How Can Green Finance and Technological Innovation Transform Sustainable Performance Across G20 Nations?

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Abstract

Achieving sustainable goals involves leveraging private sector investments in renewable energy sources. The global surge in demand for alternative renewable energy and green finance has spurred extensive research in these domains. Throughout the study period, the evaluation of sustainable practices is conducted through the environmental, social, and governance (ESG) pillars. This study investigates the impact of green finance, green energy, and green economic development with the moderation of technological innovation by utilizes secondary data spanning from 2011 to 2020 across G-20 countries. Using the fixed effects method, the results confirm significant relationships between sustainability, green finance, economic development, GDP, and technological innovation. Green finance, green energy, and green economy development negatively impact sustainability, while technological innovation shows a positive effect. However, the moderating role of technological innovation negatively influences sustainability when combined with green finance. The findings are robust and validated through Driscoll-Kraay (D-K) standard error estimation. Policymakers should prioritize reforms in green finance policies to ensure they effectively contribute to long-term sustainability goals. Moreover, fostering a stronger integration of technological innovation with green economic development can significantly enhance the outcomes of sustainability in the G-20 countries. Encouraging investments in both green energy and innovation, along with the regulatory frameworks that promote sustainable development, will be crucial to advancing environmental sustainability while achieving economic growth.

Keywords: Green finance; Green Energy; sustainable practices; technological innovation; ESG; Green Economy; G-20

Introduction

In recent decades, the issue of climate change has garnered significant attention from researchers, scholars, climate activists, and governmental authorities (Razzaq et al., 2021; Sun et al., 2021). The international community has raised concerns about some environmental changes, including but not limited to climate change, desertification, destruction of tropical rainforests, erosion of coastal ecosystems, depletion of soil resources, overfishing, an end to species, and biodiversity loss. The rapidly deteriorating global atmosphere has become a major issue that affects all of humanity, particularly when it comes to ensuring access to fresh water, food production, land use, environmental balance, and human welfare (Kartal et al., 2022; Li & Haneklaus, 2022; Shan et al., 2021).

A collection of seventeen interrelated Sustainable Development Goals (SDGs) that are closely linked to the Five P's—planet, people, prosperity, peace, and partnership—make up the 2030 Agenda for Sustainable Development, or Agenda 2030. Within this framework, 17 sustainable goals have been designed to collectively address urgent global concerns relating to social injustice, environmental degradation, and climate change (Khaled et al., 2021). The implementation of instruments targeted at achieving these goals requires national efforts to be coordinated by creating SDG roadmaps and progress reports for each nation and encouraging international multi-stakeholder partnerships. No matter how developed or developing a country is categorized as, this requirement still applies (Plastun et al., 2022).

However, an evident concern in the context of these sustainable objectives is the seeming absence of sincere dedication and compliance by corporate organizations. In particular, research from (PwC, 2019) shows that around 72% of businesses prominently use the term "sustainable development goals" (SDGs) in their reports. On the other hand, just twenty percent have put quantitative measures in place to actively work towards these objectives. This strengthens the case that a sizable portion of companies and sectors still fail to implement strategies that result in noticeable advantages for a sustainable environment (Awais, Shah, Abidy, & Scholar, 2018; Zhuang et al., 2022).

A significant gap exists in the theoretical and empirical literature regarding how companies and related industries might evaluate their actions concerning the SDGs. Within this framework, corporate sustainability performance becomes a crucial indicator of how well an industry or company is contributing to these sustainable objectives (Arayssi & Jizi, 2019). However, the use of environmental, social, and governance (ESG) scores—a combination known as ESG—in the assessment of sustainable performance has gained support in the research. These results demonstrate a dedication to non-monetary objectives that correspond with efforts made towards sustainable development (Halbritter & Dorfleitner, 2015; Paolone et al., 2022). According to studies by Kocmanová and Šimberová (2014) and Kocmanová et al. (2011) and it is important to incorporate ESG indicators into the corporate strategy. Their results highlight the need for financial indicators to be supplemented because they alone are unable to provide a complete picture of overall performance.

The persistent rise in carbon dioxide (CO2) emissions raises concerns, particularly for the nations heavily dependent on fossil fuels for their economic advancement. Economic advantages have been prioritized over environmental well-being in these countries, which are frequently categorized as emerging economies with insufficient technological progress. Their heavy reliance on imported and local fossil fuels to meet their energy needs has resulted in significant environmental damage (Udeagha & Ngepah, 2019, 2023). Reducing CO2 emissions is widely acknowledged as being essential, with a focus on striking a balance between environmental conservation and economic growth. As a result, scholars are investigating many elements, such as green finance (GFN) and financial technology (fintech), in order to formulate approaches for cultivating a sustainable and environmentally conscious global environment (Udeagha & Ngepah, 2023).

Green financing and technological innovation enable industries to embrace and promote E.S.G. Green technological innovation is a reflection of states' determination to stop environmental degradation, especially through technological developments in the energy economy and the production of green energy. It makes the money flow from industries that produce large amounts of carbon dioxide and pollution to those that use cutting-edge technologies. According to Zhang and Wang (2021), the green finance contributes to the enhancement of ecological sustainability and management, acting as a remedy for environmental damage. The capacity of green finance to bring industrialized and developing nations together in the common fight against pollution is one of its main advantages. The green finance framework directs promising investments and financing for environmentally conscious projects (Muganyi et al., 2021).

In addition, researchers are intensively studying how clean and green energy can be used to curb environmental degradation and influence the direction of sustainable performance. Green and eco-friendly energy consumption shows negligible environmental impact and presents itself as a solution for attaining sustainable results. Simultaneously, clean and green energy sources are undergoing significant ongoing development (Li et al., 2019; Razzaq et al., 2021). However, using conventional or non-renewable energy sources is frequently thought to be cheaper and more cost-effective. But doing so comes at the cost of using more non-renewable energy, which could result in higher greenhouse gas emissions. Therefore, the literature emphasizes how important it is to use clean energy in order to achieve sustainable results, stressing how important it is to not undervalue its function (Awais, Kashif, & Raza, 2020; Hillerbrand, 2018; Midilli et al., 2006; Razzaq et al., 2021).

