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UNVEILING THE EFFECT OF DIGITAL FINANCIAL INCLUSION ON ENVIRONMENTAL DEGRADATION IN ASIAN ECONOMIES UNDER LCC HYPOTHESIS

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ABSTRACT

Purpose: Digital financial inclusion (DFI) is a vital element for a country's growth and progress. Access to digital financial services not only enhances individuals' capacity to contribute to economic activities, but it also has the likely to contribute to environmental degradation. The main aim of this study is to scrutinise the role of DFI in environmental degradation in selected Asian nations within the framework of the LCC hypothesis.
Design/Methodology: The research study used annual secondary data collected from various sources, including the WDI website from 2017–2023. The dependent variable is environmental degradation, which is proxied by consumer-based carbon dioxide emissions. Likewise, for the independent variable, DFI, the study used the availability dimension (automated teller machines (ATMs) per 100,000 adults) and usage dimensions (number of depositors with financial institutions per 1000 adults and number of mobile money transactions per 1,000 adults), respectively. The study applied panel quantile regression along with some pre-requisite diagnostic tests.
Findings: The findings of the study showed that there is a significant relationship between DFI and environmental degradation. Likewise, the study also confirms the presence of the Load Capacity Curve (LCC) hypothesis for selected Asian economies.
Implications: The study holds significant implications for countries, encouraging them to enhance their inclusive energy efficiency, boost economic activity, and devise strategies to mitigate environmental degradation. Therefore, it is suggested that countries may use advanced technologies in order to improve environmental practices, which will later in the long run help them to mitigate GHG emissions and increases environmental sustainability.

Keywords: *digital financial inclusion, regression analysis, environmental sustainability, LCC hypothesis*

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INTRODUCTION

Sustainable development and global warming are two main challenges the world is facing today (Zaidi et al., 2021). In the past several decades, developing countries have seen large increases in economic development that has led to intensifying extraction and depletion of natural resources. Moreover, these countries have been affected by intensifying environmental damage that demands raising the level of awareness on environment and search for other mitigation strategies (Du et al., 2022). The cumulative emission of greenhouse gases (GHGs) into our environment as a result of human activities has led to climate change and an increase in average global temperature (Zheng et al., 2021). Carbon dioxide emissions (CO2), for instance, play a key role in global warming and result in considerable economic damage and social disruption (Rode et al., 2021). In earlier research, it has been found that mega diverse factors can impact CO2 including demographic expansion (Ali et al., 2022), use of renewable and non-renewable energy resources (Zhang et al., 2023), globalization, and economic development. Similarly, the environmental quality is negatively affected by the rapid growth and economic development (Wei & Lihua, 2022). Tackling these interrelated challenges is a necessary prerequisite to realise sustainable development in the region. Innovative solutions and collaborative efforts will be crucial as countries attempt to balance economic growth (GDP) with environmental preservation. Implementing DFI in their strategy can thus increase resource efficiency and cultivate sustainable behaviour, so to achieve a greener future (Khan et al., 2023; Wang et al., 2024).

Financial inclusion (FI) refers to the provision of accessible, affordable, and user-friendly financial products and services to all segments of society, with particular emphasis on under-served and marginalized populations. These services typically encompass transactions, payments, savings, credit, and insurance delivered in a responsible and sustainable manner (Ramesh et al., 2024). Digital financial inclusion (DFI), building on FI, uses the latest modern digital technologies to better access and lower transaction costs and offer new innovative financial solutions that are restructuring the global financial system architecture (Ozili, 2018). Informal dependency on formal institutions for access to finance by increasing access to finance, DFI can increase formal economic participation by broadening opportunities within and across sectors effectively lowering barriers to entrepreneurship, easing consumption smoothing, and allowing households and firms to better manage risks. Equally important, an inclusive financial system potentially creates incentives for environmental sustainability: ready access to credit, insurance and payment services can all support adoption of green technologies, energy efficient equipment and sustainable agricultural practices with implications for reducing carbon footprints at the household and firm level (Jiang & Ma, 2019). Technological breakthroughs inherent in DFI such as mobile banking, digital wallets, fintech-enabled lending and decentralized finance platform approaches can help clean up production techniques and stimulate investment in renewable energy; energy-efficient machinery and circular-economy solutions (Abbasi & Riaz, 2016; Acheampong et al., 2022). Research based on empirical evidence indicates that for DFI to show tangible impacts, it needs to take effect along with tailored incentives and adequate regulatory mechanisms to reduce emissions of CO2 through technology uptake and overall resource-use efficiency improvement (Liu et al., 2022).

The potential of DFI to promote inclusive growth and environmental sustainability is significant, but it is a not straight forwardly positive relationship. The growth of digital finance can be positively correlated to GDP and lead to increases in industrial or manufacturing activity, which under specific conditions could yield more GDP but also higher greenhouse gas emissions (GHGs), especially when emerging industries are not paired with corresponding investments in clean technologies (Frankel & Romer, 2017; Wang et al., 2022). Improved access to credit and payments can drive down barriers to entry, allowing for rapid scaling in production which can drive increased resource extraction, energy use and emissions associated with those actions if firms and consumers default towards the cheaper more carbon intensive option. In addition, despite DFI allowing investment in green solutions, a lack of financing is still one of the key barriers to widespread adoption of low-carbon energy interventions; many players have inadequate capital, collateral and also specific financial products required for switching to less carbon-intensive alternatives (Baulch et al., 2018; Fareed et al., 2022). This gives rise to a dual challenge for policymakers: leverage the ability of DFI to increase access to finance and stimulate innovations while also implementing strong regulation, segmented subsidy structures, and incentives that direct where money flows in terms of decarbonization. Appropriately crafted regulation, green financing instruments and public–private partnerships can reduce the risks associated with DFI-encouraged environmental degradation while maximizing its potential to facilitate cleaner production, resilient energy systems and sustainable development in the long-term (Wang et al., 2022). DFI offers a route towards inclusive economic growth and environmental progress, but achieving that potential is highly dependent on governance challenges, developing appropriate financial instruments for sustainability and coordination between financial policy with industrial strategy and environment policy.

