To analyze the role of technological innovation in reducing carbon emissions.
(iii) To investigate the link between environmental legislations and carbon dioxide emissions, and
(iv) To elucidate the Pollution Haven Hypothesis in a country.

To determine the link between the variables in the causality analysis and intertemporal forecasting estimations, sophisticated statistical approaches such as the robust least squares regression approach, the Granger causality test, and the innovation accounting matrix would be used.

2. Literature review

The literature review is divided into two sub-themes that are described as follows: First, a review of the literature is conducted to determine the significance of green industrial transformation and environmental legislation in the context of carbon emissions reduction. Second, a literature review is conducted on technical advancements, inbound foreign direct investment, and carbon emissions. Both themes are critical to comprehend to formulate sustainable policies for the nation and the whole world.

2.1. Environmental legislation, carbon emissions, and green industrial transformation

Despite the abundance of research on industrialization, environmental laws, and carbon emissions, working on the mentioned issue remains a feasible choice due to a lack of sustainable policies to increase production, ecological regulations, and environmental quality. Ouyang et al. [39] investigated the contribution of several factors to reducing carbon emissions in various Chinese cities, using time series data from 2005 to 2015. The study used a generalized system technique for estimations. Investment in fixed assets, industrial structure, and energy efficiency are critical factors considered in this study. The findings reveal that industrial structure and fixed asset investment increase carbon emissions, while energy efficiency decreases carbon emissions. According to the research findings, improving industrial structures and upgrading environmental standards in China's heavy industries are recommended. Haseeb et al. [40] investigated the relationship between textile and garment production and carbon emissions in Asian nations from 1990 to 2018, using data from the World Bank. The Quantile and Quantile regression methods and Granger causality in the quantile technique were used in this work. The study's findings indicate that textile and garment production positively influences carbon emissions in Pakistan, India, and China. Textiles and clothing have a detrimental influence on carbon dioxide emissions in Vietnam. According to the research findings, the government should provide incentives and subsidies to investors in the industrial sector for mitigating carbon emissions and moving towards green industrial transformation. Ullah and Khan [41] explored the link between the green revolution and lowering carbon emissions in Pakistan from 1972-to 2014. The researchers utilized the Johansen cointegration and the ARDL bound test to analyze their link. The findings indicate a favorable long-term association between the industrial revolution and environmental quality. According to the research findings, green transformation minimizes carbon emissions and provides a way forward towards achieving sustainable development goals for Pakistan.

Majeed and Tauqeer [42] investigated the influence of urbanization and industrialization on deteriorating environmental quality in a panel of 156 countries from 1990-to 2014. The first and second-generation tests were employed in this investigation. Climate change, industrialization, urbanization; financial development; and economic expansion are all factors to consider. The findings indicate that urbanization and industry positively influence carbon emissions. Industrialization and urbanization need long-term reforms to ensure a sustainable environment. Neves et al. [43] used time-series data from 1995 to 2017 to examine the influence of environmental legislation, renewable energy use, and inbound FDI on carbon emissions in the European Union countries. The autoregressive distributed lag (ARDL) approach was used in this work for its analysis. According to the research findings, environmental restrictions are an efficient method of reducing carbon emissions. Consumption of renewable energy and inbound FDI negatively influence carbon emissions to support the pollution halo hypothesis and green energy embodied growth function across countries. Using data from 2008 to 2016, Zhang et al. [44] investigated the link between environmental regulations, overseas investment, and carbon emissions in 30 provinces of China. The threshold model was used in this investigation. The relationship between environmental regulation and carbon emissions is fashioned like an Inverted-U shape. Environmental legislation effectively controls emissions of carbon dioxide. It is critical to developing environmental policies to minimize carbon emissions, including carbon pricing, command-and-control mechanism, and incentives-

Table 1
A Literature Review on the Transition to Sustainable Manufacturing, Ecological Legislation, and Carbon Pollution.

Authors	Country	Time Period	Factors	Results
Wang et al. [48]	126 cities of China	2005–2017	Emission concentration, sustainable financing, environmental venture funding, scale of financial industry competition, and research and development	Credit and green venture capital have been essential in reducing CO_2 emissions in many places around China at the most current level of green finance.
Ali et al. [49]	Pakistan	1970–2019	Industrialization, population densification, and CO_2 emissions	Industrial expansion and population density both contribute to CO_2 emissions in the environment in the short term, but industrial growth has the potential to cut CO_2 emissions significantly in the long term.
Li et al. [50]	Pakistan	2000–2018	Carbon emissions, environmental protections, energy intensity, overseas investment, and density of population	In Pakistan, the quality of the environment was hampered by vertical budgetary imbalances. Industries are more supportive of green innovation when it comes to the structure of the environment.
Feng and Wu [51]	China	2000–2018	Structure of the industrial sector, social capital, urbanization, and Pollutant emissions	The restructuring of China's industrial structure has the effect of lowering CO_2 emissions.
Zhang and Chen [52]	China	2008–2017	Industrialization, rapid urbanization, and emissions of carbon dioxide	The rise in industrialization and urbanization is associated with a U-shaped connection in CO_2 emissions.
Muganyi et al. [53]	China	2011–2018	Green financing policies, carbon emissions	Green finance helps to reduce carbon emissions and motivates environmental projects that promote green consumption.
Sarwar and Alsaggaf [54]	Saudi Arabia	1970–2018	Effectiveness of governance, regulatory power, and Carbon intensity	Environmental regulatory authority and governance effectiveness have resulted in a decrease in CO_2 emissions.
Abid et al. [55]	Pakistan	2000–2017	competence of government, law and order, clean energy, and co2 emissions	gray analysis with the greatest value is an effective technique to mitigate the effects of CO_2 emissions in pakistan.
Qin et al. [56]	G7-countries	1990–2019	Environmental legislation, carbon dioxide emissions, green process innovation, green energy, and research and development spending	Environmental legislation and green innovation will aid in the reduction of the impact of carbon dioxide emissions.

based regulations. Using time-series data from 2005 to 2017, Xu and Lin [45] investigated the influence of environmental regulation, urbanization, and economic development in China. The quantile regression method was utilized in the analysis of the time-series data. The findings revealed that environmental legislation had the least impact on mitigating carbon emissions. According to the research findings, additional environmental regulations coupled with green energy sources and climate financing should be implemented to mitigate the effects of carbon emissions. Du and Li [46] investigated the link between environmental regulations and carbon pollution in China. It was conducted using time series data from 2000 to 2010, and both a panel fixed model and a meditative effect model were utilized in the analysis. The findings demonstrate that environmental regulations in China efficiently reduce the impact of carbon emissions from companies in the country. Using time-series data spanning 2006–2015, Wu et al. [47] investigated the link between environmental regulation, energy consumption, and carbon dioxide emissions in China. The generalized method of moments (GMM) approach was used in this investigation. According to the research findings, green energy and environmental legislation lowering the carbon emissions helps the country move forward towards green transformations. Table 1 summarizes a recent evaluation of the research on green industrial transformation and carbon emissions mitigation, emphasizing the mediating effect of environmental legislation globally.

Based on the cited literature, the following hypotheses have been proposed for future investigation, i.e.,

H1. *Industrial green transformation is projected to contribute significantly to lowering carbon emissions, and*

H2. *Environmental control would be likely to influence carbon emissions reduction significantly.*

2.2. Inbound FDI, technological innovation, and carbon emissions

A large amount of literature on the pollution haven/halo hypothesis, combined with environmental innovations that emphasized the need to improve ecological quality through sustainable technology transfers and stringent environmental regulations, has paved the way for cleaner production technologies. Malik et al. [57] looked at the long-term and short-term effects of inward FDI, oil prices, and economic development in Pakistan with time-series data covering the period 1971–2014. Both linear and nonlinear ARDL, as well as Granger causality, were used in the estimations. According to the findings, due to the asymmetric impact of industrialization, carbon emissions decreased in the long and short terms. Increasing urbanization and economic development have a favorable influence on lowering greenhouse gas emissions. Inward FDI and economic growth increase carbon emissions in the short and long-run to verify the pollution haven hypothesis in a country. The cleaner technology transfers and sustainable growth is pivotal for the long-term sustained growth of the country. Using the ARDL bound test and utilizing data from 1971 to 2014, Nadeem et al. [58] evaluated the association between overseas investment and environmental deterioration in Pakistan. The researchers in their investigation did not discover a definitive finding of the pollution haven hypothesis in a country. Sustainable climate financing and switching non-renewable to renewable fuels in production processes would allow a competitive edge over the rival firms to make the corporate profits more green and clean. Ahmad et al. [59] examined the link between overseas investment and carbon emissions using time-series data spanning 1984–2017 in Pakistan's agriculture sector. The ARDL and causality tests were used in this investigation. According to the study's findings, FDI influences agriculture sectors, but carbon emissions negatively impact the agricultural sector. It is essential to attract more inbound FDI in the agriculture sector that helps to attain green outcomes.

