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Green Innovation and Green Economic Growth in Regional Comprehensive Economic Partnership (RCEP) Countries: Moderating Effect of Financial Development

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Abstract: *This study examines the relationship between green innovation and green economic growth in Regional Comprehensive Economic Partnership (RCEP) member countries from 2000 to 2021, with a focus on the moderating role of financial development. Using a two-way fixed effects (TWFE) model, the analysis reveals that green innovation significantly enhances green economic growth by improving production efficiency and reducing reliance on resource-intensive industries. Financial development amplifies this effect by optimising resource allocation and providing long-term capital support. These findings are confirmed by robustness tests, highlighting the critical role of financial development in maximising the benefits of green innovation. In addition, the contributions of human capital, research and development (R&D) personnel, and clean energy production are discussed. A well-educated workforce accelerates the adoption of green technologies, R&D personnel drives their innovation and industrilialisation, and clean energy production reduces fossil fuel dependency, laying a stable foundation for sustainable growth. Accordingly, policies that strengthen financial systems, incentivise green R&D, and promote regional cooperation are essential to achieving sustainable economic growth in RCEP countries.*

Keywords: Green innovation; Financial development; Green economic growth; Regional Comprehensive Economic Partnership countries; Two-way fixed effects
JEL Classification: Q56, O44, G21

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1. Introduction

Economic growth has historically relied on the intensive consumption of natural resources, prioritising gross domestic product (GDP) growth and overall economic output while neglecting environmental impact. However, this growth model is increasingly considered unsustainable as global climate change intensifies (Fernandes et al., 2021). Consequently, policymakers and scholars introduced the concept of green economic growth (also called green GDP) in 2011. This framework aims to balance economic development with environmental protection by reducing carbon emissions and promoting the efficient use of natural resources (OECD, 2020). This concept aligns with the objectives of the Paris Agreement and the 2030 Sustainable Development Goals (SDGs), providing a theoretical foundation for countries pursuing environmentally sustainable development.

In contrast to traditional economic growth models, green economic growth emphasises resource efficiency and environmental sustainability. According to the Organization for Economic Cooperation and Development (OECD, 2020), green economic growth involves promoting economic development while ensuring that natural assets continue to provide the resources and services essential for human well-being. In recent years, countries have significantly increased their investments in renewable energy, energy-efficient technologies, and cleaner production methods. For example, China saw a surge in green technology patent applications after introducing its "dual-carbon" target—carbon peaking and carbon neutrality—underscoring the importance of policy in driving green economic growth (Khan & Ulucak, 2020). Nevertheless, the legacy of resource-intensive industrialisation has caused a dual crisis of environmental degradation and resource depletion. Green economic growth offers a more holistic vision of sustainability by integrating environmental management into the broader development framework.

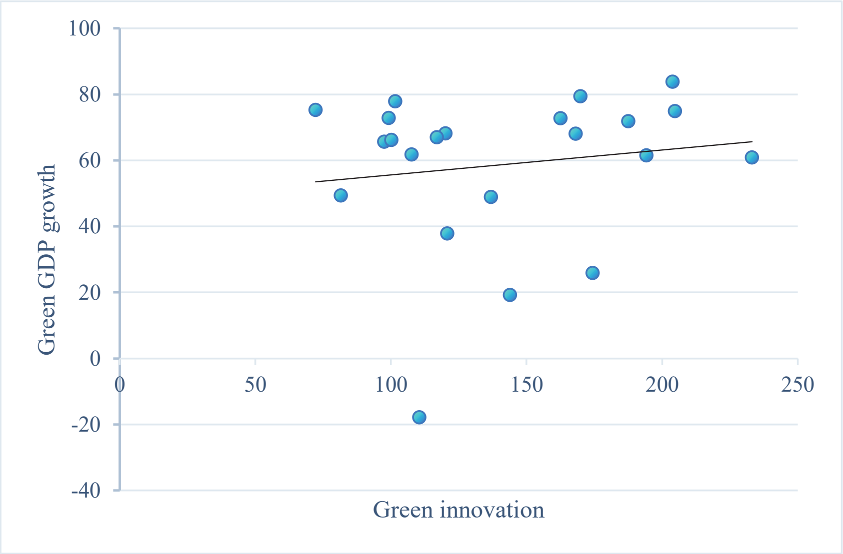
The Regional Comprehensive Economic Partnership (RCEP), Asia's largest free trade area, includes developed and developing economies at different stages of economic development. Despite recent environmental efforts, economic growth in most RCEP countries has remained closely linked to high carbon emissions and consumption of natural resources. In 2021, RCEP countries accounted for 40% of global CO_2 emissions from fuel combustion (Tian et al., 2022). Industrialisation and trade expansion have increased energy demand, posing significant environmental challenges. Therefore, the balance between economic advancement and environmental preservation has become an urgent necessity in these countries. As a core technological approach to reducing carbon emissions, green innovation requires policy support and substantial financial investment to ensure its widespread adoption and impact.

Despite the increasing focus on green innovation, the enabling role of financial development remains insufficiently understood—particularly in rapidly industrialising economies. Without a clear understanding of how financial systems influence the adoption and scaling of green technologies, policymakers may misallocate resources, underestimate infrastructure needs, or delay critical investments in clean production. This knowledge gap could lead to slower technological diffusion, prolonged dependence on carbon-intensive sectors, and missed opportunities to align economic growth with environmental goals. For RCEP countries, where environmental pressures and development challenges intersect, addressing this gap is crucial for ensuring a smooth and inclusive green transition.

Green innovation refers to innovative activities that reduce environmental harm by producing, introducing, or adopting eco-friendly products, processes, or management practices (Horbach et al., 2013). These activities have recently received considerable attention from scholars and policymakers. In addition to reducing environmental protection costs, green innovation accelerates the development and application of clean technologies, thereby improving economic productivity and resource efficiency. Figure 1 shows a statistically significant positive correlation between green innovation and green economic growth. Accordingly, the adoption of green innovation technologies can help RCEP countries promote sustainable development, enhance resource utilisation, and mitigate environmental degradation.