Furthermore, while early strands of literature assumed a strictly uniform or linear baseline for technological and financial externalities, contemporary economic realities dictate a non-linear trajectory. Financial digitization does not influence ecological parameters in isolation; rather, its structural impact scales and morphs alongside an economy's core developmental stages and emission intensities. Consequently, this study explicitly integrates non-linear dynamics into its core empirical framework by tracking both scale and technique effects across a quadratic economic growth setting and varying institutional emissions thresholds.

Many South Asian countries have experienced rapid economic grow in recent decades. For South Asian countries meeting their environmental sustainability targets without compromising economic progress, the simultaneous reduction in environmental quality raises questions about the veracity of those growth assertions. Accordingly, the relevant authorities focus on curing environmental challenges of these countries (Wang et al., 2024). Ramesh et al. (2024) invested the necessary time to study how much change has taken place in Asian countries over past decades regarding the characteristics of financial services globalisation. Modern technologies are significant in the technological developments of the banking system from very simple traditional banking to DFI. As the economy grows, so does the need for economic and financial services globalization. Rapid growth of internet accessibility, widespread usage of mobile devices, and continuous financial innovation have caused a seismic shift in levels of access. As a result of this, previously disconnected communities have been able to access banking services, digital wallets and e-payment platforms. Consumer interests are also a huge factor that influences the way technology advancements are used and executed by governments and regulatory bodies. Likewise, Asian economies have also diversified financial ecosystem where some of the nations into world are adopting health banking practices as innovative fintech startups but in other part we still used old style commercial bank system.

With its role in making financial services more accessible and affordable, FI has significantly benefited economic development, while at the same time the environmental impacts of it must not be neglected (Shabir, 2024). We seek to close a significant existing gap in knowledge, as this study investigates the effects of DFI on carbon dioxide emissions among selected Asian economies. Past research on CO2 focused mostly only its Environmental Kuznets Curve (EKC) theory (Bekun et al., 2021; Wang et al., 2024). The study shifts attentions to the LCC hypothesis in a few Asian nations. The study used three proxies for DFI, including the number of ATMs per 100,000 individuals, which indicates access to financial services. Furthermore, it includes usage indicators such as the number of bank deposits per 1,000 individuals and the frequency of mobile money transactions per 1,000 adults (Ramesh et al., 2024; Shen et al., 2021). These indicators provide a comprehensive overview of the reach and utilization of digital financial services, which allows for an in-depth analysis on their potential environmental impact. Unlike most previous studies which have employed metric tons per capita as a proxy for CO2 (Patel et al., 2024), this work employs consumer-based CO2 as a more direct measure of ecologic damage than is possible with aggregated estimates. The study employs the panel quantile regression, a novel statistical technique that can consider the influences of explanatory factors along different quantiles ranging from 0.10 to 0.90. This yields a better assessment of the DFI–CO2 relationship, and how these relations might alter at different emission levels. Understanding these intricate and multifaceted relationships between DFI and CO2 is essential for governments, companies, and communities to more adeptly formulate solutions for the facilitation of both DFI and environmental degradation.

By mapping these complex variables, this study provides three core theoretical and empirical contributions to the extant literature:

First, it expands the theoretical frontier by moving beyond the over-researched Environmental Kuznets Curve (EKC) framework to test the Load Capacity Curve (LCC) hypothesis under the influence of financial digitization. While the EKC focuses narrowly on environmental degradation via carbon outputs, the LCC framework provides a more robust, holistic perspective by accounting for the environmental carrying capacity, biocapacity, and supply-side constraints of ecosystems. Second, this study advances empirical accuracy by replacing traditional, production-based aggregate CO2 metrics with consumption-based CO2 emissions. Traditional indicators distort the environmental footprint of developing nations by neglecting trade-embodied emissions and international supply-chain transfers. Because digital financial technologies (such as mobile money and digital credit) primarily empower the demand-side capacity of households and domestic small-to-medium enterprises (SMEs), using consumption-based emissions ensures a direct, uncorrupted look at how localized digital spending patterns trigger environmental degradation. Third, from a methodological standpoint, rather than assuming a uniform impact through conditional mean estimators (like OLS or fixed-effects models), This study deploy a comprehensive panel quantile regression framework. This approach reveals structural asymmetries across different emission thresholds. It allows us to observe whether the environmental consequences of digital financial integration change as a country transitions from a low-emission, clean-energy state to a highly polluted, fossil-fuel-dependent industrial state. This granular tracking provides policymakers with targeted, quantile-specific environmental regulations rather than generic, one-size-fits-all mandates.

This study is structured as follows: Section 2 presents the state of relevant accessible literature. Section 3 explains the data collection and methodology. Sections 4 and 5 of this work offer a discussion of the results obtained, along with conclusions.

LITERATURE REVIEW

Digital Financial Inclusion and Environmental Degradation

There have been several recent studies exploring complex interconnections between financial inclusion (FI) and other, usually technological, development processes, as well as environmental outcomes like CO2 emissions, generating mixed results. In Oanh (2024), the interaction of technological progress, financial development, DFI and ecological variables is investigated based on annual data. The study found that DFI positively impacts environmental quality in a low-development-country context, meaning that where financial technologies make affordable access to financial services more widespread, they also help drive investments in less-polluting technologies and energy-efficient machinery and process codes among other things beneficial for sustainability. That finding suggests that in contexts with limited traditional finance infrastructure, the use of digital channels can help alleviate capital-access barriers and facilitate greener transitions at both household and firm levels.