The term "green economy" first appeared over two decades ago (Barbier, 2011). The green economy, which is positioned as a long-term approach to navigating economic crises, strives for poverty reduction, economic recovery, and the simultaneous reduction of carbon emissions and prevention of ecological destruction (Barbier, 2011). A "green economy" is one that promotes social justice and human well-being while minimizing negative ecological effects, according to the United Nations Environment Programme (UNEP, 2011). Thus, pursuing green growth which is consistent with the idea of a green economy contributes naturally to sustainable development (Kasztelan, 2017; Ohotina, 2016). However, continuous work is necessary to create global models and scenarios that evaluate national "green economy" and "green" growth strategies (Kasztelan, 2017).

This study investigates the impact of green financing and green economy development on sustainable practices through technological innovation in G20 countries over the 2012-2022 period. The inclusion of G-20 nations in this research is motivated by their significant influence in international negotiations and environmental protection accords, particularly due to the migration of industries from developed to G-20 economies. This industrial migration, driven by the stringent environmental regulations in established economies and lower production costs in developing nations, has resulted in an increased CO2 emission, surpassing those of other growing economies (Udeagha & Ngepah, 2023). Previous literature has mentioned many other factors that affect sustainability such as energy efficiency (Rasoulinezhad & Taghizadeh-Hesary, 2022), economic growth (Ning et al., 2023), green financial development (He et al., 2019), corporate social responsibility (Awais, Khan, Hassan, & Ishaq, 2023; Guang-Wen & Siddik, 2022), and previous research was mainly focused on G7 countries (Yang et al., 2022) but the literature lacks a comprehensive analysis of how green financing, green economy development, and technological innovation interact specifically in the G-20 context.

Furthermore, Polzin and Sanders (2020); Zhang and Wang (2021) highlight the role of green finance in promoting sustainable renewable energy development by attracting private investors and fostering collaboration between state and private sectors. Insights from Sarangi (2018) emphasize the contribution of the growing green energy financing market to enhancing green projects in India, thereby increasing the overall share of green energy in the country's energy portfolio. The direct and positive influence of green finance on renewable energy development is contingent on financial market mechanisms and state policies related to green finance, as argued by Ahn et al. (2022), emphasizing the necessity of green economic reforms for boosting the investment in environmentally friendly energy production.

Lastly, the incorporation of a green technology innovation in this study adds a significant contribution to the literature, as it is recognized as an effective solution to the environmental pollution problems and a means to enhance ecological quality. Green technology innovation has the potential to substantially reduce the carbon emissions (Castellacci & Lie, 2017). Evaluating the green technology innovation of enterprises becomes a pivotal strategy in determining their ability to achieve green and sustainable development (Ghulam, Rizwan, & Awais, 2024; Huang & Li, 2017). Beyond mitigating ecological damage, the upgrading and transition of green technology within enterprises can confer a competitive advantage and establish long-term sustainable goodwill (Hernández-Chea et al., 2021).

Literature Review

Numerous studies have delved into the correlation between Green Finance (GF) and Sustainable Development (SD). According to (Wang & Zhi, 2016), GF is essential to the sensible balance between environmental and financial resources and the efficient management of environmental risks. Although there are differences in how green finance is conceptualized, (Liu et al., 2020), suggest that its core components are a dedication to environmental preservation and social responsibility. Green finance, positioned as a new catalyst, has become a major force behind the expansion of the green economy.

According to Ng (2018), green finance is an economic initiative that supports the preservation of the environment, maximizes the use of available resources, and tackles climate change. Green finance prioritizes sustainable development, the green sector, and ecological conservation over traditional finance (Falcone & Sica, 2019; Kang et al., 2019). Kandpal and Agarwal (2024) highlight that attaining environmental, social, and governance (ESG) objectives can be facilitated by allocating more funds for environmental planning in conjunction with finance mechanisms designed for projects that are climate-friendly. According to Zhang and Wang (2021), there is evidence that a strong growth in green financing may greatly reduce the use of coal and advance the development of sustainable energy sources. Green finance dramatically lowers carbon emissions over the long and short terms, according to Al Mamun et al. (2022). To optimize resource allocation and handle environmental externalities, Zhao et al. (2022) contend that China's green financial strategy needs to be better planned and designed. It is noteworthy, therefore, that green funding does not invariably result in a favorable influence on sustainable development. According to Sachs et al. (2019), different players in green financing have different beneficial relationships. Sinha et al. (2021) provide additional evidence that the green financing method may progressively harm social and environmental responsibility. Increased investor knowledge of environmental issues, according to Strand (2024) will result in a rise in green bond investments and cheaper borrowing for lenders. Green bonds are used for environmental initiatives and are thought to be a major instrument of innovation in green financing over the previous decade (Gabr & Elbannan, 2024). As green bonds are issued more frequently, Tolliver et al. (2019) show that more and more individuals are questioning whether they are a viable source of funding for ecological restoration. Green bonds, loans, and other financial instruments are presented by Niyazbekova et al. (2021) as efficient ways to allocate funding to projects that solve the climate crisis.

Numerous investigations have explored the relationship between environmentally sustainable practices and green financing. Fu and Irfan (2022) study, which examines the relationship between green finance and environmental sustainability in the economies of the Association of Southeast Asian Nations (ASEAN), serves as an example of one of these investigations. Khan et al. (2024) studied the systematic review on green finance and environmental sustainability. According to their research, green financing and environmental sustainability are positively correlated; nevertheless, there may be trade-offs with possibilities for economic growth in this relationship. Shahzad and Riaz (2022) are conducting another study to understand how green finance affects environmental sustainability in five regions. To evaluate green financing, the study uses five variables: GDP, investment in renewable energy sources, R&D for eco-friendly initiatives, output of renewable electricity, and public-private energy investment. Further, Ma and Huang (2023) studied the impact of green finance on sustainability. The results show that reducing CO2 emissions is facilitated by increasing the output of renewable energy, improving research and development, and growing public-private partnerships that invest in renewable energy. Based on all these studies, it can be hypothesized that:

H1: Green Finance significantly influence the Sustainability.

A considerable body of the scholarly literature has explored the nexus between the green energy and sustainable development. In an early contribution, Midilli et al. (2006) delineated the key green energy strategies aimed at fostering sustainable development. These strategies encompassed metrics such as green energy impact ratio, the green energy-based sustainability ratio, and the green energy utilization. The authors noted a positive correlation between green energy-based sustainability ratio and the technological, sectoral, and implication impact ratios. Moreover, the recent policy initiatives within the BRICS nations advocates an intensified commitment to a renewable energy investment as a catalyst for the sustainable development. According to Li et al. (2021) implementing strategies including cutting back on coal usage, increasing the use of renewable energy, and streamlining energy structures are essential to attaining sustainable and environmentally friendly economic development. Thus, it can be hypothesized that:

H2: Green Energy significantly influence the Sustainability.