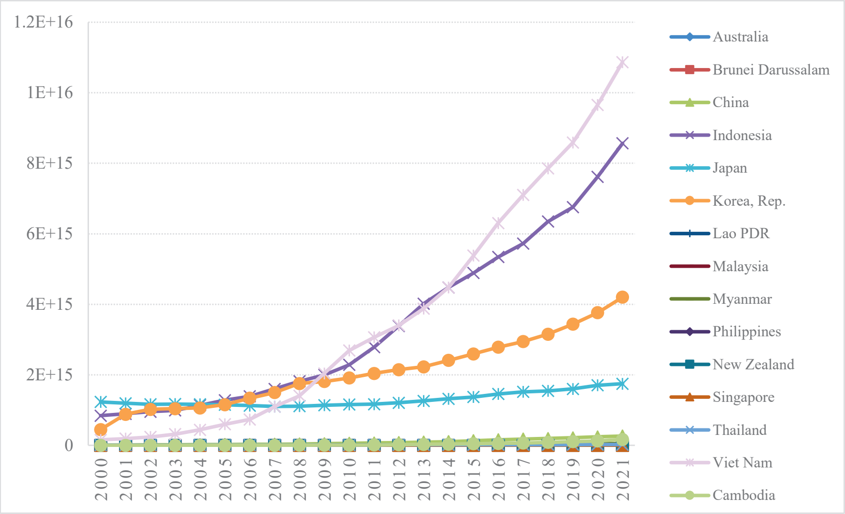
Furthermore, financial development is vital for promoting green innovation and green economic growth (Hasan & Du, 2023). According to the growth pole theory, the agglomeration and spillover effects of financial resources can effectively facilitate the dissemination of technological innovation and efficient allocation of resources, thereby optimising economic structures (Thomas, 1975). However, the level of financial development varies greatly among RCEP member countries. Figure 2 illustrates the financial development trends in different countries. Japan demonstrated

Figure 1: Green innovation and green economic growth (2000–2021)



Source: World Bank Indicators, Online World Bank Database (2022).

Figure 2: Financial development performance in RCEP countries (2000–2021)

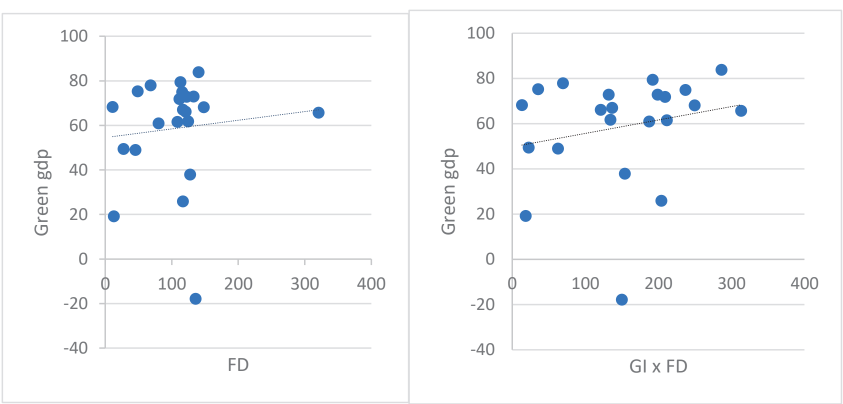


Source: World Bank Indicators, Online World Bank Database (2022).

remarkable financial market stability through its bank-led financial system, whereas Vietnam exhibited rapid credit market expansion in the latter part of the sample period. In contrast, Brunei, Laos, and Cambodia exhibited relatively underdeveloped financial systems and limited credit growth, indicating substantial room for improvement in their financial support for economic activities. According to our findings, well-functioning financial systems promote green growth through efficient capital allocation towards sustainable innovation projects.

The direct relationship in Figure 3(a) reveals that financial development has a positive and pivotal influence on the green economy, serving as a crucial enabler for sustainable growth. The flourishing landscape of green financial development bolsters the macroeconomic resilience of RCEP countries and acts as a significant assurance for green growth. As shown in Figure 3(b), financial development can play a constructive and essential moderating role in member countries by effectively stimulating green technologies, thus supporting the expansion of the green economy. Direct and indirect relationships significantly contribute to promoting sustainable economic development, further emphasising the centrality of financial development in green economic growth.

Figure 3: Direct and indirect relationship between financial development and green economic growth



(a) (b)

Although previous studies have explored the relationship between green innovation and economic growth, this study contributes to the literature theoretically and empirically in several respects. First, this study systematically examines the moderating effect of financial development on the relationship between green innovation and green economic growth. The introduction of an interaction term between financial development and green innovation enables this study to analyse the direct impact of financial development and uncover its indirect role in enhancing the effectiveness of green innovation, thus expanding the discussion of this moderating mechanism in the literature. Second, unlike traditional studies that use conventional GDP measures, this study employs green GDP—an indicator incorporating environmental costs—to measure economic growth. Green GDP can accurately capture the balance between economic growth and environmental sustainability, providing clearer practical guidance for formulating green development policies. Finally, this study focuses on RCEP member countries, covering multiple economies at different stages of development. This approach addresses the limitations of previous studies that predominantly examined single economies or groups of countries with similar levels of development. It also provides a unique comparative perspective, highlighting differences in financial development and green innovation mechanisms across economic contexts. Methodologically, this study employs a two-way fixed effects (TWFE) model to effectively control for time and regional heterogeneity, thus enhancing the robustness and reliability of the empirical findings.