Munir andAmeer [60] used data from 1975 to 2016 to investigate the influence of inward FDI, industrialization, and economic development on environmental degradation. The Granger causality test was used in this investigation. The findings indicate that overseas investment and industrialization positively influence carbon dioxide emissions, which confirmed the pollution haven hypothesis and industrial-embodied emissions in a country. It is concluded that the government of Pakistan should take the lead in regulating the industrial sector to combat environmental degradation. Nguyen et al. [61] investigate the impact of inward FDI and trade on carbon emissions in 33 developing markets by analyzing data from 1996 to 2014. Following analysis of the data, it was discovered that the EKC hypothesis in 33 developing markets and overseas investment positively influenced carbon emissions. A long-term relationship exists between trade openness and carbon emissions. The findings showed that, rather than manufacturing sectors, international environmental standards should implement initiatives for enhancing trade openness and integrated FDI inflows in the flexible sector. In a study conducted between 1991 and 2017, Khan et al. [62] looked at the variations in the link between carbon emissions and technological innovation based on the industry studied. Quantile regression was used in this research, and the findings indicate a positive relationship between technological innovation and carbon emissions. The results conclude that technological innovations should align with the country's environmental standards that help lower carbon emissions make the industrial processes green and clean. Using data spanning 1980–2018, Villantenkodath and Mahalik [63] investigated the link between technological innovation and environmental quality in India. The findings demonstrate that technical progress and economic expansion harm the value of the environment. The research offers a technological innovation design that is environmentally friendly to lower CO2 emissions levels. In a study conducted between 1990 and 2007, Khan et al. [64] assessed the impact of energy and technological innovation on consumption-based carbon dioxide emissions in China. According to the findings, public-private investment and technological innovation significantly influence carbon emissions in the long term. The greenfield investment and eco-friendly innovations are desirable for the long-term sustained growth of the country. Bai et al. [65] looked at renewable energy, technological innovation, and carbon emissions in a panel of heterogeneous countries from 2000 to 2015. The panel fixed and panel threshold models were utilized to analyze this work. The results showed that consumption of renewable energy and technological progress positively influences the environment's carbon footprint. Alternative energy resources and environmental innovations are desirable for improving environmental quality across countries. Wang et al. [66] assessed the dynamic of carbon emissions in the N-11 nations from 1990 to 2017. Technological innovation, renewable energy, carbon emissions, and financial development are used in the study for analysis. The augmented mean group was utilized in the research. According to the findings, technological progress and renewable energy negatively influence carbon dioxide emissions across countries. The need for eco-friendly innovations and energy mix strategies are imperative for maintaining ecological quality. Table 2 shows the recent literature on pollution haven/halo hypothesis, environmental innovations and sustainable development across countries.

Based on the cited literature, the study formulated the following hypotheses, i.e.,

H3. *Technological advancements contribute significantly to the increase in carbon emissions in the environment, and*

H4. *The effect of inward FDI on carbon emissions is expected to have a negative impact.*

Using data from 35 countries in Sub-Saharan Africa between 2000 and 2014, Sun et al. [77] analyzed the correlation between sustainable development and pollution levels in the natural environment. Pollution rises as a function of per capita income but falls due to environmental entrepreneurship and human growth. Supports the EKC hypothesis and recommends laws to curb pollution while increasing green investment and entrepreneurship. According to Li et al. [78]'s research, managers in China's energy-intensive industries may learn how green innovation has affected company sustainability. Results show that green innovation boosts economic, ecological, and societal outcomes, and green publicity has a far more significant influence on environmental performance than recycling does on social performance. Using an extended STIRPAT model using panel quantile regression, Thio et al. [79] examine the variables that led to the most significant increases in carbon emissions in the top 10 carbon emitter nations between 2000 and 2014. Overpopulation, energy intensity, world commerce, and the purchase and sale of ICT are other significant contributors to environmental devastation, as is the level of personal yearly income. The study supports the EKC theory, offering suggestions for climate issues and encouraging innovation and energy conservation.

The present study contributes to the existing literature on sustainable development and environmental policy by filling some of the gaps in the literature from three different perspectives. Firstly, while earlier studies have mainly used industrial value added as a significant predictor that increases global carbon emissions [80–82], this study focuses on green industrial transformation to identify sustainable progress towards Pakistan's economic development. Secondly, unlike many previous studies that have used different environmental regulations, such as carbon tax, formal and informal regulations, and emissions-cap trading [83–85], this study employs a ratio of carbon emissions with respect to its price level to provide more accurate insights for handling environmental quality efficiently. Thirdly, while technological innovation is widely used as a critical predictor of the pollution damage function in the literature [86–88], this study considers the impact of technological intensification on the environment and the need for cleaner technologies to address environmental damages sustainably.

Moreover, the study employs two control variables, inbound FDI and R&D expenditures, to evaluate a country's pollution haven/halo hypothesis and innovation-led emissions hypothesis. In addition, robust least squares regression is used to estimate the relationship between carbon emissions and the independent variables, which accounts for potential outliers and model misspecification, providing more reliable estimates of the relationships between the variables. Impulse response function and variance decomposition analysis are also employed to examine the independent variables' short- and long-term effects on carbon emissions. These provide essential insights into the potential impacts of policy interventions to reduce carbon emissions and inform policy decisions to promote sustainable development and environmental protection.

In summary, this study contributes to the literature through innovative methods and variables employed and insights into the complex relationships between carbon emissions and the independent variables. The study is an essential addition to the broader literature on sustainable development and environmental policy by providing a more comprehensive analysis of the factors contributing to carbon emissions in Pakistan.

3. Data source and methodological framework

Table 3 shows the list of variables used and their expected relationship between them. Carbon intensity is the outcome variable that is influenced by the green industrial transformation, environmental regulations, technological innovation, inbound FDI and R&D expenditures. The time series data is collected from the World Bank [89] database for the stated variables in the context of Pakistan for a period of 1975–2020. Missing data is filled by the preceding and succeeding values of the respective variables, where required.

While acknowledging that patents are an essential metric of innovative activity, the study used R&D spending as a proxy variable to gage investment in human capital development. Our decision was based on the fact that R&D spending encompasses a broader spectrum of innovative activities than patent applications alone. Additionally, R&D spending reflects the quantity and quality of innovative activities, including basic research, applied research, and experimental development. These activities may only sometimes result in patentable inventions, yet they are critical for fostering a competitive edge over the long term. In the context of our research, investment in R&D spending is a superior gage of a nation's capacity to foster innovation and cultivate its human capital, promoting sustainable economic growth and green industrial transformation.

Table 2
A Review of the Literature on Inbound Foreign Investment, Climate Innovation, and Environmental Sustainability.

Authors	Country	Time period	Key Factors	Results
Wang et al. [67]	China	2000–2018	Carbon emissions, overseas investment, and scientific advancement	Direct investment and technical innovation have had a favorable influence on the impact of carbon emissions in the environment.
Tanveer et al. [68]	Pakistan	1985–2017	Carbon emissions, capital flows, financial deepening, energy usage, and globalization	Energy consumption and financial deepening contribute to environmental degradation, but overseas investment and globalization contribute to a reduction in carbon emissions.
Tan et al. [69]	China	1985–2018	Carbon emissions, capital inflows, capital formation, and energy demand	The use of energy and the expansion of financial markets have a substantial influence on air quality.
Balsalobre-Lorente et al. [70]	(EU-5) countries	1990–2015	Carbon footprint, clean energy, and direct investment	Foreign investment increases the amount of carbon emissions, and renewable energy reduces the level of effect of carbon emissions.
Hamid et al. [71]	Oman	1980–2019	Carbon emissions, capital inflows, economic expansion, and private investment	Direct investment, working capital, and economic expansion all have a strong influence on the rise of carbon emissions in the long term.
Zhao et al. [72]	62 countries	2003–2018	Innovation in technology, investment risk, and carbon emissions	Financial risk resulted in a decrease in carbon emissions, but technical innovation resulted in an increase in carbon emissions.
Cheng et al. [73]	35 OCED countries	1996–2015	Carbon emissions and technological advancements	Carbon emissions were mitigated through technological progress.
Weimin et al. [74]	46 developing economies	1990–2016	CO2 emissions, sustainable energy usage, overseas investment, and innovation	The influence of innovation has a positive impact on the environment's quality.
Ghazouani [75]	Tunisia	1980–2016	Capital, urbanization, carbon pollution, energy usage, and scientific innovation	Overseas investment and technical innovation have little impact on carbon emissions, however urbanization has an inverted-U shaped association with carbon emissions.
Adebayo and Kirikkaleli [76]	Japan	1990–2015	Renewable energy sources, product innovations, globalization, economic output, and air pollution	Economic Output, scientific advancement, and globalization all have a significant impact on carbon emissions.