Economic development and organizational health are important factors that influence the knowledge base of the finance industry and boost economic expansion. Additionally, it contributes significantly to economic growth by lowering obstacles to investment and expediting the procedures for financial support. According to Masuda et al. (2022), this promotes trust between investors and customers, which in turn facilitates business expansion and stimulates consumer spending on higher-value items. These benefits of contemporary banking markets are not without a price, though. The global economy faces a big problem in maintaining environmental sustainability in this era of fast economic growth. Resources are viewed as assets by the world economy of a country. Large businesses and assets can now be leveraged by developing countries, but the ecosystem suffers as a result of these sources of income and reckless resource use. In industrialized nations, petroleum, petrol, and coal are the main causes of environmental harm (Zhabko et al., 2019). Examining the SDGs embraced in developed and developing economies has received a lot of interest in the literature since the creation of the Sustainable Development Goals for 2030. However, patterns in this research have shown that corporate groups and industries place little focus on taking into account green finance, clean energy, and the green economy as key factors influencing sustainable development practice (Ling et al., 2022; Qiao et al., 2022). Investment in renewable energy for sustainable development appears to be moving more quickly according to recent BRICS policy efforts. The dynamics of renewable energy and economic activity are examined for 17 G20 countries between 1980 and 2012 by Paramati et al. (2018) from the standpoint of sustainable development. The study's conclusions support a long-term equilibrium relationship between the variables and emphasize the important and advantageous role that renewable energy consumption plays in economic activity. This, in turn, ensures low carbon emissions and sustainable economic growth in the member states that were chosen. Based on these studies, it can be hypothesized that:

H3: Green Economic Development significantly influence the sustainability.

Technological advancement is currently one of the most powerful forces in the global effort to mitigate climate change. As noted by Sohag et al. (2021), innovations in technology are crucial in addressing the challenges of environment by providing new solutions to reduce carbon emissions and promote sustainable practices. The evolving landscape of environmental legislation has further bolstered the adoption of direct environmental technologies which drive steady progress in reducing CO2 emissions through enhanced efficiency and cleaner production methods (Raihan et al., 2022b). One of the key ways technological innovations contribute to mitigation of climate change is by facilitating the shift from traditional, production-driven economic models to more sustainable, innovation-driven ones. This transition is pivotal in reducing CO2 emissions, particularly in industries that have historically been major contributors to pollution (Sohag et al., 2015). Technological progress also plays an essential role in improving energy efficiency. With the development of advanced technologies, economies can achieve higher levels of production while consuming less energy, which not only boosts the performance of economy but also reduces environmental strain (Ratner et al., 2022; Sohag et al., 2015).

Moreover, the role of technological innovation in transitioning from depletable to renewable energy sources cannot be overstated. Advances in renewable energy technologies, such as solar, wind, and battery storage systems, have made it possible for economies to meet the growing energy demands while significantly lowering CO2 emissions which are associated with fossil fuel consumption. By enabling cleaner energy production and reducing reliance on fossil fuels, technological innovations directly contribute to a reduction in energy consumption and overall greenhouse gas emissions. As a result, the continued progress in these technologies holds promise for creating a more sustainable and climate-resilient global economy.The dynamic relationship between sustainable development and the green economy is explored by Lavrinenko et al. (2019). The goals of sustainable development and green growth through clean energy technologies are complimentary, as noted by international policymakers, according to Barbier (2011), who also notes the policy issues facing the green economy and sustainable economic development. However, he argues that as long as environmental deterioration persists, green growth cannot provide sustainable economic development. Belmonte-Ureña et al. (2021), analyze the existing academic discourse on sustainable development in light of the SDGs, which adds significantly to the body of literature.

Introduced in the 1990s, green innovation signifies a shift from prevailing production technologies to the adoption of inventive products and processes. This transition aligns with economic, environmental, and social considerations, coupled with adherence to environmental regulations, aimed at bolstering sustainable industries and long-term production (OECD, 2022). Studies underscore the imperative for green innovation and eco-friendly technologies, emphasizing their role in facilitating environmental and social initiatives (Galdeano-Gómez et al., 2013). Albort-Morant and Oghazi (2016) illustrated two key advantages of incorporating environmentally friendly technologies in business: (1) economic benefits that can shape a competitive edge and (2) commercial benefits in the production of environmentally friendly products. Based on all these studies, it can be hypothesized that:

H4: Green Finance significantly influence the sustainability through technological innovation.

Data and Methodology

Data

To investigate the dynamic impact of Green Finance (GF), Green energy (GE) and Green Economic Development (ED) on sustainability (SUS) through technological innovation in G-20 countries. This study uses panel data from 2011 to 2020 due to the availability of consistent and comprehensive data on key variables, such as green finance, GDP, technological innovation, and sustainability practices. Further, these years are marked by the policy shifts, such as the adoption of the Paris Agreement in 2015, which set clear climate goals for countries, and the increasing focus on green finance and investments in renewable energy. Green Finance is proxied using renewable energy consumption (Wu & Trinh, 2021), Green energy is measured by Natural resource Rent, Green Economic Development is proxied using productivity of CO_2, Sustainability was measured by CO_2 emission and patents were used as proxy for Technological innovation (Zhang & Lu, 2017). This dataset consists of annual observations for each variable, totaling 200 observations (20 countries over 10 years) for empirical analysis. The data for green finance, GDP, trade openness, sustainability practices and technological innovation was obtained from WDI. Trade openness is the sum of a country's exports and imports of goods and services which is expressed as a percentage of its Gross Domestic Product (GDP). This indicator reflects the degree of an economic integration of a country with the global economy, where higher values indicate a more open economy. Whereas, data for green economic development were obtained from the OECD. In a panel framework, the transformed log-linear model's augmented multivariate function is given as follows:

$$\ln SUS_{it} = \alpha+\beta_1 GF_{it} + \beta_2 GE_{it}+ \beta_3 ED_{it} + \beta_4 TI_{it}+ \beta_5 GDP_{it}+ \beta_6 TO_{it}+\varepsilon_{it}$$

where α is constant term, $\beta 1$, ..., $\beta 3$ show how flexible Sustainability practices are with green finance, green economic development, green energy, trade openness, GDP and technological innovation. Individual cross-sections are denoted by the letters i and, t which stand for time (2011–2020). The measurement and the source of the parameters are illustrated in Table 1.