Using panel data from RCEP countries spanning 2000–2021, this study investigates the mechanism by which financial development moderates the relationship between green innovation and green economic growth. The remainder of this study is organised as follows: Section 2 reviews the relevant literature, Section 3 outlines the data and research methodology, Section 4 presents empirical results and discussions, and Section 5 offers policy recommendations.

2. Literature Review

2.1 Theoretical Review

2.1.1 Theoretical Review of the Determinants of Green Growth

The concept of green growth has gained prominence through various theories, including classical models, growth stage theories, dual economy models, dependency theories, and exogenous and endogenous growth theories, which define its role in green economic growth.

2.1.2 Classical Model

Solow's (1954) classical growth theory attributes economic output to technology, human capital, physical capital, and labour, with growth driven by capital investment, labour force expansion, and productivity gains. Labour force growth stems from advances in health, education, participation, and demographics, whereas productivity gains arise from social capital and technological innovation. Although Solow's (1956) model treats labour force and productivity growth as exogenous, the models proposed by Arrow (1962), Romer (1994), and Aghion and Howitt (1998) shift toward endogenous growth, linking productivity to education, research, and policy-driven capital accumulation. However, these models often overlook the contribution of environmental factors to sustaining growth.

Malthus (1798) first introduced environmental considerations, which were later expanded by Nordhaus (1974), Dasgupta and Heal (1974), and Solow (1974), framing the environment as "natural capital." According to Dasgupta and Heal (1979), the complementarity or weak substitutability between environmental quality and production inputs makes environmental protection essential for sustaining productivity. Zhang and Gong (2022) underscored the importance of integrating environmental factors into growth models, offering a holistic framework for sustainable economic development.

2.1.3 Growth Stage Theories

Rostow's growth stage model, a fundamental framework in 20th-century development theory, describes five linear stages of economic development: 1) traditional society, 2) preconditions for takeoff, 3) takeoff, 4) maturity, and 5) age of mass consumption (Rostow, 1959). The traditional society stage is characterised by agriculture-based economies with labour-intensive production and limited technology. Under the preconditions of the takeoff stage, agriculture becomes commercialised, markets expand, and early industrialisation begins, although weak institutions may hinder progress (North, 1990). The takeoff stage is marked by accelerated industrialisation driven by investment and institutional development. During maturity, advanced technologies enhance resources, replace outdated sectors, and sustain growth through innovation and effective policies. The age of mass consumption represents technological maturity, in which innovation drives sustainable growth and improves quality of life (Venter, 2022).

2.1.4 Dual Economy Models

The dual economy model explains growth in developing economies through labour transitions from agricultural (subsistence) to industrial (capitalist) sectors. Lewis (1954) argued that surplus agricultural labour shifts to industry for higher wages, with industrial profits reinvested as fixed capital to drive growth. Technological progress, which substitutes knowledge for labour and capital, supports this transition, enabling industrial expansion (Narula, 2018). Dual economies, historically dominated by feudal and artisanal systems, emerged as advanced industrial technologies outpaced traditional sectors (Samuelson & Nordhaus, 1985). However, capital-driven growth often failed to improve living standards, with real wages stagnating or declining (Morawetz, 1977). Temple (2005) declared that the slower adoption of technology in agriculture compared to industry exacerbates economic disparities and reinforces dual structures. Technological dualism, characterised by the coexistence of capital- and labour-intensive methods, perpetuates these imbalances, necessitating institutional reforms, incentives for technological renewal, and large-scale innovation strategies to promote balanced economic development (Sukharev, 2021).

2.1.5 Dependency Theory

Dependency theory posits that structural dependence on industrialised nations constrains economic growth in developing countries, which disproportionately benefit from resource transfers, perpetuating global inequality (Egbo & Ezeaku, 2020). Emerging after World War II as a critique of colonial systems and traditional development models, the theory emphasises how resource exploitation and economic integration marginalise poor countries while favouring wealthy ones, framing underdeveloped nations as weak participants in the global market rather than early-stage economies (Kvangraven, 2017). According to Frank (1967), colonial powers entrenched underdevelopment by extracting resources from peripheral regions in exchange for manufactured goods. This pattern was sustained after independence through global capitalist structures aligned with elite interests, reinforcing disparities under the guise of comparative advantage (Schumacher, 2013). Dependency theory, which has been widely applied in regions such as Latin America, Africa, and Asia (Chilcote, 1974; Hein, 1992; Nhema and Zinyama, 2016), offers insights into systemic barriers. However, it has been criticised for overlooking internal political, social, and natural factors that hinder development (Gabrielyan, 2014).

2.1.6 Exogenous Growth Theory

Exogenous growth theory proposes that external factors, rather than internal dynamics, influence economic growth. Domar (1946) first explored the relationship between capital accumulation and full employment in his neoclassical growth model, which considered a closed economy without external economies or diseconomies. The Domar model emphasises the equilibrium between productive capacity and investment-driven demand. However, this model has several limitations, including instability of equilibrium growth paths and its sole reliance on capital as a determinant of output growth. These issues highlight the need for a more comprehensive framework.

Accordingly, Solow (1956) addressed these shortcomings by developing an alternative model that combined capital and labour in varying proportions. Unlike the Domar approach, Solow introduced the concept of exogenous technological progress as a key driver of long-term growth. Solow posited that technological advancements alone could sustain per capita income and consumption growth over time. Solow's model emphasises that exogenous factors determine the long-run growth rate in a closed economy, underscoring the critical role of technical progress in driving sustained economic development.

2.1.7 Endogenous Growth Theory

According to endogenous growth theory, sustained economic growth arises from improvements in total factor productivity driven by technological advancement (Mankiw et al., 1992). Unlike neoclassical models that treat technological progress as exogenous, endogenous growth models emphasise internal innovation (Artelaris et al., 2006). Romer (1990) highlighted knowledge externalities as central to technology-driven growth, whereas Lucas (1988) underscored the role of human capital accumulation through skills and learning. Moreover, Grossman and Helpman (1991), Aghion and Howitt (1992), and Stokey (1995) highlighted knowledge spillovers, where technological advancements enhance the knowledge stock, creating a cycle of diffusion and growth.