Table 3
List of Variables.

Variables	Measurement	Symbol	Definition/Aim	Expected sign	Economic Rationale
Carbon Intensity	Kg/ kg of oil equivalent energy use	CO2	The amount of carbon released into the air per unit of energy used is referred to as the carbon intensity.	Huang et al. [90–92], Chen et al. [93].	
Green Industrial Transformation	Interaction term of Renewable energy & Industrial value added (US$)	GIT	Green industrial transformation increases resource utilization capability, reduces environmental damage, increases productivity, and strengthens the economy's capacity for sustainable growth.	Negative	Industrial transformation is the resulting factor of system innovation, collaborative governance, efficient urban land use, green finance, and environmental legislation.
Environmental Regulation	Ratio of carbon intensity to price level	EREG	Environmental regulations seek to protect the environment and public health from pollution caused by industrial and development operations.	Negative	Strict environmental rules, such as carbon taxes, emissions-cap trading, and a formal and centralized framework for emissions management, all contribute to emissions reductions.
Technological Innovation	ICT export (% of service export)	TINOV	Technological innovation refers to the process through which new technologies get integrated into manufacturing and consumption.	Positive	Technology-embodied emissions is verified in the resource constraints environment.
R&D Expenditures	% of GDP	RNDE	R&D expenditures are the funds spent on innovative work in order to develop new applications.	Positive	The hypothesis of innovation-driven emissions is substantiated in a resource-constrained context.
FDI Inflows	% of GDP	FDI	FDI inflow is the amount of inward direct investment made by foreign countries including non-resident investors.	Positive / Negative	The positive correlation between inbound FDI and carbon emissions supports the pollution haven hypothesis, while the negative correlation supports the pollution halo concept.

This study aims to examine the role of green industrial transformation in reducing carbon intensity in Pakistan. Pakistan faces numerous challenges related to carbon intensity. Pakistan is one of the countries most adversely affected by climate change and has polluted air due to the pollution caused by industry. Many pollutants from industrial activities are released into the atmosphere. Industrial pollution causes harm to the environment and all living things on the planet because of the waste of chemicals generated by companies, the emission of ionizing radiation, and the usage of pesticides. Additionally, it has negatively influenced economic development and social welfare. In the concept of green industrial transformation, reducing carbon emissions from the environment was established. Industries become more efficient and productive due to technological innovation and effective work organization methods. Regarding the emission objective, the industrial sector of Pakistan should take steps to stimulate green industrial transformation, which helps to reduce air pollution levels.

3.1. Theoretical underpinning

Cobb Douglas production function is a functional form of production function. It is used to represent the technological relationship among inputs and outputs. The Cobb Douglas production function was introduced by Charles Cobb and Paul Douglas. It is generally used function in macroeconomics, microeconomics, and forecast production because Cobb Douglas models have appropriate and logical properties. Cobb Douglas production function addressed a simple breakdown of economic growth in to its components. Economist approaches want a function of labor and capital as inputs and selection of best method of production to return output that can be produced by inputs so Cobb Douglas production function is broadly used.

The Cobb Douglas production function can be estimated as a non-linear relationship, i.e.,

$$\ln(y) = a_\circ + \sum_i a_i \ln(I_i)$$

The Cobb Douglas production function generally used in microeconomics modeling as follows:

$$Y = A\ L^{\alpha} K^{\beta}$$

Where L is a labor and K is a capital and A is total factor productivity.

When the sum of model exponent (α, β) is equal to 1, the production function is homogenous. Function displays constant return to scale mean that doubling the inputs, outputs will be double as well, i.e.,

$$\alpha + \beta = 1 \text{ (Constant return to scale)}$$

When the sum of model exponent (α, β) is < 1, the production function is decreasing return to scale. Function display decreasing return to scale when inputs are double, output will be half of inputs, i.e.,

$$\alpha + \beta < 1 \text{ (Decreasing return to scale)}$$

When the sum of model exponent (α, β) is > 1, the production function is increasing return to scale. Function display increasing return to scale when inputs are double, outputs will be double more than inputs, i.e.,

$$\alpha + \beta > 1 \text{ (Increasing return to scale)}$$

We have a Cobb Douglas production function

$$y = A\ \ L^{\alpha}\ \ K^{\beta} \tag{1}$$

We take natural logarithm

$$\ln(y) = lnA + \alpha lnL + \beta lnK + u$$

$$\ln(y) = c + \alpha lnL + \beta lnK + u \tag{2}$$

Where c= lnA

Putting value of $\alpha = 1 - \beta$ in Eq. (2)

$$\ln(y) = c + (1-\beta)lnL + \beta \ln K + u$$

$$\ln(y) = c + lnL - \beta lnL + \beta lnK + u$$

$$\ln(y) - lnL = c - \beta lnL + \beta lnK + u$$

$$ln\ (y) - lnL = c + \beta(lnK - lnL) + u \tag{3}$$

$$Y^* = c + \beta\left(K^*\right) + u$$

The study conducted a substitution of the variable 'economic growth' in Eqs. (1)–(3) with 'carbon emissions', as it is widely recognized that economic activities contribute significantly to environmental pollution due to economies of scale in production. Additionally, the variable 'capital stock' was substituted with inbound FDI and green industrial transformation to reduce carbon emissions, further supported by stringent environmental regulations. Similarly, the variable 'labour stock' was replaced by investment in human capital development through R&D spending. Consequently, the resulting Eq. (4) can be expressed as follows:

$$CO2 = \beta_0 + \beta_1 GIT + \beta_2 EREG + \beta_3 TINOV + \beta_4 RNDE + \beta_5 FDI + u \tag{4}$$

Where, CO2 shows carbon intensity, GIT shows green industrial transformation, EREG shows environmental regulation, TINOV shows technological innovation, RNDE shows R&D expenditures, FDI shows inward FDI, and u shows error term.

Taking natural log on both sides of the equation

$$\ln(CO2) = ln\beta_0 + ln\beta_1 GIT + ln\beta_2 EREG + ln\beta_3 TINOV + ln\beta_4 RNDE + ln\beta_5 FDI + u \tag{5}$$

Where lnβ ∘=c

$$\ln(CO2) = c + ln\beta_1 GIT + ln\beta_2 EREG + ln\beta_3 TINOV + ln\beta_4 RNDE + ln\beta_5 FDI + u \tag{6}$$

The theoretical expectations of Eq. (6) is as follows:

$\frac{\partial CO2}{\partial GIT} < 0$ The higher the green industrial transformation, the lower the emissions concentration.

$\frac{\partial CO2}{\partial EREG} < 0$ The greater the stringent environmental regulations, the lowering the carbon intensity in the atmosphere.

$\frac{\partial CO2}{\partial TINOV} > 0$ The increase in the technological innovation leading to higher carbon intensity in a country to substantiate technological-embodied emissions.

$\frac{\partial CO2}{\partial RNDE} > 0$ The higher the R&D expenditures, more emissions are expected to release to support economic growth, and

$\frac{\partial CO2}{\partial FDI} > 0$ The greater the inward foreign investment, the greater is the chance to emit more pollutants into the atmosphere that verified the pollution haven hypothesis.

3.2. Econometric framework

The study used the following statistical techniques to analyze the variables relationship between them, i.e.,

(i) Robust Least Squares Regression
(ii) Granger Causality Analysis, and
(iii) Innovation Accounting Matrix

When data is affected by influential observations, the robust least square regression method is used instead of the standard least square regression method. It is used to identify the most influential observations. When there are many influential observations in the data, robust regression produces better estimates of the regression coefficients. Robust regression is less susceptible to outliers than traditional regression. Robust least squares are better regressions because they minimize a subsequent component's influence in the regression model, which is advantageous. There are three techniques of estimating accessible, which are as follows:

1. M-estimation
2. S-estimation, and
3. MM-estimation

M-estimation was established by Huber [94] as a stand for (maximum likelihood method). When there is a particular outlier in the dependent variable, the amount of the residual is enormous. M-estimation is used in order to overcome the enormous residual. S-estimation was first developed by Rousseeuw and Yohai [95]. When there is an outlier in an independent variable, the variables are significantly different from the mean (high leverage). S-estimation is used in order to overcome large leverage. Yohai [96]) was the first to present the MM-estimation method. It is a safe strategy that uses a mix of S-estimation and M-estimation to predict the outcome. It informs us of outliers in both the dependent and independent variables. The cross-panel technique is widely used in the recent era that need to get benefit for sound parameter inferences [97].