In addition, Shabir (2024) studied the relationship between FI and CO2 emissions while using economic globalization and technological innovation as moderators. In an analysis based on annual data from 2004 to 2018, findings showed that financial inclusion as well as increased renewable energy deployment "jointly contribute to and improve" environmental sustainability by reducing CO2 emissions. The moderating role of technological innovation and globalization suggests that FI's environmental impact is closely conditioned by the surrounding economic and technological context: backgrounded by innovation and global integration, FI redirects resources more effectively towards low-carbon alternatives. Similarly, Fareed et al. (2022) focused on 27 European countries during the period of 1995–2018 to analyze how the FI-CO2 relationship is moderated by innovation activity. They found significant connections between FI and environmental degradation, showing that financial inclusion in itself does not necessarily function as a panacea; whether its environmental impacts are positive or not are conditioned by the characters of investment choices, innovation trajectories, policy frameworks that channelise financial flows.

Zheng et al. (2023) investigated FI and eco-performance in heavily polluted countries and discovered a strong negative relationship between FI and CO2 emissions, suggesting improved access to financial services could be associated with quantifiable reductions in emissions within highly polluted environments. This implies that targeted financial mechanisms (e.g., green loans, insurance products for renewable ventures, mobile finance) for the energy-saving household appliances can generate substantial environmental non-pecuniary gains at places where pollution pressures are higher. In contrast, Le et al. (2020) used 31 Asian countries' data between 2004 and 2014 and highlighted the pronounced positive effect of income, FI, and energy consumption on CO2 emissions. Their results highlight a warning path: increased financial inclusion could lead to consumer and economic activity that elevates emissions (especially in carbon-intensive economies), unless it is accompanied by policy measures and sustainable-finance products.

Indeed, an increasing number of empirical studies have investigated the multidimensional relationships between DFI, more general FI, economic growth and CO2 emissions, yielding context-specific results that differ based on their method and country characteristics. Wang et al. (2022) used annual data for China to investigate the relationship between DFI and CO2 emissions and found a positive, statistically significant association. Their results indicate that the swift development of digital financial services in China by reducing transaction costs, expanding credit availability and supporting innovative business models might have caused indirect industrial expansion and energy consumption, resulting in more emissions. This result illustrates a possible unintended consequence of DFI growth whereby digital finance leads to economic activity that outpaces decarbonization efforts, primarily in energy-intensive economies.

Mehmood (2022) also examined the impact of FI and GDP on CO2 emissions in relation to the EKC, which concluded that both GDP and financial inclusion cause an increase in emissions. With EKC logic, emissions can increase in early stages of economic and financial development (as incomes, consumption, and industrial output grow), but at later income thresholds structural change and cleaner technologies may be able to turn that trend around. Mehmood’s findings highlight that broadening financial access, without the introduction of climate-targeted green finance instruments or regulatory incentives to reinforce low carbon consumption and production patterns, may aggravate pathways toward higher carbon lifestyles. Contrastingly, Liu et al. (2022) provided a more differentiated perspective by decomposing FI into five dimensions and adopting ARDL techniques to assess their independent environmental effects in China. Their results show that four dimensions of FI are positively associated with better environmental quality, indicating that specific manner as access to finance through savings mobilization, insurance uptake and credit can contribute to investments in cleaner technologies and efficiency measures. However, Liu et al. also found that the population growth and GDP control variables were positively related to CO2 emissions, indicating pressures of demographic and economic expansion even with some wealth channels favouring environmental gains.

Zaidi et al. (2021) examined energy use, FI, and CO2 emissions in 23 OECD countries (from the period spanning from 2004 to 2017) and found a direct positive linkage among these three variables. In developed-country situations where aggregate consumption is high, broadened financial access may perpetuate lifestyles and industrial activity that secures comparatively high emissions in the absence of policy measures to decarbonise. Meanwhile, Khan et al. (2023) focused on less developed and developing countries using IMF and WDI datasets, and found that DFI were positively related to CO2 emissions significantly, in support of lower-income settings where access to digital finance could primarily fund growth of the carbon-intensive sectors. Zhang et al. (2024) explored the interrelationships between green investment, DFI and environmental sustainability and revealed a positive correlation among these variables. Their findings indicate that when digital financial services reduce transaction costs and broaden access to customized financial products, they funnel capital toward green projects, renewable energy, energy-efficient infrastructure and sustainable agriculture, thus bolstering environmental outcomes. Digital avenues also enable transparency and oversight of sustainable investments, allowing better targeting and impact of "green" finance.

Qing et al. (2024) expanded on this question by examining annual data from 2000-2020 for G20 economies to investigate the interplay between human development, FI, resource endowments and environmental impacts. They also found that, when human development and greater uptake of financial products were taken into account, ecological footprint decreased. This means that investments in education, health and human capital more broadly together with wider access to financial services can bend consumption and production toward less environmentally intensive pathways, allowing societies to use cleaner technologies and more sustainable consumption patterns. Importantly, Qing et al. show that FI's environmental benefits are enhanced at higher levels of human development and institutional capacity. Shahbaz et al. (2022) conducted a study that proved with annual data of 30 Chinese provinces from 2011 to 2017, financial inclusion greatly helped reduce pollutants and CO2 emissions. Their findings suggest that given credit, savings and insurance access at a localized level, firms and households are able to invest in both pollution-control technologies to reduce emissions as well as energy-efficient practices at subnational scales. Complementing this, Wang et al. Those of 2024 investigated the inverse U-shaped relationship between GDP and CO2 emissions consistent with Environmental Kuznets Curve (EKC) by looking at renewable energy, FI, climate technology and technological innovation's respective effects on CO2 emissions. This pattern indicates that at low levels of development, emissions increase with GDP but ultimately fall as economies shift to cleaner technologies and higher-value, lower carbon emissions processes goals that can be accelerated by FI and climate technology. Supporting these findings even more, Du et al. (2022) focused on developing countries and discovered that while CO2 emissions are negatively related to human capital and financial inclusion, improvements in environmental quality. The studies collectively offer a nuanced but positive message: that when FI or, more specifically, digital-enabled finance is complemented with climate-smart investments in key areas such as green investment, human capital and enabling technologies for the low-carbon pathways it can unlock at relatively modest costs. But to harness such benefits, we need policy alignment that steers financial inclusion towards environmentally productive uses and innovation, while also strengthening institutions so that the growth of financial services becomes a part of sustainable development rather than a vehicle for higher resource consumption.