Research and development (R&D) is central to endogenous growth theories. The "R&D model" proposed by Romer (1990) links technological progress with economic development. However, Sala-i-Martin and Barro (1995) explored intellectual property rights in optimising technology diffusion. Czarnitzki and Licht (2006) confirmed the significant long-term growth impact of R&D despite the potential crowding-out effects of public R&D on private investments. Lucas (1988) highlighted human capital as the foundation for growth, revealing that worker training enhances productivity and comparative advantages. He (2022) extended this framework, demonstrating that innovation drives economic cycles independent of traditional factors, and introduced an inverted U-shaped cycle, offering new insights into long-term growth and economic fluctuations.

2.2 Empirical Review

2.2.1 Green Innovation and Green Economic Growth

Green growth has garnered significant attention from researchers and international organisations (Geddes et al., 2018; Guo et al., 2020). The pursuit of rapid economic growth frequently leads to environmental degradation, highlighting the need for green technologies to mitigate climate risks (Lin & Zhu, 2019). Green GDP, a key indicator of green growth, integrates the impact of emissions, resource exploitation, and externalities to guide sustainable development policies (Rahim & Noraida, 2015). For example, Popp (2012) and Ulucak and Danish (2020) stated that technological progress is essential to transforming industrial structures toward sustainability. In addition, empirical studies have supported the role of green technologies in promoting sustainable growth. Sohag et al. (2019) demonstrated the short-term benefits of technological innovation for green growth in Turkey, whereas Ulucak (2020) highlighted the significance of energy-efficient technologies in emerging economies. In newly industrialised nations, Khurshid and Deng (2021) noted that climate mitigation technologies are particularly effective in the transportation and water treatment sectors. Similarly, the adoption of renewable energy has driven sustainable growth in BRICS countries (Ulucak & Khan, 2020) and China (Wang et al., 2021). Studies on Europe (Nosheen et al., 2021), OECD nations (Sohag et al., 2021), and South Asia (Ahmed et al., 2022) have reinforced the positive relationship between green innovation and economic growth, underscoring the need for sustained investment and policy support to promote global sustainability.

2.2.2 The Role of Financial Development in the GI–GEG Nexus

With growing global concern for environmental protection and economic development, financial development has emerged as a key driver of sustainable growth, facilitating capital accumulation, resource allocation, and technological innovation (Nykvist & Maltais, 2022). As financial systems evolve, they enable economies to transition toward low-carbon and environmentally friendly pathways. United Nations Environment Programme (2008) emphasised the role of financial systems in channelling capital flows into low-carbon development projects and policy incentives, thus promoting economic progress and environmental sustainability. Similarly, Guru and Yadav (2019) highlighted the strong correlation between a robust banking sector and economic growth, with efficient resource allocation and strengthened resilience as key outcomes. Beyond traditional banking functions, Schiederig et al. (2020) noted that green lending and equity investments stimulate the research, development, and commercialisation of clean technologies, creating synergies that drive green economic growth across industries.

Further evidence confirms the role of financial development in promoting green practices and reducing environmental pollution. Li et al. (2021) demonstrated how financial systems foster green innovation, achieving the dual benefits of improved environmental quality and accelerated economic growth. Likewise, Huang et al. (2022) highlighted the contribution of green finance to enhancing green total factor productivity, improving resource efficiency, and advancing sustainable economic stability. Green finance can facilitate technological advancement and promote long-term green economic stability by encouraging investments in environmentally sustainable ventures.

2.3 Theoretical Framework

This section lays the conceptual foundation for the empirical model, building on the theoretical and empirical literature reviewed above. While Sections 2.1 and 2.2 presented the main economic growth theories and associated empirical findings, this section explicitly maps those theoretical insights to the variables in our model and clarifies their roles in the analytical framework.

Our study draws on multiple strands of growth theory to inform variable selection and model structure, each providing conceptual support for the selection and functional roles of variables, including green innovation, financial development, human capital, and clean energy production, in shaping green economic growth.

Table 1 provides a comprehensive mapping between key theoretical mechanisms and the variables in our model to operationalise these theoretical foundations within our empirical analysis. Each variable is grounded in specific growth theories, and its expected influence on green economic growth is conceptually justified through well-established propositions. This framework ensures that our empirical strategy is theoretically sound and policy-relevant.

This theoretical mapping provides the analytical foundation for the model specification introduced in the following section.

Table 1: Theoretical foundations

Variables	Theoretical mechanism	Growth theory	Theoretical proposition	Expected effect
Green innovation (LNGI)	Technology-driven productivity and eco-efficiency	Classical model Endogenous growth theory	Green innovation enhances productivity while mitigating environmental harm.	Positive
Financial development (LNFD)	Resource allocation, innovation financing	Endogenous growth theory Dependency theory	Financial development enables the implementation and diffusion of green technologies.	Positive (moderating variable)
Human capital (LNHCI)	Innovation absorption, learning-by-doing	Endogenous growth theory Growth stage theories	Human capital supports the absorption and application of green innovations.	Positive

Variables	Theoretical mechanism	Growth theory	Theoretical proposition	Expected effect
Labour force (LNLF)	Labour productivity and demographic effects	Classical model Dual economy models	A productive labour force drives output and supports efficient resource use.	Positive
Clean energy production (LNCEP)	Low-carbon transformation and resource substitution	Growth stage theories Classical models (environmental extension)	Clean energy adoption reflects sustainable transformation and efficient resource substitution.	Positive
R&D personnel (LNR)	Knowledge creation and technology advancement	Endogenous growth theory Growth stage theories	R&D investment accelerates innovation and green technology advancement.	Positive