Granger causality analysis is performed after obtaining the parameter estimates by the Robust least squares regression method. The purpose of the analysis is to identify the four alternative and plausible hypotheses, i.e.,

I) Unidirectional Causality:

The stated variables follow the unidirectional causation between them, i.e.,

CO2→GIT→EREG→TINOV→RNDE→FDI

II) Reverse Causality:

The stated variables follow the revere causality relationship between the variables, i.e.,

FDI→RNDE→TINOV→EREG→GIT→CO2

III) Bidirectional Causation:

The candidate variables follow the two-way linkages between them, i.e.,

CO2↔GIT↔EREG↔TINOV↔RNDE↔FDI

IV) No Causality Relationship:

The studied variables not follow the causality pattern between them, although may have a highly correlation in the regression instruments, i.e.,

CO2↔GIT↔EREG↔TINOV↔RNDE↔FDI

Eq. (7) shows the stated relationships between the variables in the vector autoregressive (VAR) framework, i.e.,

$$\begin{bmatrix} CO2_t \\ GIT_t \\ EREG_t \\ TINOV_t \\ RNDE_t \\ FDI_t \end{bmatrix} = \begin{bmatrix} \tau_0 \\ \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \end{bmatrix} + \sum_{i=1}^{p} \begin{bmatrix} \sigma_{11t}\sigma_{12t}\sigma_{13t}\sigma_{14t}\sigma_{15t} \\ \sigma_{21t}\sigma_{22t}\sigma_{23t}\sigma_{24t}\sigma_{25t} \\ \sigma_{31t}\sigma_{32t}\sigma_{33t}\sigma_{34t}\sigma_{35t} \\ \sigma_{41t}\sigma_{42t}\sigma_{43t}\sigma_{44t}\sigma_{45t} \\ \sigma_{51t}\sigma_{52t}\sigma_{53t}\sigma_{54t}\sigma_{55t} \\ \sigma_{61t}\sigma_{62t}\sigma_{63t}\sigma_{64t}\sigma_{65t} \end{bmatrix} \times \begin{bmatrix} CO2_{t-1} \\ GIT_{t-1} \\ EREG_{t-1} \\ TINOV_{t-1} \\ RNDE_{t-1} \\ FDI_{t-1} \end{bmatrix} + \sum_{j=p+1}^{d\max} \begin{bmatrix} \theta_{11j}\theta_{12j}\theta_{13j}\theta_{14j}\theta_{15j} \\ \theta_{21j}\theta_{22j}\theta_{23j}\theta_{24j}\theta_{25j} \\ \theta_{31j}\theta_{32j}\theta_{33j}\theta_{34j}\theta_{35j} \\ \theta_{41j}\theta_{42j}\theta_{43j}\theta_{44j}\theta_{45j} \\ \theta_{51j}\theta_{52j}\theta_{53j}\theta_{54j}\theta_{55j} \\ \theta_{61j}\theta_{62j}\theta_{63j}\theta_{64j}\theta_{65j} \end{bmatrix} \times \begin{bmatrix} CO2_{t-j} \\ GIT_{t-j} \\ EREG_{t-j} \\ TINOV_{t-j} \\ RNDE_{t-j} \\ FDI_{t-j} \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} \tag{7}$$

Eq. (8) is simplified by using VAR(2) model of multivariate system, i.e.,

$$\begin{aligned} CO2_t &= c_1 + \sum_{i=1}^{2} \beta_1 CO2_{t-i} + \sum_{i=1}^{2} \beta_2 GIT_{t-i} + \sum_{i=1}^{2} \beta_3 EREG_{t-i} + \sum_{i=1}^{2} \beta_4 TINOV_{t-i} + \sum_{i=1}^{2} \beta_5 RNDE_{t-i} + \sum_{i=1}^{2} \beta_6 FDI_{t-i} + \varepsilon \\ GIT_t &= c_1 + \sum_{i=1}^{2} \beta_1 GIT_{t-i} + \sum_{i=1}^{2} \beta_2 CO2_{t-i} + \sum_{i=1}^{2} \beta_3 EREG_{t-i} + \sum_{i=1}^{2} \beta_4 TINOV_{t-i} + \sum_{i=1}^{2} \beta_5 RNDE_{t-i} + \sum_{i=1}^{2} \beta_6 FDI_{t-i} + \varepsilon \\ EREG_t &= c_1 + \sum_{i=1}^{2} \beta_1 EREG_{t-i} + \sum_{i=1}^{2} \beta_2 GIT_{t-i} + \sum_{i=1}^{2} \beta_3 CO2_{t-i} + \sum_{i=1}^{2} \beta_4 TINOV_{t-i} + \sum_{i=1}^{2} \beta_5 RNDE_{t-i} + \sum_{i=1}^{2} \beta_6 FDI_{t-i} + \varepsilon \\ TINOV_t &= c_1 + \sum_{i=1}^{2} \beta_1 TINOV_{t-i} + \sum_{i=1}^{2} \beta_2 GIT_{t-i} + \sum_{i=1}^{2} \beta_3 EREG_{t-i} + \sum_{i=1}^{2} \beta_4 CO2_{t-i} + \sum_{i=1}^{2} \beta_5 RNDE_{t-i} + \sum_{i=1}^{2} \beta_6 FDI_{t-i} + \varepsilon \\ RNDE_t &= c_1 + \sum_{i=1}^{2} \beta_1 RNDE_{t-i} + \sum_{i=1}^{2} \beta_2 GIT_{t-i} + \sum_{i=1}^{2} \beta_3 EREG_{t-i} + \sum_{i=1}^{2} \beta_4 TINOV_{t-i} + \sum_{i=1}^{2} \beta_5 CO2_{t-i} + \sum_{i=1}^{2} \beta_6 FDI_{t-i} + \varepsilon \\ FDI_t &= c_1 + \sum_{i=1}^{2} \beta_1 FDI_{t-i} + \sum_{i=1}^{2} \beta_2 GIT_{t-i} + \sum_{i=1}^{2} \beta_3 EREG_{t-i} + \sum_{i=1}^{2} \beta_4 TINOV_{t-i} + \sum_{i=1}^{2} \beta_5 RNDE_{t-i} + \sum_{i=1}^{2} \beta_6 CO2_{t-i} + \varepsilon \end{aligned} \tag{8}$$

The null and alternative hypothesis is tested through chi-square statistics as follow:

H_0: $\beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 0$
H_A: $\beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq \beta_6 \neq 0$

The rejection of the null hypothesis verified one out of four stated Granger causal relationships between the variables. After obtaining the Granger causality estimates, the study estimated impulse response function (IRF) and variance decomposition analysis (VDA) in the innovation accounting matrix. Both the techniques used for forecasting the relationships between the variables over a time horizon. The IRF estimates suggested the directions between the variables over time, whereas, the VDA estimates suggested the error variance shocks between the variables in the next preceding years. Eq. (9) shows the innovation accounting equation, i.e.,

$$\begin{aligned} &Var(\sigma(CO2, GIT) = Var(E[\sigma \perp GIT]) + E[Var(\sigma \perp GIT)]c \\ &\Rightarrow Var(E[\sigma \perp GIT]) \leq Var(\sigma[CO2, GIT)] \\ &Var(\sigma(CO2, EREG) = Var(E[\sigma \perp EREG]) + E[Var(\sigma \perp EREG)] \\ &\Rightarrow Var(E[\sigma \perp EREG]) \leq Var(\sigma[MCO2, EREG)] \\ &Var(\sigma(CO2, TINOV) = Var(E[\sigma \perp TINOV]) + E[Var(\sigma \perp TINOV)] \\ &\Rightarrow Var(E[\sigma \perp TIONV]) \leq Var(\sigma[CO2, TINOV)] \\ &Var(\sigma(CO2, RNDE) = Var(E[\sigma \perp RNDE]) + E[Var(\sigma \perp RNDE)] \\ &\Rightarrow Var(E[\sigma \perp RNDE) \leq Var(\sigma[CO2, RNDE)] \\ &Var(\sigma(CO2, FDI) = Var(E[\sigma \perp FDI]) + E[Var(\sigma \perp FDI)] \\ &\Rightarrow Var(E[\sigma \perp FDI]) \leq Var(\sigma[CO2, FDI)] \end{aligned} \tag{9}$$