Table 1

Measurement and Description of Variables

Abbreviations	Variables	Description	Sources
GF	Green Finance	Renewable Energy Consumption	WDI
GE	Green Energy	Natural resource rent	WDI
ED	Green Economic Development	Productivity of CO_2	OECD
SUS	Sustainability practices	CO_2 emission	WDI

TI	Technological Innovation	Patent non-resident+ Patent resident	OECD
GDP	Gross Domestic Product	Per Capita GDP growth (Annual percentage)	WDI
FDI	Foreign Direct Investment	FDI, Net Inflow (percentage of GDP)	WDI
TO	Trade Openness	% of GDP	WDI

3.2 Methodological framework

This research is carried out with the cross-sectional dependency test, panel unit root test, casualty test, and panel estimation technique.

Cross-Sectional Dependency Test

The problem of cross-sectional dependence (CSD) is often ignored by longitudinal data analysis since it compromises the validity of methods, and leads to the generation of ambiguous results and bias. CSD emerges when there are unobservable characteristics that are inherent in all cross-sectional units which leads to cross-sectional dependence (Pesaran, 2007). Some of the leading causes of CSD are proximity, globalization, spatial factors and economic interdependence. Ignoring CSD issues can lead to biased results in unit root and cointegration analyses (Yao et al., 2020). Thus, it is necessary to examine if CSD exists in each of the cross-sections. To address CSD, we employed three specific tests: These tests include (a) the Pesaran Common Correlated Effects (CSD) test following Pesaran (2004), (b) the Pesaran Scaled LM test following Pesaran (2004), and (c) the Bias-corrected LM test following Baltagi et al. (2012). These methods are especially appropriate for large panel datasets that include many cross-sectional units (De Hoyos & Sarafidis, 2006). Every test produces a test statistic under the assumption that the arrangement of the data is independent across sections and a significant outcome supports the existence of CSD in the data.

Unit Root Test

The next step in the econometric process after tests on cross-sectional dependence (CSD) is to test for the levels of stationarity or integration. To this end, we employ two other panel data cointegration estimators, namely panel data cointegration estimator 1 and panel data cointegration estimator 2. First, we employ the cross-sectional augmented Dickey-Fuller (CADF) test, which is a second-generation panel stationarity test suggested by Pesaran (2007). This method also takes care of cross-sectional dependence within the dataset which as a result provides a test statistic that encompasses the correlations thus making the results of stationarity to be more accurate. The CADF test is especially useful in a panel context where CSD issues are expected since it uses cross-sectional averages of lagged levels and first differences of the variables and provides useful information on the integration properties of the panel data under test. To support the result of using the CADF unit root test, another unit root test known as the Cross-Sectional Im-Pesaran-Shin (CIPS) test was applied. This methodology is very useful in controlling for heteroscedasticity and within-group serial correlation in panel datasets with cross-sectional dependence whereby data available across countries or regions may be interrelated.

Regression Analysis

We utilized Pesaran (2004) Fixed Effects — Ordinary Least Squares (FE-OLS) approach that enables the estimation of coefficients with fixed intercepts but allows for differing serial correlation of the panel variables. Consequently, the traditional panel data estimation method includes either fixed or random effects models. These issues suggest that the random-effects model is well-appropriate for unobserved heterogeneity across cross-sections, where some variables are fixed over time but vary across entities. Therefore, the random-effects model can be used when the cross-sections are ‘large’ and randomly selected within the sample (Hadri, 2000). The fixed effects model on the other hand eliminates the omitted variable bias by making it fixed over time so it is more appropriate to use it in smaller cross-sections (N). To determine the appropriate estimation technique for our models, we had to choose between the random-effects and fixed-effects panel regression. The optimal method can be identified through the Hausman test, which helps assess whether the random-effects model is suitable. The null hypothesis of the Hausman test suggests that the random-effects model is appropriate. However, given the significant p-value obtained from the test, we reject the null hypothesis which led us to opt for the fixed-effects panel regression to analyse equation (1). The fixed-effects model accounts for heterogeneity or individuality across the countries by allowing each country to have its unique intercept. The term "fixed effect" refers to the fact that while the intercept varies across countries, it remains constant over time which make it time-invariant. This approach better captures the country-specific characteristics that influence the dependent variable which improve the robustness of our analysis.

The sample of our study consists of 20 cross-sections (N= 20) with 7 variables variables (k = 7) and with 200 observations (T= 200). Since all the presented data indicate that N is smaller than T (N < T), we used the FE-OLS method for estimation per the approach described by Anwar et al. (2021). Furthermore, following the method by Driscoll and Kraay (1998) and Ullah et al. (2021), we outlined the role of our explanatory variables on sustainability practices, including moderation effects, on the G-20 countries. The advantage of the Driscoll-Kraay approach is that it is designed to handle CD and provides sensible standard errors. This method involves using the heteroscedasticity and autocorrelation-consistent (HAC) estimator to estimate the average of the products between the explanatory variables and residuals.

Casualty Test

To conduct causality analysis, the Dumitrescu and Hurlin (2012) causality test is employed which is developed from the Granger causality test developed in 1969 and involves averaging the Wald statistics for the raw cross-section data in a non-parametric manner. The test is used in the analysis of panel data to define the direction of causality between those variables. The null hypothesis postulates that there is no causality between the given variables while the alternative hypothesis holds the contrary and points to the existence of a causality between the chosen variables. It is flexible in the sense that it permits different forms of heterogeneity across sections enabling it to be used effectively in panel data analysis. It gives a sound analysis of the relationships as well as dependencies in the data set.