3. Research Methodology and Data Collection

3.1 Model Specification

The neoclassical Solow growth model assumes that the savings rate (s) and depreciation rates (δ) of capital (K) are exogenously constant. Y denotes the output, and the production function is characterised by scale invariance. Labour (L) and knowledge (A) expand steadily at respective rates n and g. Although this model captures the drivers of traditional economic growth, it overlooks environmental and sustainability concerns. To address this limitation, following Sohag et al. (2019), we define green economic growth (GG) as a sustainable economic growth model that adjusts conventional GDP by incorporating education expenditure and deducting the economic costs of natural resource depletion and environmental degradation. The formulation of green GDP is expressed as follows:

$$GG_{\mathrm{t}} = GDP_t + EE_t - NRP_t - NFD_t - CO_{2t} \quad (3.1)$$

where GG is green economic growth, GDP is gross domestic product, EE is education spending, NRP and NFD are the monetary values of natural and forest resource depletion, CO_2 reflects environmental damage from emissions, and t denotes time.

Following the definition of green GDP, this study extends the growth framework by incorporating green innovation. Acemoglu et al. (2012) stated that green innovation supported by clean technologies and sustainable practices drives long-term economic growth. Romer (1990) and Lucas (1988) emphasised the role of human capital in knowledge-based economies. However, Stern (2004) highlighted the importance of labour quality. Accordingly, green economic growth is modelled as a function of green innovation (GI), human capital (HCI), labour force (LF), and other relevant factors (Z) as follows:

$$GG_{it} = GI_{\mathrm{it}}^{\lambda} HCI_{it}^{\alpha} LF_{it}^{\beta} Z_{it}^{\delta} \tag{3.2}$$

This study constructs an empirical model that integrates GI, human capital, and labour as primary determinants based on this theoretical framework. This model is estimated using data from RCEP member countries, drawing on empirical insights from Wang et al. (2020), Maity and Sinha (2021), Salleh et al. (2022), and Li et al. (2023). All explanatory variables were log-transformed to facilitate regression and enable the elasticity-based interpretation of coefficients. The baseline regression model is presented as follows:

$$\begin{aligned} GGDP_{it} = {} & \alpha_0 + \alpha_1 LNGI_{it} + \alpha_2 LNFD_{it} + \alpha_3 LNHCI_{it} + \\ & \alpha_4 LNLF_{it} + \alpha_5 LNCEP_{it} + \alpha_6 LNR_{it} + \phi_i + \lambda_t + \varepsilon_{it} \end{aligned} \tag{3.3}$$

Furthermore, this study introduces the interaction term green innovation financial development to the model to test whether financial development moderates the relationship between GI and the green economy. After considering all factors and combining equation (3.3), the augmented model can be presented as follows:

$$\begin{aligned} GGDP_{it} = {} & \alpha_0 + \alpha_1 LNGI_{it} + \alpha_2 LNFD_{it} + \alpha_3 LNGI_{it} \times LNFD_{it} \\ & + \alpha_4 LNHCI_{it} + \alpha_5 LNLF_{it} + \alpha_6 LNCEP_{it} + \alpha_7 LNR_{it} + \phi_i + \lambda_t + \varepsilon_{it} \end{aligned} \tag{3.4}$$

GGDP, *LNGI*, *LNFD*, *LNGI*LNFD*, *LNHCI*, *LNLF*, *LNCEP*, *LNR*, and μ represent green *GDP*, log of *GI*, log of financial development, log of green innovation, log of financial development, log of *HCI*, log of the *LF*, log of cleaner energy production, and log of researchers in *R&D*, respectively. φi and λ_t represent the unobserved country- and time-specific effects, respectively. ε_{it} represents the error term.

This study employs the TWFE model for estimation to examine the relationship between GI and GG and explore the moderating role of financial development. The TWFE concept developed gradually from the late 1970s to the early 1980s, and it was expanded and refined by Baltagi (1985) and Justman and Thisse (1988). This method can simultaneously control for unobserved country- and time-specific effects, reducing the bias caused by these factors and offering superior explanatory power compared with alternative models (Wooldridge, 2021). In addition, the TWFE approach effectively mitigates omitted variable bias because it controls for individual and time-invariant characteristics, improving the reliability and precision of the estimation results (Hasan & Du, 2023).

3.2 Data Collection

This study uses a balanced panel data set covering 15 RCEP countries from 2000 to 2021. The description and data source of each variable are shown in Table 2.

Table 2: Description of variables and data sources

Variables	Description	Unit of Measurement	Data Sources
Green economic growth	Green GDP	Green GDP per capita = GDP + EE − NRP − NFD − CO_2	World Development Indicator (WDI)
Green innovation	Green patents	Number of green patents related to the environment	Organisation for Economic Cooperation and Development (OECD)
Financial development	Net domestic credit from the financial sector	Local currency	World Development Indicator (WDI)
Human capital index	Schooling duration and educational returns	Index	Penn World Table
Labour force	Labour supply from those aged 15 and above	Total working population aged 15+	World Development Indicator (WDI)
Cleaner energy production	Renewable energy sources	Renewable energy sources used to generate electricity (kWh)	World Development Indicator (WDI)
Researchers in R&D	Number of people engaged in R&D	Millions of people	World Development Indicator (WDI)

4. Empirical Results and Discussions

This study uses the TWFE model to analyse the relationship between GI and GG and examine the moderating effects of financial development. This model effectively reduces the influence of unobserved factors on the estimation results by controlling for country- and time-specific effects.

4.1 Baseline Regression Results

Table 3 presents the baseline results using a TWFE model to examine the effect of GI (LNGI) on green GDP (GGDP) and the moderating role of financial development (LNFD). Column 1 includes LNGI and control variables. Column 2 adds LNFD to assess its direct effect. Column 3 introduces the interaction term between LNGI and LNFD to capture the moderating effect of financial development on the green innovation–green GDP relationship.