Economic Expansion and Environmental Deterioration

Several recent empirical studies have explored the complex relationships among economic growth, natural resource rents, ICT, and environmental outcomes, with mixed support for the EKC and limited support for the LCC hypotheses across different regional contexts. Li and Haneklaus (2021) conducted an investigation on the case of China also found a strong U-shaped relation between CO2 emissions and GDP per capita. Their results suggest that, instead of the standard inverted-U, EKC that first predicts emissions rise, and then reduction with increasing income, China's path exhibits a sudden decline at certain levels of income, accompanied by renewed growth in emissions, consistent with structural factors including energy mix changes and policy processes causing rebound as development evolves forward. This U-shape finding underscores the appreciation of early action environmental and energy policies that can avert eventual emission growth during later stages of development. Shahzad et al. (2024) examined the LCC hypothesis in tourism and renewable energy of dominant global tourism economies using WDI data from 2000 to 2020. Their findings show that the singled-out countries do not optimize on the LCC spectrum, meaning that for these economies, tourism-fuelled growth and renewable energy uptake do not lead to an outcome of the predicted non-linear tax-revenue–or pollution–related dynamics extrapolated from those behind LCC. This finding reveals effort-induced heterogeneity in how tourism growth interacts with energy transitions and environmental pressures; for instance, tourism may be decoupled from emissions owing to clean-tourism strategies or carbon-laden where infrastructure and energy sources are lagging. Erdogan (2024), focusing on Africa, also documented the effects of natural resource rents on ecological sustainability over 1992 to 2020 and found evidence in favor of the EKC hypothesis but against the LCC hypothesis. Erdogan's research indicates that in African countries, development through resource extraction at first correlates with increasing environmental degradation that ultimately stabilizes or declines once economies cross certain income or institutional thresholds. The lack of LCC validity suggests, natural resource rents do not yield the same non-linear dynamics as posited by LCC due in part to divergent fiscal structures, governance quality and the character of rent allocation within resource abundant sub-Saharan African economies.

Ulussever et al. (2024) investigated the impact of income, globalization and two ICT indicators mobile cellular subscriptions and Internet consumption on environmental quality in six Gulf countries using annual data for the period from 2000 to 2019. Their findings show that adopting ICT improves environmental quality, which implies digital connectivity can lead to efficiency gains, better monitoring of the environment and diffusion of greener practices. Alternatively, economic growth and wealth among the GCC sample does not alter this relationship with ICT environment, and the LCC hypothesis cannot be universally applied to the entire panel; it applies individually for Qatar only. This heterogeneous outcome highlights that small, high-income, energy exporting countries have particular environmental dynamics, for which logic ICT-based improvements are not always the case; with sectoral energy profiles and the decisions on how to govern them obliterating any impact in some cases but being a major contributor in others. Recent empirical studies give mixed evidence for a relationship between GDP and CO2 emissions with strong heterogeneity across countries and time periods. Erdoğan et al. (2024) examine Canada and find a negative effect of GDP on CO2 emissions, implying that the scale of development reached by Canada allows for economic growth to be associated with cleaner production structures (with respect to carbon), technology adoption, and sufficiently strong environmental regulation that emission and economic growth can be decoupled. This finding reflects the downward arm of the EKC, where greater incomes ultimately provide funds for efficiency investments and structural changes toward less carbon-intensive sectors.

In contrast, multiple studies centered on China present a more nuanced picture. Usman et al. Using secondary data, (2024) refute the LCC hypothesis in the case of China by showing that the nonlinear dynamics proposed by LCC do not apply to China. Liu et al. (2023), covering China from 1995 to 2020, observe a positive relationship between GDP, energy use, and CO2 emissions such that economic growth continues to lead to increased emissions, where the fossil-fuel-based economy and growing energy demand remain. Conversely, Jin et al. (2022) find a signal effect between GDP and CO2 emissions in China when considering eco-innovation and human capital developments, which may offer an indication consistent with EKC: growth can go along with diminishing emissions as innovation and human capital improve. These divergent results for China imply that the effects of GDP on emissions are highly sensitive to complementary factors, such as energy mix, speed of technological diffusion, policy stringency, and growth composition. Regional studies also indicate variation. Pata et al. (2023) explore six ASEAN countries and find the

EKC among that group, suggesting that those economies may hint turning points in their growth paths after which emissions decrease as development continues and cleaner technologies spread. Osobajo et al. (2020) find a positive relationship between GDP and CO2 emissions, leaning towards the conclusion that in numerous cases, economic growth continues to entail increasing emissions, especially given the carbon-dependence of energy systems in many regions and weak environmental regulation.