Empirical Results and Discussion

Descriptive Statistics

The table 2 presents descriptive statistics for several variables: Sustainability (Sus), Green Energy (GE), Green Finance (GF), Gross Domestic Product (GDP), Economic Development (ED), Technological Innovation (TI) and Trade Openness (TO). Co-efficients of mean values show that generally negatives exist for both; GE, and for ED; -0.013, and -0.040, respectively whereas positives are seen for; GF, TI, and TO; with mildly positive mean effect, 0.017, 0.045, and 0.018 respectively were estimated. Mean for GDP is also slightly positive skewed with a mean value of 0.001. However, the medians are slightly in different value compared to the means with GE, ED, and Sus having negative median while GF, TI and GDP having positive median. This implies that the mean values could be skewed by a few high or low values especially in the case of GE and ED. The maximum and minimum values reveal a broad range in all variables, with extreme values particularly evident in GDP, where the maximum is 6.301 and the minimum is -6.021. Similarly, GF and GE exhibit high variability, as their maximum and minimum values are notably far apart, reflecting a substantial spread in the data.

Table 2

Descriptive Statistics

	Sus	GE	GF	GDP	ED	TI	TO
Mean	0.006	-0.013	0.001	-0.040	-0.001	0.032	-0.003
Median	-0.011	-0.094	0.019	-0.045	0.019	0.018	-0.007

Maximum	2.108	4.236	5.036	6.301	1.242	4.537	1.215
Minimum	-1.946	-2.876	-5.919	-6.021	-1.091	-5.133	-0.645
Std. Dev.	0.346	0.728	0.639	1.018	0.234	0.889	0.171
Skewness	0.938	1.997	-1.801	0.602	-0.496	-1.256	1.948
Kurtosis	21.702	16.391	60.563	16.843	17.064	20.654	20.087
Jarque-Bera	2796.970***	1545.980***	26334.675***	1520.601***	1573.560***	2517.361***	2431.595***

Notes: The table shows the summary statistics. The Jarque-Bera test (***) indicates all variables deviate significantly from normality, with high skewness and kurtosis which suggests non-normal distributions.

From the skewness statistics it is apparent that the Sus, GE and TO are positively skewed with the ‘long tail’ to the right while the GF, GDP, ED and TI are negatively skewed with the ‘long tail’ to the left. The kurtosis values for all variables are larger than 3, which means the variables are leptokurtic or have fat-tailed distrion, in others words, there are outliers in the data. The high Jarque-Bera test statistics of which all are significant at 1% level confirms this finding that none of the variables is normally distributed notwithstanding the moderate deviations from normality noted on all the four measurements

Result of Cross-sectional Dependency

The results of the cross-sectional dependency (CSD) tests presented in Table 3 which indicate significant evidence of CSD across variables at the 1% significance level. This confirms that shocks, whether positive or negative which affects a variable in one country are likely to influence the same variable in other countries within the panel. The Breusch-Pagan LM, Pesaran scaled LM, bias-corrected scaled LM, and Pesaran CD tests collectively provide robust evidence of interdependence, with consistent rejection of the null hypothesis of no CSD. For variables such as GE, GF, ED, TI, TO, and SUS the significant test statistics confirm strong interconnectivity among the countries. Specifically, the Breusch-Pagan LM test, which is suitable for larger panels, shows very high values (e.g., GE: 766.8331, and GF: 1160.6 which indicate pronounced dependence. The Pesaran scaled LM and bias-corrected scaled LM tests which aes designed to address size distortions in finite samples, also yield significant results across most variables. These findings reinforce the robustness of the observed interdependence.

However, the Pesaran CD test, which is more effective in smaller panels and detects average pairwise correlation, shows nuanced results. For instance, while GE, GF, ED, and TO exhibit significant dependence at the 1% or 5% level, SUS and TI yield non-significant or even negative test statistics. This variation suggests that while cross-sectional dependence is a general feature of the dataset, its intensity may vary across variables which is possibly influenced by the nature of the variable or regional heterogeneity. Given the strong evidence of cross-sectional dependency, a fixed-effects model was employed in the FE-OLS estimation to account for unobserved heterogeneity and mitigate biases which arises from interdependence. The approach aligns with the methodological recommendations of Hunjra et al. (2020) and ensures the reliability of parameter estimates in the presence of CSD.

Table 3

Cross-sectional dependency

	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
GE	766.8331***	32.21896***	31.16341***	7.321413***
GF	1160.6***	53.51142***	52.45587***	5.109877***
ED	1065.238***	48.35488***	47.29932***	2.468514***

SUS	1345.575***	63.51373***	62.45818***	0.546265
TI	1270.45***	59.45142***	58.39587***	-1.34226
GDP	173.6999***	0.145993***	-0.90956***	2.174251
TO	850.9355***	36.7667***	35.71114***	2.161433**

Note: *** shows the 1% level of significance.

4.3 Results of Unit Root Test

In this study, the panel unit root tests were performed using the CADF and CIPS methods, which account for cross-sectional dependence (CSD) as per Pesaran (2007). The results from the CIPS and CADF tests show a order of integration among the variables. All variables are stationary at level, as indicated by a significant test statistic. Similarly, the CADF test also confirms the stationarity of all variables, with strong significance as shown in Table 4.

Table 4

CIPS and CADF Unit Root Test

Variables	***CIPS***		**CADF**	
	1(0)	1(1)	1(0)	1(1)
GE	**-5.80*** **	**-**	**-1.969***	**-**
GF	**-5.11*** **	**-**	**-3.462*** **	**-**
ED	**-10.56*** **	**-**	**-2.191** **	**-**
SUS	**-4.31*** **	**-**	**-3.994*** **	**-**
TI	**-5.30*** **	**-**	**-2.374** **	**-**
GDP	**-2.28*** **	**-**	**-3.939*** **	**-**
TO	-10.90***	-	-2.072*	-

*Notes: The CIPS and CADF unit root tests were applied to assess stationarity. The values for each variable indicate significance levels, where *** represents 1%, ** denotes 5%, and * denotes 10%.*

However, Green Finance (GF) is stationary at levels, with both CIPS and CADF tests rejecting the null hypothesis of non-stationarity at the 1% significance level. Economic Development (ED), Sustainability (SUS), Technological Innovation (TI), Green Energy (GE), Trade Openness (TO), and Gross Domestic Product (GDP) are found to be stationary at levels, with significant test statistics at 5% or 10% levels in both tests. Since, our results shows that all variables are stationary at level so there is no need for differencing. The lag length for the unit root tests was determined automatically on the basis of standard information criteria, such as the Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC), to ensure optimal lag selection. This approach helps to minimizes the serial correlation in residuals while avoiding overfitting. By adhering to this selection method, the reliability of the stationarity results is reinforced, and the tests are robust against misspecification.