Green innovation (LNGI) drives green economic development in RCEP member countries. Specifically, a 1% increase associated with 1.678, 1.691, and 1.086 percentage point increases in Green GDP across Models 1-3, respectively. This effect holds even after including financial development in Model (2) and the interaction term between green innovation and financial development in Model (3). This finding suggests that technological innovation is a key tool for environmental protection and a driver of sustained economic growth (Schumpeter, 1942). The Green Solow model's theoretical framework emphasises that sustained economic growth depends heavily on technological progress regarding limited resources and increasing environmental pressures. Green innovation is central to increasing productivity, reducing waste, and optimising resource allocation (Söderholm, 2020; Sohag et al., 2021; Ahmed et al., 2022; Maiti, 2022).

Table 3: Estimation results: Moderating Effect of Financial Development on the Green Innovation–Green GDP Nexus

	Model 1 **GGDP**	**Model 2** **GGDP**	**Model 3** **GGDP**
LNGI	1.678*** (0.419)	1.691*** (0.415)	1.086** (0.446)
LNHCI	11.47** (5.408)	11.23** (5.356)	11.22** (5.260)

	Model 1 **GGDP**	**Model 2** **GGDP**	**Model 3** **GGDP**
LNLF	14.27*** (3.556)	13.83*** (3.525)	15.12*** (3.502)
LNCEP	0.327*** (0.105)	0.319*** (0.104)	0.314*** (0.101)
LNR	1.803*** (0.585)	1.802*** (0.579)	1.689*** (0.569)
LNFD	—	3.379** (1.365)	3.361** (1.341)
LNGI*LNFD	—	—	0.285** (0.110)
_cons	−249.3*** (57.53)	−242.3*** (57.04)	−264.5*** (56.75)
Year	Yes	Yes	Yes
Country	Yes	Yes	Yes
N	330	330	330
R-sq	0.368	0.383	0.407
F-test	58.37	53.09	54.92

Note: The dependent variable is green GDP. GI: green innovation, FD: financial development, LF: labour force, HCI: human capital index, CEP: cleaner energy production, and R: researchers in R&D. GI*FD is the interaction term between green innovation and financial development. All independent variables are estimated in logarithmic form. *, **, and *** refer to significance at 10%, 5%, and 1%, respectively, and parentheses indicate standard errors.

Furthermore, human capital (LNHCI) significantly and positively impacts green GDP. A 1% increase in human capital is associated with a 11.47 percentage point increase in GGDP in Model (1), a 11.23 percentage point increase in Model (2), and a 11.22 percentage point increase in Model (3). This demonstrates that a labour force with more education possesses higher productivity and innovation capacity, enabling it to absorb and apply green technologies more efficiently. Our results are consistent with the Cobb–Douglas production function theory, which posits that human capital amplifies the role of capital in driving economic growth by increasing labour's marginal productivity and optimising the combination of capital and labour (Brock & Taylor, 2010; Bello & Suleiman, 2020).

Financial development (LNFD), measured as the logarithm of net domestic credit provided by the financial sector, shows a significantly positive effect in Columns 2 and 3, with coefficients of 3.379 and 3.361, respectively. In practical terms, a 1% increase in financial development contributes to a rise in green GDP exceeding 3 percentage points, emphasising the importance of credit availability and financial intermediation in mobilising investment toward low-carbon sectors. The magnitude of the impact highlights the central role of financial systems in enabling environmentally aligned economic transformation. This result aligns with the findings of Rafindadi and Usman (2020), Zhang et al. (2021), Jiang and Ma (2022), and Liu et al. (2023). The growth pole theory further explains its spillover effect, as financial support enhances the development of core industries and green technologies, promoting economic transformation (Perroux, 1950; Levine, 2005).

Similarly, labour force (LNLF) exhibits a positive and statistically significant coefficient across all model specifications, underscoring the central role of labour resources. A 1% increase in the labour force corresponds to a 14.27 percentage point increase in GGDP in Model (1), a 13.83 percentage point increase in Model (2), and a 15.12 percentage point increase in Model (3). In labour-intensive RCEP countries (e.g., Vietnam and Indonesia), broad labour force participation facilitates the diffusion and application of green technologies, enabling these countries to quickly adapt to technological changes and achieve green economic growth (Hassan & Rafique, 2020; Amin & Ayub, 2020).

The interaction term between LNGI and LNFD (LNGI*LNFD) is positive and significant at the 1% level in Column 3, with a coefficient of 0.285. This finding indicates that financial development enhances the impact of green patent activity on green GDP. For every 1% increase in financial development, the marginal contribution of GI to green GDP increases by 0.285 percentage points. Specifically, RCEP countries promote green economy growth through credit and investment and by enhancing this effect when combined with green innovation. This finding supports the view that financial development funds innovation and facilitates its diffusion and commercialisation, mainly for technologies that align with sustainability goals, enabling them to transform more effectively into economic growth drivers (Wang et al., 2020; Zhang et al., 2021; Zhang & Wang, 2021).