Eq. (10) show sthe mean suqare error (MSE) for the provided set of explanatory variable,s i.e.,

$$\begin{aligned} MSE_\mu &= E_{GIT}[MSE_\mu(GIT)] \\ MSE_\mu &= E_{EREG}[MSE_\mu(EREG)] \\ MSE_\mu &= E_{TINOV}[MSE_\mu(TINOV)] \\ MSE_\mu &= E_{RNDE}[MSE_\mu(RNDE)] \\ MSE_\mu &= E_{FDI}[MSE_\mu(FDI)] \end{aligned} \tag{10}$$

4. Results and discussion

The descriptive statistics for the variables are shown in Table 4. Carbon intensity ranges from 1.109 kg per kg of oil equivalent energy usage to 1.741 kg, with an average value of 1.510 kg. The standard deviation is 0.177 kg, indicating a negatively skewed distribution with a high peak. The proportion of carbon intensity to the cost of carbon emissions grows

Table 4
Descriptive Statistics.

Methods	CO2	EREG	FDI	GIT	RNDE	TINOV
Mean	1.510	0.101	0.818	1064.588	0.227	14.003
Maximum	1.741	0.077	3.668	1332.087	0.632	22.884
Minimum	1.109	0.016	0.062	823.617	0.109	6.519
Std. Dev.	0.177	0.067	0.772	157.898	0.124	3.597
Skewness	-0.692	1.421	2.296	-0.081	1.869	-0.397
Kurtosis	2.658	4.455	8.216	1.479	5.932	3.580

Note: CO2 shows carbon intensity, EREG shows environmental regulations. FDI shows inbound FDI, GIT shows green industrial transformation, RNDE shows R&D expenditures, and TINOV shows technological innovations.

Table 5
Correlation Matrix.

Variables	CO2	GIT	EREG	TINOV	RNDE	FDI
CO2	1					
	——					
GIT	-0.761	1				
	(0.000)	——				
EREG	0.483	-0.593	1			
	(0.000)	(0.000)	——			
TINOV	-0.250	0.310	0.099	1		
	(0.092)	(0.035)	(0.511)	——		
RNDE	0.585	-0.558	0.004	-0.742	1	
	(0.000)	(0.000)	(0.975)	(0.000)	——	
FDI	0.553	-0.391	0.007	-0.503	0.810	1
	(0.000)	(0.007)	(0.960)	(0.000)	(0.000)	——

Note: CO_2 shows carbon intensity, EREG shows environmental regulations. FDI shows inbound FDI, GIT shows green industrial transformation, RNDE shows R&D expenditures, and TINOV shows technological innovations. Small bracket shows probability value.

with a maximum value of 0.077% and an average of 0.101%. The lowest standard deviation value, 0.067%, corroborated the values' proximity to the mean value with a positively skewed distribution and a high kurtosis value. Inbound FDI and R&D expenditures account for around 0.818% of GDP and 0.227% of GDP, respectively. The percentage of inward FDI in a nation's GDP is much more than the share of R&D expenditures in a country, indicating that the respective country has limited innovation skills and relies on outside investors to spend vast amounts on R&D to boost the country's GDP. On the other hand, unsustainable investment tends to increase carbon emissions, indicating the presence of a pollution haven hypothesis in a country. The phrase "green industrial transformation" refers to the interaction between renewable energy and industrial value-added, which provides synergy to the country's financial operations to boost environmentally friendly industrial output. The average cost of green industrial transformation is US$1064.588, with a high of US$1332.087 and a low of US$823.617. It is about equal to the average per capita income of the nation. Technological innovation is employed as an export factor for ICT, with a maximum value of 22.884% and a minimum value of 6.519%, with an average value of 14.003%. The negatively skewed distribution and high kurtosis value, together with a high standard deviation value of 3.597%, demonstrate the considerable variability in the corresponding data series that much exceeds the mean value. As a result, its divergence may impact the country's long-term objective.

Table 5 presents the correlation estimations, revealing a negative link between green industrial transformation and carbon emissions (r = -0.761, $p < 0.000$). Consequently, the higher the percentage of green energy in industrial production, the more environmentally friendly the output, resulting in improved environmental quality. However, there is a positive link between environmental regulations and carbon emissions, indicating that environmental regulations are insufficient to reduce carbon emissions since the cost of carbon emissions exacerbates air pollution, which harms the country's sustainability agenda. As a result, it is critical to go forward with strict carbon pricing, command-and-control mechanisms, and incentive-based regulations that obstruct a country's filthy output. The negative but insignificant relationship discovered between technological innovation and carbon emissions suggests a promising future for reducing carbon emissions by increasing technological innovation infrastructure in a country, which would be beneficial to achieving the green development agenda in the future. The positive association between R&D expenditures and carbon emissions, while incoming FDI is positively connected with carbon emissions, suggests a nation is a pollution haven. Increased R&D spending attracts more foreign investors into the country, who engage in unsustainable production, causing the country's environmental quality to deteriorate. As a result, it is critical to limit it through strict environmental regulations and invest in eco-friendly products to reduce carbon emissions.

Before estimating the parameter coefficients, it is prudent to inspect the leverage plots of the regressors, which enables the appropriate functional specification of the regression apparatus to be chosen. For convenience, Fig. 2 depicts the regressors' leverage graphs.

Fig. 2 confirmed that the model's regressors spread around the average value of the respective variables, particularly in the green industrial transformation, technological innovation, and R&D expenditures, indicating the presence of some potential outliers in the given model. Therefore, further verification of the outliers is necessary using another test, i.e., influential statistics, which provides potential model outliers. The relevant statistics for identifying outliers in the model are shown in Fig. 3.

Fig. 3 depicts two apparent outliers in the RStudent test that fall outside the stated thresholds. In the provided model, the Hat Matrix test reveals a single outlier. The DFFITS test has three outliers, while the COVRATIO test has four potential outliers. As a result, after confirming the presence of probable outliers in the given model, the traditional cointegration test and its unit root process are uncertain; thus, the study used the Robust least squares S- estimation approach to deal with outliers in the regressors. Table 6 shows the estimations for ready reference.