Results of Regression Analysis

Table 5 presents the estimates of the Fixed Effect OLS regression that illustrate the significance of core variables prospective to latent sustainability experiences. Green Finance (GF) is positively correlated with sustainability, with a 1% increase in GF leading to a 0.071% and 0.063% rise in sustainability in Models 1 and 2, respectively. This confirms that sustainable green finance can encourage a better environment by offering funding and promotion for more energy-efficient technologies and reducing the detrimental impacts of environmental depreciation agreeing with earlier studies done by Shahbaz et al. (2018) and Zafar et al. (2019).

Table 5

Fixed effect OLS

Variable	1	2
Constant	0.004	0.001
	(0.030)	(0.016)
GE	-0.163***	-0.159***
	(0.030)	(0.030)
GF	-0.181***	-0.210***
	(0.029)	(0.035)
ED	-0.912***	-0.853***
	(0.101)	(0.110)
TI	0.039*	0.041*
	(0.026)	(0.026)
GDP	0.024*	0.023*
	(0.017)	(0.017)
TO	0.513***	0.522***
	(0.121)	(0.121)
GF*TI		-0.030**
		(0.013)
R2	0.632	0.615
Adjusted R2	0.575	0.600
Regression SE	0.226	0.219
F statistics	11.20	41.41
Prob (F statistics)	0.000	0.000
Durbin Watson test	1.327	1.24

*Notes: Standard errors are shown in parentheses. Statistical significance is indicated by *** denotes 1%, ** represents 5%, and * denotes 10%. R^2 and Adjusted R^2 show the model's explanatory power, with higher values indicating better fit.*

Economic Development (ED) has a strong and statistically significant positive impact on sustainability, with a 1% increase in ED resulting in a decrease of economic development -0.912% and -0.853% improvement in sustainability across both models. This means that any attempt to improve environmental policies and practices are essential for the realization of sustainability objectives. Previous literature also establishes the relationship between efforts toward environmental development such as pollution control efforts, and the adoption of renewable energy sources for quality environmental improvement (Saud et al., 2019; Shahbaz et al., 2018).

Technological Innovation (TI), however, shows a significant negative correlation with sustainability, with a 1% increase in TI leading to a 0.039% and 0.041% increase in sustainability in Models 1 and 2, respectively. These results align with the previous study of Cao (2023) who found that Technological innovation and scientific research and development (R&D) are widely accepted as important sources of growth to an economy making them focal areas of interest to economists. The process works as follows: Technological and innovation activities generate new knowledge and improvements in efficiency that occur in micro, meso and macro levels—firm, industry, and country levels. As productivity increases it means that the returns on investment rise hence higher incomes and better and durable economic progress. As a result, it will be possible to observe that the level of investment in R&D positively impacts the countries' economic performance. On the other hand, inefficient R&D means that the resources invested in research and development may yield a lower return in the future for the countries involved.

Moreover, green energy is negatively and significantly related to sustainability. This means a 1% increase in investment in renewable energy projects will lead to a reduction in carbon emissions of -0.163%. Muganyi et al. (2021) noted that energy security necessitates governments to increase the use of renewable energy sources across multiple sectors. However, to support the sustainable development of the economy, governments need to encourage investment in renewable energy projects, which play a significant role of fighting climate change. Therefore, by increasing the share of clean and renewable energy in the total supply, we can, to some extent, reduce the pace of environmental degradation and promote further climate change mitigation. Green Finance (GF) is negatively associated with sustainability. This means 1% increase in investment in renewable sources can result in a decrease in the value of carbon dioxide emission by -0.181%. Green production implies the use of a lesser degree of pollutive technologies in production processes in financial investment, which is in line with the objectives of green financial development. Khan et al. (2022) have stated that there are indeed high possibilities of increasing the level of environmental sustainability with such investments. Chen and Chen (2021) have pointed out that green financial networks (GFN) have a great influence on consumers and organizations making them shift towards using products that are eco/logically friendly and those that do not contribute to excessive emission of greenhouse gases. This shift is not only good for the environment but is also part of a push toward sustainable initiatives. Research findings also corroborate these observations indicating that GF is the useful and efficient financial strategy in enhancing environmental sustainability. Nawaz et al. (2021) and Shen et al. (2021) have highlighted that GF plays a crucial role in the overall enhancement of sustainable development and realization of environmental objectives.

GDP is also positively associated with sustainability, with a 1% increase in GDP leading to a 0.024% and 0.023% increase in sustainability. This relationship sustains the hypothesis of the Environmental Kuznets Curve (EKC) in line with the assumption that economic development directly results in environmental degradation before positive changes happen when the development reaches some certain level (Charfeddine et al., 2018; Özokcu & Özdemir, 2017).

An interesting finding from Model 2 is the interaction between Economic Development and Technological Innovation (GF*TI), which has a significant and negative impact on sustainability. A 1% increase in this interaction leads to a -0.030 % decrease in sustainability which implies that during the early stages of such innovations, there might be resource-intensive processes, for instance; production and installation of new technologies, which could lead to a temporary increase in emissions and environmental costs before achieving the desired sustainability benefits (Sohag et al., 2021c). This phase of transition could explain the negative relationship between technological innovation and sustainability, as it reflects the complex dynamics of innovation adoption and impact of an environment. Additionally, the interaction term's negative impact point that technological innovation is being implemented in regions or sectors where green finance policies are not fully aligned with the environmental goals. This misalignment could result in inefficient allocation of resources where investments in technology are not accompanied by the necessary policy frameworks or market incentives to drive substantial sustainability improvements. In this context, technological innovation may be underutilized or misdirected which dampen its effectiveness in reducing carbon emissions and promoting long-term sustainability (Shahbaz et al., 2018). The models show strong explanatory power, with R-squared values of 0.632 and 0.615 which indicate that the included variables explain a substantial portion of the variation in sustainability. These findings highlight the importance of green finance, economic development, green energy, and the integration of technological innovation with environmental policies in driving sustainable outcomes which is consistent with earlier research (Saud et al., 2019; Tamazian et al., 2009).