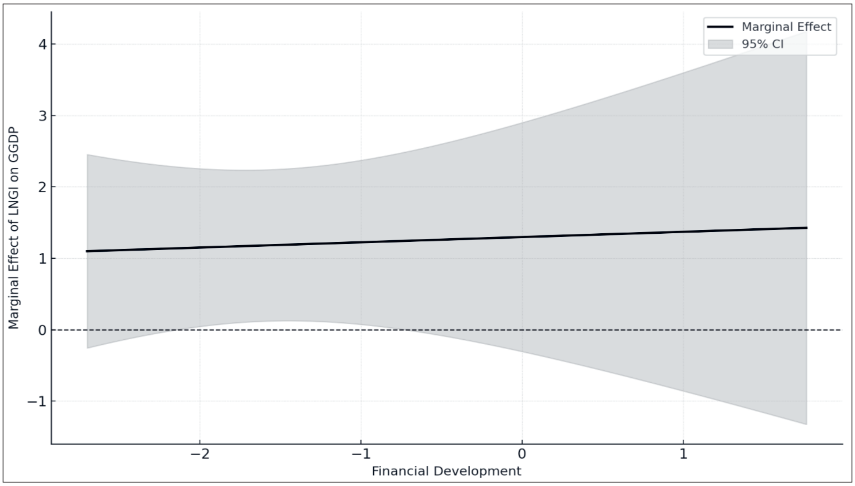
Moreover, clean energy production (LNCEP) and R&D personnel (LNR) demonstrate strong and significant positive associations with green GDP. Expanding clean energy sources reduces dependence on fossil fuels, mitigates carbon emissions, and ensures long-term energy security, which are critical outcomes for sustained green growth in RCEP countries (Pan & Dong, 2023). Meanwhile, increased R&D personnel indicate stronger innovation capacity and scientific progress, accelerating green technology breakthroughs and industrial applications and reinforcing the innovation-led sustainability transition (Zhang & Li, 2022).

These findings are consistent with the theoretical framework discussed in Section 2 and reinforce the multidimensional pathways through which GI and enabling conditions affect sustainable economic performance.

Figure 4 provides a marginal effects plot that illustrates the moderating relationship.

The marginal effect of GI remains positive and increases with higher levels of financial development (Figure 4). It rises from approximately 1.2–1.5 percentage points as financial development progresses from its lower to upper range, reinforcing the interpretation of financial development as a meaningful moderator. This visual evidence supports the regression findings by revealing that countries with more developed financial systems benefit more from green innovation in terms of GG.

Figure 4: Financial development as a moderator of the effect of green innovation on green economic growth



Note: Figure 4 illustrates the marginal effect of green innovation (LNGI) on green economic growth (GGDP) at varying levels of financial development. The solid black line represents the estimated marginal effect, and the shaded grey area denotes the 95% confidence interval.

4.2 Addressing Endogeneity Using 2SLS

The findings based on the TWFE model may not be reliable because of the potential endogeneity of the independent variables. This study employs instrumental variables for Two-Stage Least Squares (2SLS) estimation to eliminate simultaneous bias, with the aim of mitigating the endogeneity problems caused by omitted variables, measurement error, or reverse causality. Specifically, the lagged value of LNGI is used as an instrument for GI and regressed on the instrumental and other variables in the model (Table 4).

The 2SLS results (Table 4) confirm the validity of the instrumental variable (L.LNGI), which is significant at the 1% level with a coefficient of 0.553 in the first-stage regression. The weak identification statistic (143.854) far exceeds the critical threshold of 16.38, indicating strong instrument relevance. In the second stage, green innovation (LNGI) remains positively associated with green GDP (GGDP), with a coefficient of 3.208, which is significant at the 1% level. Accordingly, the impact of GI on GG is robust even after addressing endogeneity concerns.

Table 4: 2SLS estimation

	Model 4 **LNGI**	**Model 5** **GGDP**
L.LNGI	0.553*** (0.046)	—
LNGI	—	3.208*** (0.728)
LNHCI	0.292** (0.077)	11.343* (5.493)
LNLF	−0.375 (0.424)	14.637*** (3.629)
LNCEP	0.038** (0.013)	0.222** (0.003)
LNR	0.056** (0.052)	1.449* (0.609)
LNFD	0.037* (0.056)	3.445* (1.400)
N	315	315
R-sq		0.405
Under identification test	108.445	
Weak identification test	143.854	

Note: *, **, and *** refer to significance at 10%, 5%, and 1%, respectively, and parentheses indicate standard errors.

4.3 Robustness Tests

Several robustness checks were conducted to ensure the reliability of the baseline findings, such as quantile regression, trimming extreme values, the inclusion of additional control variables, and instrumental variable regression (2SLS).

Quantile regression confirms that the positive effect of GI and the interaction term holds across different quantiles of green GDP distribution, with stronger effects observed at the upper quantiles. Consequently, innovation yields greater economic benefits in more developed or environmentally advanced economies.

Trimming regression excludes the top and bottom 1% of observations to mitigate the impact of outliers. The results remain stable and statistically significant, indicating the robustness of the findings to data extremes. Additional controls, such as population density and national competitiveness, were included to test model specification robustness. The inclusion of these variables does not materially affect the signs or statistical significance of the main coefficients.

Detailed tables for each robustness specification are included in Appendix Tables A1–A2 to avoid overloading the main text. The key findings are summarised in Table 5.

Table 5: Summary of Robustness checks

Robustness Specification	Key Findings	Implications
Quantile regression	Effects remain positive across quantiles (Q25: 0.094*, Q50: 0.102**, Q75: 0.124***, Q90: 0.098***)	Green innovation has stronger impact in economies with higher green GDP performance
Trimming top and bottom 1%	Coefficients (LNGI: 2.317***, LNGI × LNFD: 0.281**) comparable to baseline	Results are not driven by extreme values or outliers
Inclusion of additional controls	Coefficients retain sign and significance after including population density and national competitiveness	The relationship is robust to model specification changes

4.4 Summary

The baseline results demonstrate a strong and economically meaningful relationship between GI and GG. In addition to its direct contribution to green GDP, financial development strengthens the impact of innovation. These findings are robust to various specifications and are supported by the visual analysis of marginal effects. The convergence between theory, regression output, and interaction plots provides compelling evidence that financial development significantly enhances the effectiveness of GI in driving sustainable economic growth. The following section discusses policy implications based on these findings.