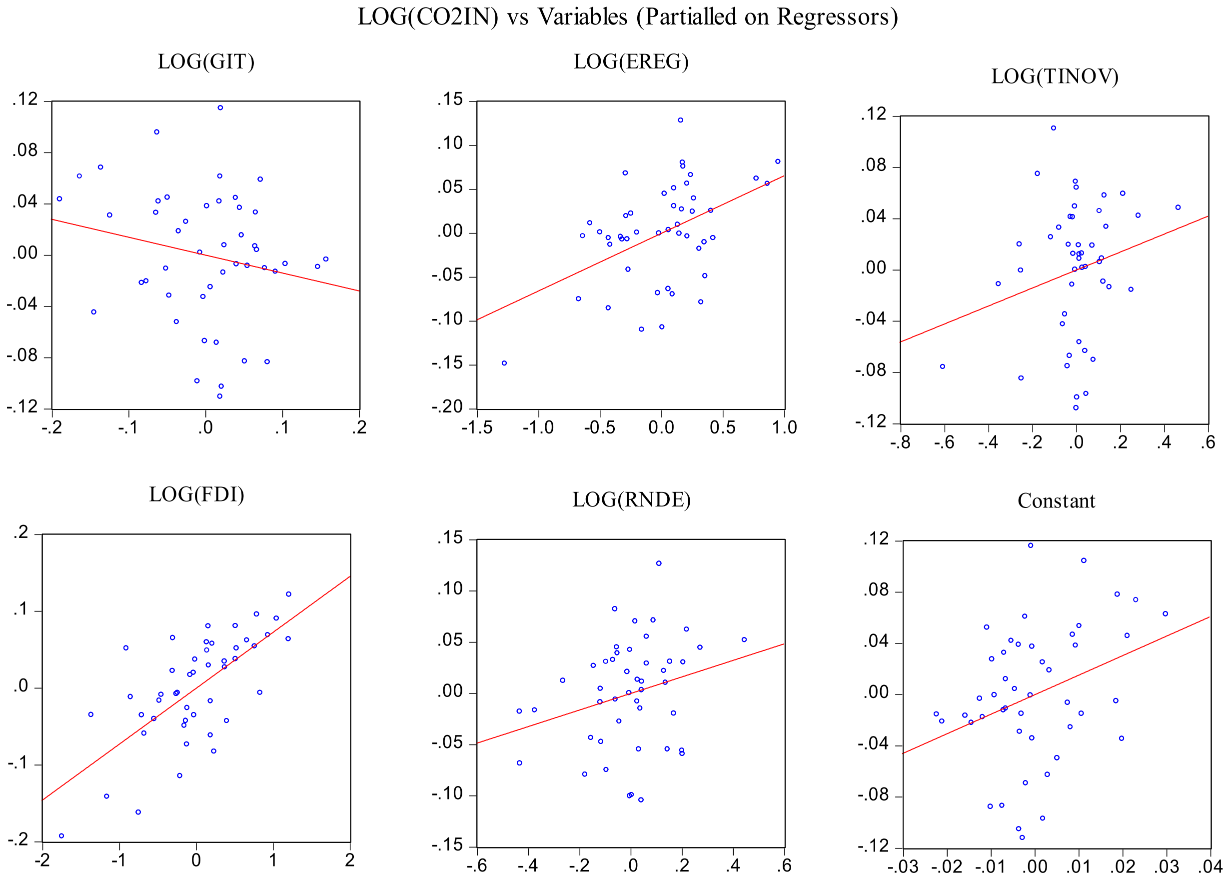

Fig. 2. Leverage Plots. Source: Author's estimation. Note: CO_2 shows carbon intensity, EREG shows environmental regulations. FDI shows inbound FDI, GIT shows green industrial transformation, RNDE shows R&D expenditures, and TINOV shows technological innovations. Small bracket shows probability value.

Table 6
Robust Least Squares Regression: S- Estimates.

Dependent Variable: ln(CO2)				
Variables	Coefficient	Std. Error	z-Statistic	Prob.
ln(GIT)	-0.252	0.079	-3.170	0.001
ln(EREG)	0.008	0.014	0.561	0.574
ln(TINOV)	0.083	0.036	2.304	0.021
ln(RNDE)	0.075	0.035	2.112	0.034
ln(FDI)	0.038	0.009	4.143	0.000
C	2.135	0.525	4.066	0.000
Robust Statistics				
R^2	0.670	Adjusted R^2	0.629	
Scale	0.040	Deviance	0.001	
Rn^2	165.558	Prob(Rn^2)	0.000	
Non-robust Statistics				
Mean dependent var	0.405	S.D. dependent var	0.123	
S.E. of regression	0.075	Sum squared resid	0.229	

Note: CO_2 shows carbon intensity, EREG shows environmental regulations. FDI shows inbound FDI, GIT shows green industrial transformation, RNDE shows R&D expenditures, and TINOV shows technological innovations.

The findings indicate a negative association between green industrial transformation and carbon emissions, with a 1% rise in green industrial transformation resulting in a -0.252% drop in carbon intensity. The result implies that the greater the proportion of renewable energy sources in the industrial production process, the greater the degree to which carbon intensity is reduced in a country. The government should be required to increase the proportion of renewable energy sources in the conventional energy mix since this would aid in the expansion of environmentally friendly industrial output and reduce carbon emissions. Significant reductions in carbon emissions necessitate shifting to a more sustainable and low-carbon energy mix, supported by these findings. Moreover, it highlights the need to promote renewable energy technology as a crucial part of any all-encompassing approach to reducing CO2 emissions. Countries can make substantial progress in reducing their carbon footprint by enacting policies and incentives that encourage the adoption of renewable energy sources in their industrial production processes. They can minimize their carbon intensity and help spur green industrial transformation and long-term economic development. According to Li et al. [98], upgrading the local industrial structure would be beneficial in improving environmental quality and enabling

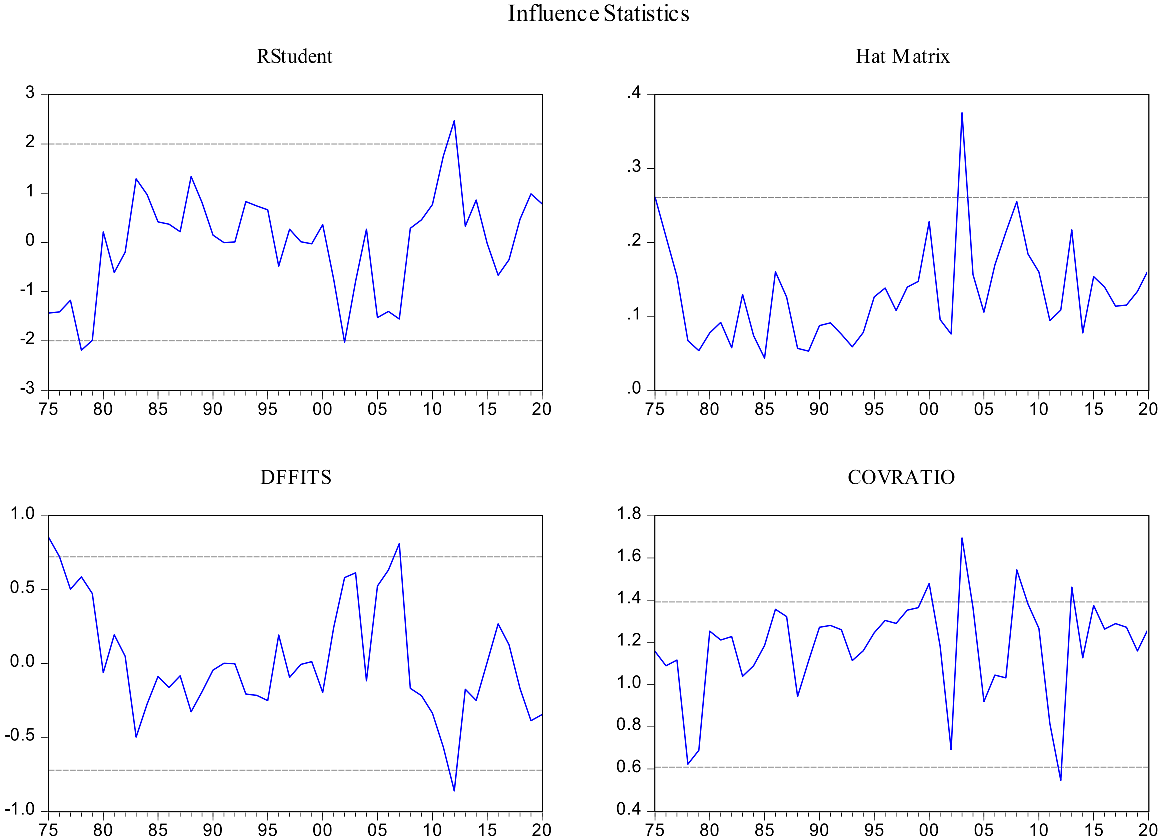

Fig. 3. Influence Statistics. Source: Author's estimation.

the manufacturing of environmentally friendly products to get underway more quickly. According to Xu et al. [99], the necessity to restructure the industrial structure in conjunction with technology transformation would be beneficial in materializing environmental advantages that would shift dense manufacturing cities towards green transformation. Shen et al. [100] discovered that climate finance, sustainable financial development, and natural tax legislation might all be used to boost the green transformation agenda, therefore assisting businesses in their transition to more environmentally friendly manufacturing. Zhai and An [101] concluded that to meet the difficulties of climate vulnerability and ecological devastation; industrial enterprises must strengthen their green transformation processes to keep the average world temperature below 1.5 °C. Qin et al. [56] argued that global countries must strengthen their innovation capabilities, increase their share of renewable energy sources, improve industrial capacities to adopt cleaner technologies, and spend an enormous amount of money on green research and development activities for mitigating global carbon emissions.