Results of the Robustness Test

The results in Table 6 display robust outcomes using Driscoll–Kraay (D-K) standard error estimation, providing consistent findings with the earlier FE-OLS estimations. Specifically, the variables Green Finance (GF), Economic Development (ED), Green Energy (GE), Technological Innovation (TI), Trade Openness (TO), and Gross Domestic Product (GDP) show significant relationships in both models. GF has a strong negative impact on carbon emission, as indicated by the highly significant coefficients (-0.181% and -0.210%) in both models, which aligns with prior literature on the role of green finance in enhancing environmental outcomes (Zafar et al., 2019). The results in Table 6 present comparable results applying the Driscoll-Kraay (D-K) standard error estimations which yield similar findings as the FE-OLS estimations. Indeed, Green Finance (GF), Economic Development (ED), Technological Innovation (TI), and Gross Domestic Product (GDP) present a strong correlation in both models. The findings of this study also reveal that GE has a highly significant and negative effect on CO2 emission with highly significant coefficients (-0.163% and -0.159%) in both models which is consistent with the existing literature on the effect of green energy on sustainability (Wang et al., 2021). ED in the same way also shows a negative and significant effect indicating that economic development can reduce carbon emissions to a greater extent and the coefficients are -0.912% and -0.853% in both models.

Table 6

Robust outcomes using standard error estimate from Driscoll–Kraay (DK)

Variable	1	2
Constant		0.001*
		(0.009)
GE	-0.163***	-0.159***
	(0.044)	(0.042)
GF	-0.181***	-0.210***
	(0.013)	(0.007)
ED	-0.912***	-0.853***
	(0.083)	(0.089)
TI	0.039**	0.041***
	(0.010)	(0.011)
GDP	0.020*	0.023*
	(0.018)	(0.016)
TO	0.513***	0.522***
	(0.044)	(0.039)
GF*TI		-0.051***
		(0.011)
N group	20	20
F statistics	5728.7	7649.68
Prob (F statistics)	0.000	0.000
R squared	0.596	0.600

*Notes: Standard errors are shown in parentheses. Statistical significance is indicated by *** denotes 1%, ** represents 5%, and * denotes 10%. R^2 and Adjusted R^2 show the model's explanatory power, with higher values indicating better fit.*

On the other hand, TI is significantly positive and the coefficients for this variable are 0.039 and 0.041%, it seems that CO2 is directly related to technological innovation in this regard. Ahmed and Jahanzeb (2020) discussed the impact of technological change on CO2 emissions in the context of Brazil. They found that an increase in exports calls for increased technological advancement and also economic growth promotes technological advancement. Thus, this advancement in technology helps in reducing the levels of emission of CO2. GDP, although relatively small, shows a positive association with environmental degradation in both models, with coefficients of 0.020 and 0.023, suggesting that economic growth continues to be a driver of CO2 emissions, supporting the Environmental Kuznets Curve (EKC) hypothesis. Thus, Model 2 reveals that the interaction between GF and TI is negative and statistically significant at -0.051%, which implies that, when supported by technological innovation, investment in renewable sources efforts will help result in decreasing carbon emissions.

The high R-squared values (0.569 & 0.600) in both models further highlight the robustness of the findings which shows that the variables collectively explain a significant portion of the variance in environmental outcomes. Additionally, the F-statistics and their associated probabilities confirm the overall significance of the models.

Additional Analysis

The impact of the 2015 climate policy on sustainability outcomes was examined using a Difference-in-Differences (DiD) approach. The DiD model estimates the causal effect of policy adoption on sustainability by comparing policy adopters (treatment group) and non-adopters (control group) before and after the 2015 policy implementation.

Table 7

Difference-in-Difference Method

Sustainability	
Policy Adopters	1.169***(0.376)
Policy adopters*Post Policy Adopter	0.756***(0.218)
Year fixed effect	Included
Constant	0.051**(0.03)
Adj.R^2	0.224

*This table provides the result of the difference in the difference analysis of the 2015 climate policy's impact on sustainability outcomes is shown in this table. The following are the model's specifications: Sustainability = $\alpha + \beta 1$ Policy Adopter + $\beta 2$ (Year Dummy) + $\beta 3$ (Policy Adopter × Post-2015) + ϵit. A dummy variable in this model called Policy Adopter indicates whether a nation is in the treatment group, which means it embraced the 2015 climate policy. A dummy variable called "post-2015" has a value of 1 for the time after the 2015 policy's introduction and 0 for the time prior. The impact of being a policy adopter throughout the post-2015 era is captured by the interaction term, Policy Adopter * Post-2015.*

With a coefficient of 1.169 ($p<0.01$), the regression results show that policy adopters had a significantly higher sustainability score than non-adopters prior to the 2015 climate policy. Policy Adopters * Post Policy Adopter's interaction term is 0.756 ($p<0.01$), indicating that the policy significantly and favorably impacted adopters' sustainability, raising their score by 0.756 units above that of non-adopters following implementation.

Robustness Analysis

The Generalized Method of Moments (GMM) is a widely used estimation technique in econometrics, particularly for panel data. It is designed to address issues of endogeneity that arise when explanatory variables are correlated with the error term. GMM uses instrumental variables, which are uncorrelated with the error term but correlated with the endogenous regressors, to produce consistent and efficient parameter estimates. This method is particularly useful in dynamic panel data models and when dealing with potential reverse causality and omitted variable bias.

Table 8

System GMM

Variable	
Constant	0.401
	(0.127)
GE	-0.082***
	(0.041)
GF	-0.124*
	(0.070)
ED	-6.026***
	(1.114)
TI	0.090*
	(0.069)
GDP	0.057**
	(0.008)
TO	0.012**
	(0.089)
Sargan	0.632
AR1	0.020
AR2	0.065

*Notes: The table presents the results of the Generalized Method of Moments (GMM) estimation. Standard errors are reported in parentheses. Statistical significance is denoted by *** at the 1% level, ** at the 5% level, and * at the 10% level. The Sargan test confirms the validity of the instrumental variables used in* *the estimation. AR1 and AR2 represent the p-values for the Arellano-Bond test for first-order and second-order autocorrelation, respectively.*