On the empirical side, nuances between relations among economic growth, technological change, energy sourcing, and environmental outcomes continue to be explored in recent research, with a varying degree of results depending on country context, time horizon, and how one chooses to measure environmental indicators. Pata et al. (2024) contribute to this literature by analyzing LCF, a composite measure of environmental carrying capacity over the period 1980–2018. Their findings show that the LCC (load capacity curve) hypothesis does not apply in the timeframe examined here; rather, renewable energy deployment and R&D related technologies have a clear positive impact on environmental quality. Thus, this indicates that investments in technology and a transition to renewables could bolster ecological resilience even where the non-linear income–environment dynamics assumed by LCC are missing. Deng et al. (2024) extend this work by applying panel-data methods to test for the LCC hypothesis across a cohort of 10 top emitters from around the world during the period 1998–2018. They incorporate the economic complexity index (ECI), energy security measures, and renewable energy penetration as covariates of interest/ explanatory variables. Their results provide qualified support for the LCC hypothesis: empirical evidence only arises in the short-to-medium run rather than being stable as a long-run phenomenon. Additionally, Deng et al. confirm that the relationship between GDP and load capacity factor gave a U-shape, which means, at some stage of development, the influence direction may reverse. The addition of the ECI and energy-security indicators highlights that structural economic complexity, along with stable access to energy sources, conditions how growth interacts with environmental carrying capacity. In the context of more complex and energy-secure economies, the slope that connects GDP to environmental stress could vary altogether from simpler resource-dependent economies.

Studies focused on specific countries and regions also show heterogeneity in GDP emissions dynamics. Jinqiao et al. (2022) find a substantial negative effect of GDP on CO2 emissions for several E7 economies, indicating that in some fast-growing countries, expansion can be simultaneously compatible with emission abatement, perhaps due to modernization, structural transformation away from energy-intensive sectors, and rapid diffusion of new technologies. In contrast, Khan et al. (2020) discuss Pakistan and report that not only GDP but also energy consumption act as significant drivers leading to CO2 emissions, which is in line with findings in many developing economies where growth continues to be locked into fossil-fuel-intensive energy use and breakthroughs related to cleaner energy alternatives have not yet scaled.

METHODOLOGY

Data

The study used annual data for the selected ten Asian economies from 2017 to 2023. Specifically, the sample covers 10 Asian economies: Pakistan, Malaysia, Bangladesh, China, the Philippines, Turkey, Afghanistan, Indonesia, Thailand, and Cambodia. These countries were selected to ensure geographical representation across South, East, and Southeast Asia, and due to the complete availability of balanced data for all digital finance and emission variables. Table 1 presents the details about the variables, data sources, and measurements.

Table1: List of Variables and their Measurement

Variable	Measurement	Source
CO2 emissions	Consumer-based CO2 emissions	Global Carbon Atlas https://globalcarbonatlas.org/
Economic Growth (EG)	GDP per capita, Constant US Dollar 2015	World Bank https://data.worldbank.org/
Economic Growth (SQEG)	Square of GDP Per capita, Constant US Dollar 2015	World Bank https://data.worldbank.org/
Availability Dimension (ATM)	Number of automated teller machines (ATMs) per 100,000 adults	IMF https://www.imf.org/en/Data
Penetration Dimension (DAFI)	Number of deposit accounts with financial institutions per 1000 adults	IMF https://www.imf.org/en/Data
Mobile Money Transactions (MMT)	Number of mobile money transactions per 1,000 adults	IMF https://www.imf.org/en/Data
Trade (TR)	Trade (% of GDP)	World Bank https://data.worldbank.org/
Population (POP)	Population growth (annual %) (POP)	World Bank https://data.worldbank.org/

Industrialization (IND)	Industry (including construction), value added (% of GDP)	World Bank https://data.worldbank.org/

While a single composite index can offer an aggregated view of financial digitization, this study purposefully includes these three indicators individually as an un-aggregated proxy matrix. Collapsing them into a single index can introduce aggregation bias and conceal whether environmental impacts are driven by physical access (ATM) or transactional intensity (DAFI and MMT). Evaluating them as parallel parameters structurally captures the holistic digital finance ecosystem while ensuring granular, dimension-specific policy insights across the quantiles.

Model specifications

This study examines the impact of digital financial inclusion (DFI), on consumer-based carbon emissions (CO2) for selected Asian nations between 2017 and 2023. The dependent variable is consumer-based CO2, which we have selected to represent household- and consumption-side emission pressures. The main independent variable, DFI (digital financial services the access and usage dimension of the digital finance ecosystem), is proxied by three indicators as explained below (each one comes from the most recent available data): (1) ATMs per 100,000 adults (access to physical digital financial infrastructure); (2) number of depositors with financial institutions per 1,000 adults (financial account penetration/availability) and; (3) mobile money transactions per 1,000 adults (digital transactional usage). These proxies further enable the study to differentiate between the environmental impact of DFI in terms of physical interactions versus the volume of online transactions. The model allows for non-linear income environmental dynamics under LCC by including GDP and SQGDP.

It is critical to emphasize that this study does not assume a simplistic linear baseline between digital finance infrastructure, macroeconomic progression, and environmental footprints. The underlying framework explicitly accounts for complex polynomial and structural non-linearities under the Load Capacity Curve (LCC) hypothesis. First, polynomial non-linearity is explicitly modeled by embedding both linear economic growth (GDP) and its quadratic form (SQGDP) into the empirical equation. This structural inclusion ensures that the environmental impacts generated by scaling digital financial services are captured as dynamic forces that can transform or hit critical tipping points as a nation's per capita income expands.

Second, the deployment of Panel Quantile Regression (PQR) incorporates a vital layer of distributional non-linearity into this study analytical framework. Unlike traditional conditional mean estimators (such as Ordinary Least Squares or standard Fixed Effects models) which assume a static, linear impact across all data points, the PQR technique allows the parameters of our digital financial inclusion variables to fluctuate non-linearly. By tracking coefficients across varying conditional thresholds of the emission distribution (0.10, 0.20, 0.90), the model evaluates whether the environmental consequences of digital connectivity are fundamentally asymmetric when transitioning from a clean, low-emission regime to a highly polluted, high-emission regime.

Regarding our sample size (N=10, T=7), Panel Quantile Regression with Koenker's (2004) penalized fixed-effects approach is mathematically designed to remain highly efficient in focused panel datasets. Unlike OLS or GMM estimators that require large-sample distributions, this quantile layout resists outlier bias and avoids the incidental parameters problem, ensuring stable and valid threshold parameters for our 70 observations.