5. Conclusion

This study provides important insights into the relationship between GI and GG, as well as the key moderating role of financial development in promoting sustainable development in RCEP member countries. The empirical results demonstrate that GI contributes to advancing GG, enabling countries to reduce their dependence on resource-intensive industries by improving production efficiency and encouraging the adoption of clean technologies. Moreover, financial development amplifies this effect by facilitating more efficient resource allocation, reducing financing barriers for innovation, and providing long-term capital to support the diffusion of green technologies.

Furthermore, this study highlights the importance of complementary factors, such as human capital, LF expansion, clean energy production, and R&D investment. These elements support the development and deployment of eco-friendly technologies while enhancing the overall innovation capacity and the economy's resilience to environmental shocks. A series of empirical tests confirmed the robustness of these findings, providing strong support for the proposed relationships.

Beyond its regional focus, this study makes several significant theoretical and methodological contributions. First, it introduces and empirically tests the moderating effect of financial development on the green innovation–green growth nexus, revealing how financial systems can enhance the productivity and impact of green technologies. Although this interaction mechanism has been widely acknowledged in theory, it has been underexplored in empirical studies. Second, the study provides a more accurate reflection of the trade-offs between economic development and environmental sustainability by adopting green GDP instead of conventional GDP to measure economic performance. Third, the inclusion of a diverse set of RCEP economies enables a comparative analysis of how institutional and economic heterogeneity influences the effectiveness of GI and financial development, enriching the cross-country understanding of green transition pathways.

Building on the empirical results, this study identifies two key mechanisms through which financial development promotes GG. First, it enhances access to capital and reduces financing constraints, enabling industrial sectors to invest in clean production processes and energy-efficient technologies. Second, it supports the development of green financial instruments (e.g., green bonds, green credit, and sustainability-linked loans), which help internalise environmental costs and lower the financial burden of green transitions. These mechanisms are particularly critical in RCEP economies, many of which remain heavily reliant on fossil fuels. Therefore, financial development serves as a catalyst for GI while facilitating structural transformation in carbon-intensive industries.

In conclusion, this study emphasises the importance of leveraging the synergistic interaction between GI and financial development to accelerate the transition toward environmentally sustainable economic growth. Policymakers in RCEP countries should focus on strengthening the institutional frameworks that support green finance, promoting financial inclusion for clean technology enterprises, and incorporating environmental risks into financial decision-making processes. Moreover, adopting green GDP as a policy evaluation tool can help governments better monitor progress and align economic goals with environmental responsibilities. These efforts will enable RCEP economies to lead the global green transition while contributing meaningfully to achieving SDGs.

Declaration

There is no conflict of interest associated with this manuscript.

CRediT author statement:

(i) **Wei Zhai, Hanny Zurina Hamzah, Wan Norhidayah W Mohamad**: Conceptualization/ formulation of ideas. (ii) **Wei Zhai, Hanny Zurina Hamzah, Wan Norhidayah W Mohamad**: Development/ Design of methodology. (iii) **Wei Zhai**: Data collection/ curation. (iv) **Wei Zhai**: Formal analysis. (v) **Wei Zhai**: Writing- Original draft preparation and editing.

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Appendix

Table A1: Sensitivity analysis

Variables	Model (6) Q25	Model (7) Q50	Model (8) Q75	Model (9) Q90
LNGI	0.094*** (3.927)	0.102*** (5.958)	0.124*** (5.282)	0.098*** (6.548)
LNHCI	0.054 (0.277)	0.578** (2.127)	1.107*** (8.781)	0.914*** (10.473)
LNLF	0.002 (0.138)	0.053** (2.025)	0.109*** (8.295)	0.093*** (9.447)
LNCEP	0.030*** (6.352)	0.026*** (3.090)	0.028*** (3.908)	0.011*** (1.627)
LNR	0.033** (1.972)	0.022 (1.161)	0.001** (0.093)	0.011** (2.061)
LNFD	0.008 (1.790)	0.007* (1.290)	0.013*** (2.803)	0.005*** (1.063)
LNGI*LNFD	0.012** (5.326)	0.015*** (5.124)	0.018*** (4.147)	0.010*** (4.030)
Constant	2.267*** (5.729)	3.861*** (6.947)	5.272*** (23.879)	5.504*** (37.656)
Observations	330	330	330	330

Note: *, ** and *** refer to significance at 10%, 5% and 1% respectively and parentheses indicate standard errors.

Table A2: Sensitivity analysis

	Model (10) GGDP_w	Model (11) GGDP_w	Model (12) GGDP_w	Model (13) GGDP
LNGI	1.733*** (0.289)	1.885*** (0.302)	2.317*** (0.325)	1.069** (0.441)
LNHCI	4.656*** (1.475)	4.565*** (1.498)	5.519*** (1.500)	12.682** (5.202)
LNLF	8.984*** (2.287)	9.509*** (2.393)	10.07*** (2.358)	31.531*** (6.418)
LNCEP	0.350** (0.171)	0.359** (0.177)	0.396** (0.174)	0.336*** (0.101)
LNR	0.629** (0.271)	0.921** (0.365)	0.908** (0.359)	1.432** (0.578)
LNFD	–	2.142** (1.347)	2.398* (1.326)	3.217** (1.321)

	Model (10) GGDP_w	**Model (11) GGDP_w**	**Model (12) GGDP_w**	**Model (13) GGDP**
LNGI*LNFD	–	–	0.281*** (0.0852)	0.251** (0.110)
LNPOP	–	–	–	-32.146*** (10.614)
LNNC	–	–	–	2.833* (3.386)
_cons	-133.130*** (35.630)	-145.6*** (37.30)	-152.4*** (36.71)	-386.315*** (68.098)
Year	Yes	Yes	Yes	Yes
Country	Yes	Yes	Yes	Yes
N	330	330	330	330
R-sq	0.320	0.346	0.371	0.429
F-test	64.29	57.64	60.39	51.09