The results of the GMM estimation reveal significant insights into the relationships between the variables and their impact on sustainability. The constant term is positive but statistically insignificant which suggests that sustainability outcomes do not have a substantial baseline effect in the absence of explanatory variables. Green Energy (GE) has a negative and statistically significant coefficient which indicates that an increased reliance on green energy currently contributes to a reduction in the dependent variable. This could reflect challenges in the efficiency or scope of green energy implementation. Similarly, Green Finance (GF) exhibits a negative and moderately significant impact which point to potential limitations in the mechanisms of green finance to fully address sustainability challenges. Economic Development (ED) demonstrates a strongly negative and highly significant effect which emphasize the pressing need for integrating sustainability measures within economic growth strategies to mitigate environmental harm. On the other hand, Technological Innovation (TI) positively influences sustainability, albeit modestly, highlighting its role as a supportive factor in achieving the outcomes of sustainable. Gross Domestic Product (GDP) and Trade Openness (TO) both show positive and statistically significant effects which suggest that economic growth and openness to trade enhance sustainability by enabling access to cleaner technologies and sustainable practices. The diagnostic tests validate the robustness of the model. The Sargan test confirms the validity of the instruments used, while the absence of second-order autocorrelation which is indicated by the AR2 test, ensures the reliability of the results. However, the presence of first-order autocorrelation (AR1) is consistent with expectations in GMM models, affirming the appropriateness of the estimation technique

Conclusion and Policy Implications

This research study aims to investigate the moderating role of Green Finance, Green Energy, Green Economy Development, and Technological Innovation on sustainable performance in the context of G20 countries. The study also shows that Green Finance has a negative impact on sustainability as it fosters investment in energy efficiency technology and minimizes environmental pollution. Likewise, Economic Development has a significant negative impact on reducing carbon emissions which in turn highlights the need to implement good environmental policies and standards. However, Technological Innovation is directly related to sustainability which shows that innovation may results in reduced carbon emission and greener environment. In line with earlier studies, this result suggests and stresses the challenges associated with technological advancement and environmental conservation. Moreover, the results indicate a significant inverse correlation between the dependent variable and sustainability in relation to the EKC hypothesis, which suggests that economic growth causes harm to the environment before reaching a level where sustainable improvements occur.

One of the key findings of the study is the synergy between Green Finance and Technological Innovation. Technological changes make a negative contribution to sustainable development results when they are aligned with effective environmental development initiatives. This shows that there is the possibility of innovation and environmental policies to be complementary to bring about sustainable growth. Given the conclusions derived from this investigation, the results are of sheer importance as they can assist the G20 countries in fulfilling their environmental development obligations under the Paris Climate Agreement and the UN SDGs. Although some of the G20 countries have limitations in terms of capacity to fully adhere to these commitments, this research outlines the way forward for the improvement of the situation toward compliance through policy-based decision-making. Considering the goal of achieving environmentally sustainable development in G20 countries, the following policy implications are suggested for stakeholders, governments, and policymakers based on the estimated outcomes.

The study provides several policy implications based on its findings. Firstly, it demonstrates that Green Finance is effective in reducing the carbon emissions by facilitating the financing of energy-efficient technologies and sustainable initiatives. To strengthen Green Finance, it is recommended that governments should introduce specific policy instruments such as tax incentives for green investments, subsidies for renewable energy projects, and the establishment of green bonds markets to channel private investment into sustainability-focused projects. These measures would not only drive the adoption of clean technologies but also mitigate the environmental harm which are caused by extraction of fossil fuel.

Secondly, the study finds that Economic Development negatively influences the carbon emissions which emphasize the need to integrate environmental considerations into economic policy frameworks. Policymakers could adopt strategies such as implementing carbon pricing mechanisms (e.g., carbon taxes or cap-and-trade systems) to internalize the environmental costs of development. Additionally, mandatory environmental impact assessments (EIAs) for large-scale development projects and incentivizing resource-efficient industrial practices could ensure that economic growth aligns with the goals of environmental conservation.

Thirdly, the findings highlight the role of Technological Innovation in magnifying the effectiveness of Green Finance in achieving sustainability. Governments should prioritize funding for research and development (R&D) in green technologies which include grants and public-private partnerships that are more focused on clean energy, energy storage, and carbon capture solutions. Moreover, creating innovation hubs and tax credits for green startups can foster technological advancements and expedite their deployment.

Firstly, the transition to green energy often requires substantial upfront investments in infrastructure and technology, which can temporarily increase the use of resources and emissions during the development phase. For instance, the production of solar panels, wind turbines, and batteries requires energy-intensive processes. Manufacturing these renewable energy technologies, for instance, the mining of materials for solar panels and the production of batteries for energy storage, involves significant carbon emissions. If the supply chain is not fully sustainable, it can offset the short-term environmental benefits. Research by BNEF (2020) highlights that, while renewable energy technologies have lower operational emissions, the manufacturing phase can still result in a significant environmental cost, especially when sourced from non-renewable energy-dependent production processes. Moreover, the need for a rare earth minerals and metals used in renewable technology can also have detrimental social and environmental impacts, particularly when sourced from a region with weak environmental standards (World Bank, 2020).

Furthermore, the implementation of green energy solutions in certain regions may still rely on conventional energy systems during the transition period which leads to an initial increase in carbon emissions before renewable sources fully replace the fossil fuels. Additionally, the negative impact of Green Energy on sustainability in this study could also be linked to the limited scope of a current renewable energy adoption in many G20 countries. While the renewable energy sector is expanding, it may not yet be large enough to fully mitigate the environmental impacts of traditional energy sources in some regions. REN21 (2021) notes that while global renewable energy capacity is increasing, many G20 countries still rely heavily on fossil fuels for base-load power generation which mean that adoption of renewable energy has yet to reach levels that can counterbalance the ongoing emissions from a conventional power plant.

Last but not the least to enhance the green financing ecosystem, the establishment of green funds, green exchanges, green banks, and green insurance schemes is important. Policymakers should also promote climate financialization practices, for instance, setting up public-private climate finance initiatives and adopting blended finance models to mobilize resources for large-scale green projects. Building an enabling regulatory environment, such as mandating disclosure of climate-related financial risks and providing credit guarantees for green loans, can further support green investment flows in G20 countries.

Limitation and Future Direction

The first and significant limitation of this study concerns the lack of data for recent years, which has limited the analysis period to 2011-2020. Future studies could also include social and cultural variables and study the moderating impact of institutional quality enhancements and technological advancement on sustainability and the time horizon could also be extended further. Other forms of estimation such as the panel non-linear ARDL could also be employed to establish the asymmetric effects on environmental results in ASEAN countries.

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