While the LCC framework traditionally relies on a composite index, this study uses consumption-based CO2 emissions to isolate the demand-side environmental degradation component of ecological capacity. Because digital financial inclusion primarily stimulates household consumption and retail commerce, consumption-based CO2 serves as a precise metric to evaluate how digital financial expansion impacts ecosystem limits under the LCC framework.

Methodologically, it uses panel quantile regression (PQR) to estimate the heterogeneous effects of DFI across the conditional distribution of CO2 instead of restricting itself to mean effect. The PQR, established by Koenker and Bassett (1978), adapts ordinary least squares to conditional quantile functions estimation that allows exploring the effect of covariates on other quantiles (e.g., lower, median, upper) in the emission distribution. This method is particularly useful when treatment effects vary across emission intensity for instance, there may be stronger impacts of DFI in low-emission vs high-emission country contexts. Because estimates of the fixed and covariate effects across quantiles can be biased due to the incidental parameters problem encountered by fixed-effects implementations of quantile regressions (Neyman and Scott 1948), the present study proceeds in line with Koenker’s (2004) suggestion for reducing bias by estimating fixed and covariate effects across all quantiles. The formal specifications in Equation 1 defines the τ-th conditional quantile of consumer CO2 as a function of DFI proxies, GDP and SQGDP (incorporating LCC nonlinearity), control variables and a quantile-specific error term. Robustness checks include alternative lag structures, subsample analyses, and tests for cross-sectional dependence and heteroskedasticity to ensure valid inference across quantiles and sample partitions.

$$Q_{y_{it}}(\tau \mid X_{it}, \alpha_i, \varepsilon_t = \alpha_i + \varepsilon_t + \beta_{1\tau} GDP_{it} + \beta_{2\tau} SQGDP_{it} + \beta_{3\tau} ATM_{it} + \beta_{4\tau} DFI_{it} + \beta_{5\tau} MMT_{it} + \beta_{6\tau} TRD_{it} + \beta 7\tau POPit + \beta 8\tau INDit \qquad (1)$$

Where as

y_i	=	Carbon dioxide emissions
EG_{it}	=	Economic growth
$EG^2{}_{it}$	=	Economic growth square

ATM_{it}	=	Automated Teller Machines per 100,000 adults
DFI_{it}	=	Depositors with financial institutions per 1000 adults
MMT_{it}	=	MMT stands for the number of mobile money transactions per 1,000 adults
POP_{it}	=	Population
IND_{it}	=	Industrialization
TRD_{it}	=	Trade
α_i	=	Country fixed effects
ε_t	=	Time fixed effects
t	=	Time period
i	=	country

While linear studies utilize mean-based estimators with Driscoll–Kraay errors or dynamic GMM frameworks (eg, Le et al., 2020), these setups are methodologically incompatible with our small panel layout (N=10, T=7). GMM encounters fatal instrument proliferation bias when N is small, while Driscoll–Kraay cannot capture asymmetric threshold effects across different emission quantiles. Instead, our Panel Quantile Regression employs a non-parametric cluster-robust bootstrap architecture, which natively handles cross-sectional dependence, heteroskedasticity, and autocorrelation without compromising the distribution-specific analysis.

RESULTS AND DISCUSSIONS

Descriptive Statistics

Table 2 displays the summary statistics using a measure of dispersion and a measure of central tendency. For every variable, there are 70 observations in total. 5.248, 26.560, 3.277, 3.269, 6.025, 7.733, 0.122, 3.372, and 3.994 are the mean values of CO2, GDP, SQGDP, ATM, DFI, MMT, POP, IND, and TR. Similarly, for the variables, the standard deviation is 1.860 for CO2, 1.794 for EG, 0.0067 for SQGDP, 1.319 for ATM, 1.209 for DFI, 2.258 for MMT, 0.741 for POP, 0.341 for IND, and 0.611 for TR. The selected variables have minimum and maximum values of 2.124 and 9.335 for CO2, 23.517 and 30.394 for GDP, 3.157 and 3.414 for SQGDP, -0.86 and 4.768 for ATM, 2.961 and 7.535 for DFI, 2.716 and 10.351 for MMT, -2.416 and 1.123 for IND, and 3.206 and 4.891. The results demonstrate that most of the variables are negatively skewed. The values of the Jarque-Bera test presented in the table indicate that the data set used for this study is not normally distributed. Therefore, based on this justification, this study applied a panel quantile regression approach to tackle this issue in the data set.

Table 2: Summary Statistics

	LCO2	LGDP	LSQGDP	LATM	LDFI	LMMT	LPOP	LIND	LTR
Mean	5.248	26.560	3.277	3.269	6.025	7.733	0.122	3.372	3.994
Median	5.435	26.605	3.281	3.663	6.538	8.487	0.290	3.469	3.820
Maximum	9.335	30.394	3.414	4.768	7.535	10.351	1.123	3.709	4.891
Minimum	2.124	23.517	3.157	-0.086	2.961	2.716	-2.416	2.307	3.206
Std. Dev.	1.860	1.794	0.067	1.319	1.209	2.258	0.714	0.341	0.611
Skewness	0.366	0.1140	-0.086	-0.984	-1.011	-1.012	-1.328	-1.472	0.2861
Kurtosis	3.252	3.077	2.940	3.176	3.077	3.009	4.460	4.406	1.538
Jarque-Bera	1.757	0.169	0.097	11.395	11.957	11.953	26.816	31.052	7.188
Probability	0.415	0.918	0.952	0.003	0.002	0.002	0.000	0.000	0.027
Observations	70	70	70	70	70	70	70	70	70

Source: author estimation

Correlation

Table 3 displays the outcomes of the correlation analysis. The results demonstrate a robust positive connection (0.724) between ATM and CO2, which is statistically significant at the 1% level. DFI had a weak negative correlation of -0.136, which is statistically insignificant. Similarly, MMT exhibits a negligible positive association (0.008) with CO2 and is statistically insignificant. IND exhibits a robust positive correlation (0.569) with CO2 at a 1% level of significance among the control variables. POP exhibits a robust negative association (-0.674) at a 1% significance level. The control variable, TR, exhibits a weak negative correlation of -0.0918, signifying that the connection lacks significance.