There is a positive association between technical innovation and carbon emissions; if technological innovation increases by one percent, carbon emissions rise by 0.083%. Since technological progress often results in increased productivity and output, which in turn may lead to increased energy consumption and, therefore, carbon emissions, this positive correlation may be explained. Moreover, the shift to new technologies sometimes necessitates the elimination of older, less efficient systems, which might cause an increase in emissions at that time. Nevertheless, there may be diminishing returns to innovation in terms of its influence on emissions, and the link between the two is sometimes linear. The environmental effect of an invention may also depend on factors such as the nature of the innovation and the context in which it is used. Emissions may be reduced if new technologies were developed to increase the efficiency of renewable energy sources, but the converse is true of fossil fuels. As a consequence of this finding, green innovation is critical in pursuing the carbon neutrality target. A beneficial influence of innovation on carbon emissions mitigation is impossible in resource limits. As a result, sustainable environmental policies must be developed in conjunction with strong environmental laws to address climate change vulnerability in a nation. Zeng et al. [86] said that the rate of adjustment in innovation efficiency is relatively low in reducing carbon emissions. The need to promote green energy sources and innovative skills as part of the environmental agenda would be beneficial in addressing economic and environmental concerns. Wang et al. [67] point out that technological innovation increases the energy intensity of manufacturing processes, causing carbon emissions to increase. As a result, it is critical to replace fossil fuels with renewable energy sources in the product mix to achieve greater energy efficiency. Chen et al. [102] emphasized the importance of increasing green innovation capabilities in the manufacturing process. Technological innovation generates carbon emissions that can be reduced by increasing green R&D spending, sustaining economic growth, and transferring knowledge to the next generation. Bilal et al. [103] emphasized the need to spread green innovation via technology transfers, which would be beneficial to thrive in the globalized competitive period, get an advantage in creating environmentally friendly products, and reap long-term profits. Suki et al. [104] said that the advancement of industrial technology raises the need for more sophisticated technologies and robotic intelligence to enhance the quality of the environment. When it comes to achieving the stated goal of transforming industrial output into green industrial transformations via sustainable technology transfers, the involvement of green energy sources may be quite beneficial.

There is a direct association between research and development expenditure and carbon emissions on the one hand. On the other hand, there is a direct relationship between incoming foreign direct investment and carbon emissions. Because of this, more R&D expenditures in a nation are likely to attract more foreign investors, who in turn may

Table 7
Diagnostic Tests Estimates.

Variables	VIF values	Residual-based Tests	Calculated value	Probability value
ln(GIT)	3.869	Jarque-Bera	0.786	0.674
ln(EREG)	2.201	Heteroskedasticity Test: Breusch-Pagan-Godfrey	1.918	0.112
ln(TINOV)	3.132	CUSUM	Within the 5% critical value	$P < 0.050$
ln(RNDE)	6.380	CUSUM Square	Within the 5% critical value	$P < 0.050$
ln(FDI)	1.733			

Note: CO2 shows carbon intensity, EREG shows environmental regulations. FDI shows inbound FDI, GIT shows green industrial transformation, RNDE shows R&D expenditures, and TINOV shows technological innovations.

contribute to the degradation of the country's environmental quality via colossal production and consumption as a consequence of excessive foreign investment. These results substantially impact companies and authorities working to lessen the environmental damage caused by economic activity. Mainly, they draw attention to the need to enact laws and incentives that stimulate investment in low-carbon technology and processes and promote adopting environmentally friendly practices in the sectors that attract FDI. The findings also point to the need for policies that encourage and facilitate the spread of low-carbon technology to offset the environmental damage that may emerge from R&D funding. The study's findings confirmed the concept that a nation is a pollution sanctuary. To minimize filthy production in a country, the government must act strategically by enacting stringent environmental rules, including statutory and informal regulations, or a combination of the two. Using a channel of growth-intensive national economic strategies mixed with dirty production, Lee et al. [105] discovered that inbound FDI and R&D spending both deteriorate environmental quality, thereby verifying the pollution haven hypothesis. The necessity for environmentally friendly programs driven by investment and protectionist measures would be beneficial in improving environmental quality. Alam et al. [106] suggested a method of mitigating carbon emissions by investing in research and development activities to allow more money to be invested in cleaner energy sources and enable the country's focus to shift toward green investment. According to Ma et al. [107], the imposition of environmental taxes, investments in renewable energy sources, environmental innovation, and tertiary sector development are some of the few sustainable strategies that would be beneficial to improving ecological standards and environmental quality in developing countries. Bakhsh et al. [108] found that lower institutional quality and technological innovation confirmed the pollution haven hypothesis. The fact that institutional variables are practical in establishing environmental rules that must be severe to regulate filthy manufacturing is critical. Establishing a green technological base is essential for converting the negative parts of incoming foreign direct investment into the positive transfer of cleaner technologies inside a nation. As a result, the production and consumption processes would be environmentally friendly, attracting environmentally friendly enterprises to enter the manufacturing process and gain a competitive advantage over their competitors, resulting in continuous economic benefits. The diagnostic data for the regression model are shown in Table 7.

The findings indicate that the variance inflation factor (VIF) is less than the threshold value of 10, indicating no issues with multicollinearity amongst the regressors throughout the regression test. As a result, the robust least squares regression test is accurate and reliable. The remaining three tests of normality, heteroskedasticity, and model stability, showed that the regression residual is normally distributed and Homoscedastic in structure and identified a stable model at the 5% level of confidence. As a result, the study more advanced estimating strategies. Fig. 4 depicts the CUSUM and CUSUM square tests.

Table 8 shows the VAR Granger causality test and its revealed that inbound FDI induces environmental regulations, implying that more inward FDI necessitates more stringent environmental laws to limit a country's carbon emissions. The feedback link between R&D expenditures and inbound FDI is discovered, implying that both are mutually beneficial; as R&D expenditures increase, inward FDI increases as well, and reverse causality also exists between them. Thus, it is feasible to raise R&D spending to attract foreign investors, which eventually increases a country's R&D expenditures on innovation. Technology innovation Granger cause inbound FDI, R&D spending, and green industrial transformation. The causation implies that technological innovation is critical for attracting more inbound FDI, innovative capabilities, environmental policies, and green industrial transformation. Industrial green transformation Granger causes inbound FDI and R&D expenditures, implying that foreign investment and increased investment in innovation processes contribute to developing a country's green industrial infrastructure.

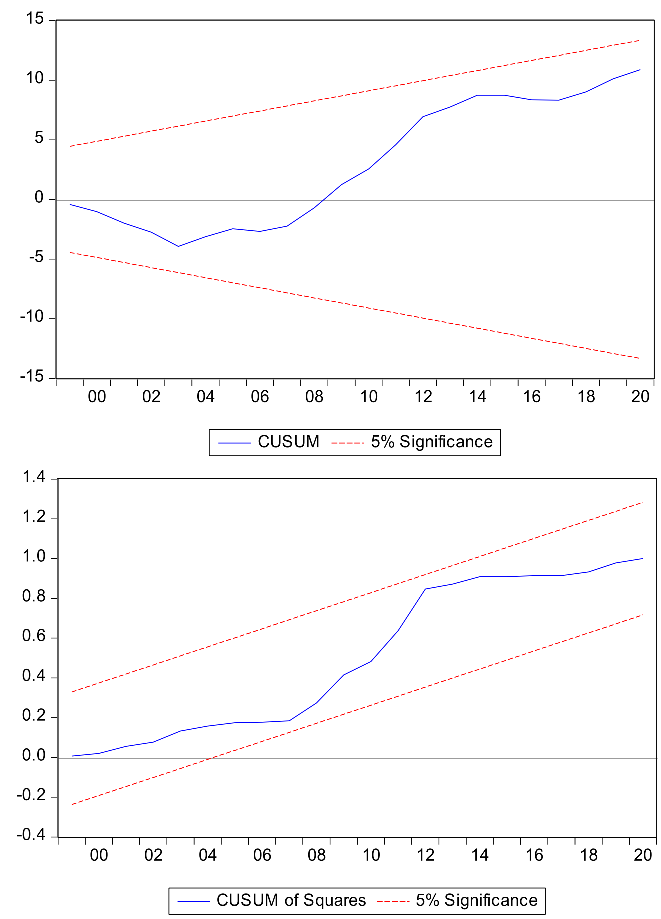

Fig. 4. Stability Test Estimates. Source: Authors estimate.

The IRF estimates in Table 9 indicate that inbound FDI is likely to directly influence the carbon intensity of a country, hence supporting the future pollution haven hypothesis. On the other hand, green industrial transformation is anticipated to affect carbon intensity over time nega-

Table 8
VAR Granger Causality Estimates.

One-way Causality	Two-way Causality	Policy Conclusion
FDI → EREG	RNDE ↔ FDI	- FDI-led environmental regulations - R&D strengthens the inbound FDI and FDI have the same effect.
TINOV → FDI		Innovation-led inward FDI
TINOV → RNDE		Innovation-led R&D expenditures
TINOV → GIT		Innovation-led green industrial transformation
TINOV → EREG		Innovation-led environmental regulations
GIT → FDI		Green industrial transformation-led inward FDI
GIT → RNDE		Green industrial transformation-led R&D expenditures

Note: FDI shows inward FDI, TINOV shows technology innovation, RNDE shows R&D expenditures, GIT shows green industrial transformation, and EREG shows environmental regulations.