Table 3: Correlation

	LCO2	LATM	LDFI	LMMT	LIND	LPOP	LTR
LCO2	1						
LATM	0.724***	1					
	0.000						
LDFI	-0.136	0.2118*	1				
	0.261	0.078					
LMMT	0.008	0.115	0.1042	1			
	0.942	0.341	0.390				
LIND	0.569***	0.813***	0.113	0.173	1		
	0.000	0.000	0.351	0.15			
LPOP	-0.674***	-0.655***	0.038	-0.229*	-0.557***	1	
	0.000	0.000	0.753	0.056	0.000		
LTR	-0.0918	0.543***	0.205*	-0.120	0.511***	-0.1909	1
	0.449	0.000	0.087	0.321	0.000	0.113	

*, **and *** represent significant level at 10%, 5% and 1% respectively

Source: author estimation

Unit Root Test

This research study applied Phillips-Perron Fisher (PP) and ADF Fisher (ADF) tests to investigate stationarity among variables. Generally, the variables may be stationary at level I (0) or at first difference I (1). The findings from both tests showed that all the selected variables are stationary at first difference. Table 3 presents the result for the unit root (PP and ADF) for this study.

Table 4: Unit Root Test Results

	PP Fisher Test		ADF Fisher Test	
Indicator	**I (0)**	**I (1)**	**I(0)**	**I(1)**
LCO2	2.090	-3.472***	5.036	-2.520***
LGDP	6.354	-1.815**	8.597	-1.897**
LSQGDP	6.266	-1.834**	8.615	-1.914**
LATM	2.057	-2.451**	1.574	-1.988***
LDFI	5.221	-1.988***	2.211	58.227***
LMMT	4.831	-2.140**	4.327	-5.036***
LPOP	3.116	1.999**	26.815	35.061**
LIND	1.535	-1.833***	8.826	-5.596***
LTR	13.595	-1.060***	9.559	57.8723***

** and *** represent significant level at 5% and 1% respectively

Source: author estimation

Cointegration Analysis

The Kao cointegration test as shown in Table 5 also finds evidence for the existence of a cointegrating relationship among the variables in model (1).

Table 5: Test Result of Cointegration

Kao Cointegration Test		
Estimations	Statistics	P-value
ADF	-4.299	0.000

*** Significant 1% levels

Source: author estimation

Panel Quantile Regression

Before analyzing the individual digital finance coefficients, the model must be checked for systemic non-linearity. As shown in the tables below, both the linear income term (GDP) and its quadratic form (SQGDP) are statistically significant across most emission thresholds (0.10 to 0.90). The alternating signs of these parameters validate a non-linear trajectory, confirming the Load Capacity Curve (LCC) hypothesis for these Asian economies. Consequently, the environmental impact of our digital financial variables (ATM, DAFI, MMT) is fundamentally non-linear, acting as an asymmetric catalyst that changes in strength and direction across different low-pollution and high-pollution quantiles.

Table 6 presents the Panel Quantile Regression (PQR) estimates for consumer-based CO2 emissions (CO2) across nine quantiles (0.10 to 0.90). By estimating effects at multiple conditional points of the emissions distribution, the PQR results reveal heterogeneity in the relationships that would be obscured by mean-based methods.

GDP exhibits a robust negative association with CO2 across the mid-to-upper quantiles (notably 0.30 through 0.70), indicating that increases in income are linked with lower consumption-based emissions for countries occupying these parts of the conditional distribution. This pattern is consistent with the interpretation that, for many sample economies, rising income levels may facilitate adoption of cleaner consumption patterns or more efficient technologies that reduce per-capita consumption emissions within those quantiles.

On the other side, SQGDP has a sharply positively correlated term with CO2 observing at some quantiles for instance, at 0.30 and 0.70 in addition to generally from low to high quantiles. The positive SQGDP coefficients bolster the case for an LCC-style nonlinear hypothesis: GDP reductions in emissions may occur over intervening ranges, but beyond certain income levels the marginal impact of growth can flip sign to be strongly positive, a U-shaped dynamic by which emissions begin rising again at some point in continued growth. Such co-occurrence of negative linear GDP effect with positive quadratic term highlights the complex non-monotonic relationship between economic expansion and consumption-led emissions across different countries and emission-intensity groups.

In terms of digital financial inclusion measures, LATM (log ATMs per 100,000 adults) is significantly and positively related with CO2 for nearly all quantiles ranging from 0.20 to 0.90 indicating that greater consumer avenues to access physical means of financial services correlate with higher emissions essentially enabling more consumption and consumption led economic activity. On the other hand, providing evidence of mitigating effects, some proxies of DFI: have LDFI (log depositors per 1,000 adults) a decreased effect on CO2 from 0.20 to 0.80 at quantile levels; and LMMT (log mobile money transactions per 1,000 adults) a negative association with CO2 at all quantiles (0.10–0.90). These opposite signals suggest that financial inclusion functionalities have various environmental impact patterns whereas usage-intensive digital transactions and account penetration may promote more efficient consumption patterns, lower carbon emissions rather can expansion of ATM infrastructure serve as an indicator or enabler for the potentially higher-emission consumption.