Table 9
IRF Estimates.

Period	CO2	EREG	FDI	GIT	RNDE	TINOV
2022	0.039621	0	0	0	0	0
2023	0.030388	0.001480	0.012045	-0.001689	-0.002042	0.000543
2024	0.030078	0.001096	0.010462	-0.008728	0.001685	-0.003353
2025	0.029184	-0.002521	0.008085	-0.011667	-0.000648	-0.007987
2026	0.023435	-0.001432	0.005060	-0.011618	0.001766	-0.005750
2027	0.022167	-0.000141	0.002788	-0.011392	0.000847	-0.002452
2028	0.019638	0.001231	0.002536	-0.010447	0.001386	0.001356
2029	0.019067	0.001275	0.002513	-0.010846	0.000751	0.004683
2030	0.018201	0.000632	0.002708	-0.011132	0.000276	0.006067
2031	0.017529	-0.000392	0.002732	-0.011915	-0.000260	0.006561

Note: CO2 shows carbon intensity, EREG shows environmental regulations. FDI shows inbound FDI, GIT shows green industrial transformation, RNDE shows R&D expenditures, and TINOV shows technological innovations.

Table 10
VDA Estimates.

Period	S.E.	CO2IN	ER	FDI	IGT	R_DE	TI
2022	0.039621	100	0	0	0	0	0
2023	0.051457	94.16151	0.082721	5.479534	0.107688	0.157418	0.011132
2024	0.061265	90.52883	0.090332	6.781403	2.105344	0.186716	0.307371
2025	0.069837	87.13326	0.199778	6.559198	4.411059	0.152309	1.544398
2026	0.075001	85.30986	0.209683	6.142202	6.223978	0.187483	1.926794
2027	0.079126	84.49653	0.188713	5.642706	7.664947	0.179903	1.827207
2028	0.082264	83.87117	0.196964	5.315393	8.704036	0.194832	1.717607
2029	0.085317	82.97049	0.205450	5.028571	9.708503	0.188878	1.898110
2030	0.088197	81.89821	0.197390	4.799742	10.67766	0.177724	2.249274
2031	0.090988	80.66374	0.187326	4.600011	11.74767	0.167810	2.633438

Note: CO2 shows carbon intensity, EREG shows environmental regulations. FDI shows inbound FDI, GIT shows green industrial transformation, RNDE shows R&D expenditures, and TINOV shows technological innovations.

tively. Environmental regulations, R&D expenditures, and technological innovation are likely to disjoint carbon intensity. Environmental regulations are likely to decrease carbon intensity between 2025 and 2027 and 2031 onward, whereas R&D expenditures likely decrease carbon intensity between 2025 and 2031 onward. While technological innovation is projected to reduce carbon intensity between 2023 and 2027, it is also likely to raise carbon emissions later in the decade. As a result, it is critical to developing stringent environmental regulations that facilitate knowledge transfer, raise R&D investments, and provide sustainable climate finance choices for carbon mitigation.

The VDA estimations in Table 10 indicate that green industrial transformation is projected to have a greater variance shock on carbon intensity during the coming decade. From 2023 to 2031, the effect of green industrial transformation would be 0.107%, increasing to 11.747% by 2031. Similarly, FDI is predicted to have a larger effect on carbon intensity, which is projected to grow from 5.479% in 2023 to 6.781% in 2024. However, its proportion is steadily declining and will reach 4.600% by 2031. Another potential factor is technological innovation, which has a variance error shock of 2.633% on carbon emissions over a time horizon. The least affected factor would be R&D spending, which would vary by 0.167% by 2031.

5. Conclusions and policy recommendations

Industrial green transformation is critical to encourage less carbon-intensive growth while creating a healthy environment and sustainable development. The study aims to analyze the influence of green industrial transformation on Pakistan's efforts to decrease carbon intensity by analyzing data spanning 1975–2020. Based on the findings, green industrial transformation is a strong predictor of carbon intensity reduction and a significant reduction in emissions intensity throughout a country. Technology innovation, R&D expenditures, and inbound FDI are responsible for increasing carbon intensity and confirming the pollution haven hypothesis in a country. According to the causality estimates, inward FDI Granger causes environmental regulations, whereas technology innovation Granger causes inward FDI, R&D expenditures, green industrial transformation, and environmental regulations in a country. The green industrial transformation causes inward FDI and R&D expenditures, which remains a viable policy option for attracting sustainable FDI and increasing innovation expenditures to move forward in environmental sustainability. The finding of bidirectional causation between R&D expenditures and inbound FDI implies that both factors are going in the same direction; as a result, if one factor's performance improves, it will eventually impact the other's productive efficiency. Policymakers must consider the factors that have been identified to enhance the country's environmental performance. According to the IRF's predictions, the green industrial transformation will most likely result in a reduction in carbon intensity over the next ten years; as a result, it is critical to establish industrial policies that are more strategically oriented for the nation. Moreover, according to the VDA estimations, the share of influencing carbon intensity would likely significantly impact promoting green industrial performance, technological innovation, and environmental legislation over time.

Environmental and economic policies should be designed in such a manner that they minimize the intensity of emissions while simultaneously improving economic activity. In addition, the following policy proposals are made:

(i) It is possible to reduce waste produced by changing the manufacturing process.
(ii) Rather than throwing away waste material, it should be recycled into new items.
(iii) It is more effective to decrease environmental emissions by imposing a carbon price and using cap-and-trade systems.
(iv) To limit pollutant emissions into the environment, the government should encourage energy efficiency and analyze new comprehensive systems for economic growth.
(v) Encourage cleaner manufacturing as a means of preventing pollution, which will result in a more cost-effective and less expensive investment.
(vi) Encouraging the use of environmentally friendly goods improves the quality of life while also securing the planet's future.
(vii) Pollutants are removed before reaching the atmosphere, which is a more efficient method of reducing emissions.
(viii) The industrial sector should pay close attention to the projects involving foreign investment and the use of foreign pollution technology in order to limit carbon emissions.
(ix) The industrial sector should stimulate the development of low-carbon technologies and expand the country's economic growth.
(x) The industrial sector must promote energy efficiency and assess new comprehensive economic growth systems to limit pollutant emissions into the environment.
(xi) Policymakers should focus their efforts on fostering research and development projects that directly reduce carbon emissions.
(xii) The government should be required to restrict the export of high-intensity technologies and decrease the high levels of carbon emissions.

The government may significantly encourage particular businesses by building an enabling environment that encourages sustainable practices and incentivizes investment in green technology and industries:

(1) Establishing policies and incentives to stimulate investment in green technology and sectors, such as tax cuts, subsidies, and grants for research and development.
(2) Creating pollution rules, waste reduction goals, and energy efficiency mandates to encourage sustainable business practices.
(3) Promoting public-private partnerships to facilitate green industrial transformation and cooperation amongst government, academic institutions, and businesses in creating and implementing sustainable solutions.
(4) Spending money on programmes that educate and train people to work in green industries and technology, and
(5) Creating a green finance system to offer money for green initiatives and stimulate investment in sustainable sectors.

Various potential future research directions might expand upon the results of this study. First, further study may be done on what policies and actions governments in Pakistan can take to encourage green industrial transformation. Criteria include looking at the results of carbon pricing methods and tax breaks for environmentally friendly projects. Second, the correlation between the independent factors and carbon emissions may be explored in more depth in future studies. For instance, the research could be done to determine which technological advancements or investments in R&D have the most significant effect on lowering greenhouse gas emissions. Third, future research might broaden the scope beyond Pakistan to assess the success of green industrial transformation programmes in other nations and areas. Such an analysis may provide light on the applicability and efficacy of similar strategies in other settings. Finally, future research might investigate the influence of energy efficiency and renewable energy legislation and the impact of consumer behavior on carbon emissions. Overall, further study in these areas may provide light on how to best craft policies to cut carbon emissions in Pakistan and other nations in a similar position.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Saima Mehmood: Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Khalid Zaman:** Software, Formal analysis, Writing – review & editing, Supervision. **Shiraz Khan:** Conceptualization, Formal analysis, Writing – review & editing. **Zohaib Ali:** Formal analysis, Writing – review & editing. **Haroon ur Rashid Khan:** Resources, Visualization, Data curation, Validation, Writing – review & editing.

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