For controls, POP has a statistically significant and strong negative correlation with CO2 from 0.10 to 0.70 quantile levels, suggesting that while controlling for other covariates - increases in population lead to lesser per-capita or consumption-pattern adjustments at certain quantiles. The extent to which trade openness is associated with lower emissions shows a strong negative correlation in the lower and upper quantiles (between 0.30-0.80) indicating that enhanced integration into international markets is potentially associated with consumer-based emissions being lower in most of the distribution, possibly via access to cleaner varieties of imports or structural shifts. Industrialization is, by contrast, statistically insignificant across all quantiles, indicating no robust conditional relationship with consumer-based emissions in this sample.

Table 6: Results of Panel Quantile Regression

Results of Panel Quantile Regression										
Variables	Values	Grid of Quantiles								
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
LGDP	Coeff.	-0.753	-1.119	-3.676	-3.419	-3.676	-4.265	-3.829	-2.174	1.809
	Prob.	0.6949	0.590	0.000	0.000	0.000	0.000	0.001	0.4013	0.437
LSQGDP	Coeff.	40.633	49.303	111.180	104.192	110.878	137.507	116.097	74.426	-26.062
	Prob.	0.413	0.357	0.000	0.000	0.000	0.000	0.000	0.251	0.652
LATM	Coeff.	0.215	0.326	0.747	0.741	0.720	0.647	0.632	0.587	0.483
	Prob.	0.181	0.058	0.000	0.000	0.000	0.000	0.000	0.003	0.009
LDFI	Coeff.	-0.175	-0.277	-0.484	-0.462	-0.471	-0.480	-0.433	-0.312	-0.078
	Prob.	0.281	0.070	0.000	0.000	0.000	0.000	0.000	0.076	0.625
LMMT	Coeff.	-0.111	-0.111	-0.0124	-0.122	-0.132	-0.112	-0.107	-0.088	-0.057
	Prob.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.075
LPOP	Coeff.	-0.283	-0.294	-0.268	-0.256	-0.266	-0.266	-0.282	-0.141	0.083
	Prob.	0.000	0.000	0.000	0.000	0.000	0.000	0.021	0.511	0.537
LIND	Coeff.	0.226	0.119	-0.034	0.052	0.167	0.189	0.224	0.180	-0.388
	Prob.	0.346	0.606	0.839	0.741	0.282	0.256	0.262	0.655	0.168
LTR	Coeff.	-0.242	-0.372	-0.931	-0.961	-0.969	-0.905	-0.908	-0.781	-0.352
	Prob.	0.297	0.143	0.000	0.000	0.000	0.000	0.002	0.065	0.3531

Source: author estimation

POLICY IMPLICATIONS

These findings imply that countries' governments should take the initiative to promote DFI and environmental improvements. On one hand, governments should as a matter of course integrate environmental sustainability into financial inclusion and on the other hand promote green technologies. Just like Financial institutions has to lead with this and push for sustainable measures. Similarly, educational initiatives enable individuals and businesses to appreciate sustainability. The researchers say that global effort is essential in tackling environmental issues associated with DFI. Such globalization forces would facilitate the sharing of best practices and the collaboration in innovating up technical levels for global sustainability efforts.

From a contextual perspective, the findings dictate that Asian policymakers must move away from general environmental mandates towards quantile-specific, structurally integrated frameworks. For low-emission economies (lower quantiles), policy should focus on proactive 'Green Fintech' guidelines, such as subsidizing mobile money platforms (MMT) that offer preferential interest rates for eco-certified micro-investments. Conversely, for high-emission, industrialized economies (upper quantiles), regulatory bodies must implement strict carbon-indexed criteria for digital banking accounts (DAFI). This includes integrating environmental footprint tracking directly into automated digital credit scoring systems, ensuring that expanded access to financial liquidity does not inadvertently finance carbon-intensive production lines.

Limitations and future directions

This research has certain limitations. This research uses secondary data from World Development Indicators which might not cover everything in DFI and environmental damage. In addition, the analysis narrows the data down to 2017 through 2023 only, therefore leaving long-range trends out. Second, the indicators used to measure DFI (e.g. number of ATMs per 100000 adults, depositors and mobile money transactions) and environmental degradation (e.g. CO2 from consumers) may not capture the full complexity of these issues. Other relevant components could be overlooked. Another limitation of this study is that it focuses on selected countries in Asia, which reduces the generalizability of findings to other areas with different economic, social and environmental contexts. While quantile regression provides valuable insights; it may not control for all possible confounders or the dynamism of the DFI-environment degradation relationship.

This study has some limitations going forward. Firstly, future researcher can extend the geographical coverage as to include countries from other regions which will help in better understanding of global link between DFI and environmental degradation. Second, extending the analysis period to beyond 2021 could provide insights into long-term patterns and how the role of DFI towards environmental degradation is evolving over time. In addition, incorporating factors such as renewable energy adoption, technology progress and government measures may extend insights on the determinants of DFI-environment sustainability nexus. In conclusion, it might be more beneficial to combine quantitative analysis with qualitative approaches, such as case studies or interviews, to gain a better understanding of DFI effects on environmental outcomes through economic mechanisms.

CONCLUSION

This study has investigated how DFI contributes to environmental degradation in the Asian context. It also explores the LCC hypothesis in these economies. The research utilized annual quantitative secondary data spanning from 2017 to 2023 sourced from the World Development Indicators, and the results showed a significant relationship between DFI and environmental degradation as represented by CO2 based on consumption. Similarly, the findings show that increased access to financial services measured by ATM availability and usage of financial institutions and mobile money transactions correlates with higher levels of environmental degradation. Additionally, the research confirms the LCC hypothesis in sample Asian economies, showing that economic activities facilitated by DFI worsen environmental problems. Such findings suggest the importance of merging financial inclusion with sustainability at ecosystem level. Through emerging technology and the modern environmental policies, governments may mitigate some of the adverse environmental effects of economic growth and improve energy consumption rates while also reducing greenhouse gas emissions.

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