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Globalization's effects on South Asia's carbon emissions, 1996–2019: a multidimensional panel data perspective via FGLS

Musarat Abbas[1✉], Ling Yang[1] & Michael L. Lahr[2]

Researchers and policymakers hold diverse opinions about the impact of globalization on environmental degradation. Over the past three decades, increased economic, social, and political interconnections have fueled this debate. However, prior studies have largely overlooked these facets of globalization concerning environmental implications, particularly carbon emissions in developing countries. We contribute to this discourse by examining how various aspects of globalization (economic, social, and political) and two specific measures, de facto and de jure trade, influenced carbon emissions in four selected South Asian countries from 1996 to 2019. The results obtained through feasible generalized least squares (FGLS) reveal that economic globalization increases carbon emissions while social and political globalization reduces them. These results further confirm that, in South Asia, the pollution haven hypothesis is associated only with economic globalization. In contrast, social and political globalization support the world polity theory, indicating potential for positive change. The results also show that both de facto and de jure measures of disaggregated globalization equally influence carbon emissions, suggesting a significant impact from policy interventions. For future environmental sustainability, the governments of these nations should intensify their efforts to strengthen social and political globalization. Meanwhile, the adverse effects of economic globalization can be mitigated by reducing reliance on fossil fuels and providing financial assistance to businesses to encourage the use of renewable energy and modern technology in production.

[1] School of Economics and Finance, Xi'an Jiaotong University (XJTU), Xi'an, Shaanxi Province, People's Republic of China. [2] Edward J. Bloustein School of Planning and Public Policy, Rutgers the State University of New Jersey, New Jersey, NJ 08901, USA. ✉email: musarat_abbas2000@yahoo.com

Introduction

Globalization has brought higher economic growth, industrialization, and well-being worldwide (Rao et al., 2023). But it has significant consequences for the environment in the form of climate change and greenhouse gases, particularly carbon emissions (Wang et al., 2023). "Globalization" connects people and organizations across distances, transcending cultural barriers and easing communications via free trade, technology transfer, and social and political agreements have significant implications for the environment (Gygli et al., 2019a; Ramzan et al., 2023). However, the relationship between globalization and its environmental effects remains ever-more contentious as concern for environmental well-being heightens. Moreover, "globalization" has taken on more dimensions, and statistical techniques for testing hypotheses about it continue to progress (Ramzan et al., 2023).

One structural debate in earlier literature focused on the interplay between the pollution haven hypothesis (PHH) and the newly developed world polity theory (WPT). The PHH suggests that more stringent regulatory policies in developed nations encourage firms to relocate or "offshore" pollution-intensive aspects of their activities to developing countries (Copeland and Taylor, 1994; Ozcelik et al., 2024). In this manner, firms that meet the demands of developed nations reduce their total costs of doing business, in part by effectively exporting pollution and waste by-products they might otherwise incur to those developing nations in which environmental regulatory policies are far more relaxed (Lee and Min, 2014; Shahbaz et al., 2015). On the other hand, WPT focuses on the political and cultural dimensions of globalization to encourage collaboration, which fosters a more tightly-knit global community (Gulmez, 2020). Under this framework, nations become more socio-economically and politically interconnected, fostering both international cooperation and trust. This, in turn, makes them better able to converge on the goals proposed by international institutional bodies (Boli and Thomas, 1997).

Indeed, trade openness and foreign direct investment are typically used in earlier studies to measure globalization's reach on the environment (Shahbaz et al., 2017; Wang and Zhang, 2021; Sun et al., 2019; Singhania and Saini, 2021; Wang et al., 2023). Rising international trade, particularly with developing economies, like those of South and East Asia, enables the developed world to enjoy lower prices for manufactured goods (Amiti et al., 2020). Heightened competition eased by such trade, international technology transfer, and foreign investment, which enabled the rise in trade, play significant roles in influencing carbon emissions. Empirical tests of trade openness and foreign direct investment as indicators of globalization have been mixed and, thus, inconclusive. The magnitude of their effects on CO_2 emissions remains uncertain and conflicting (Adebayo and Acheampong, 2022; Nan et al., 2022). To date, thus, they might misguide policy formation designed to improve environmental quality (Shahbaz et al., 2017).

Other factors beyond FDI and trade can affect globalization and, hence, carbon emissions. For this, Dreher (2006) made a first stab at producing a globalization index, which he labeled the KOF globalization index after his research institution—"die Konjunkturforschungsstelle, Eidgenössische Technische Hochschule Zürich" (the Economic Research Centre at the Swiss Federal Institute of Technology in Zurich). The index is a comprehensive measure of globalization comprised of three main dimensions: economic, social, and political globalization. Later on, Gygli et al. (2019a) revisited Dreher's index; the following retains the original three dimensions but introduces two additional measures: *de jure* and *de facto* aspects of economic, social, and political globalization to quantify globalization in a better way for almost every country in the world since 1970. The *de facto* facet relates to the tangible events and activities directly linked to globalization. It analyzes actual flows and activities occurring in economic, social, and political globalization. Globalization's *de jure* aspects are concerned with the legal and regulatory structures that, in principle, oversee and promote these flows and activities of globalization (Gygli et al., 2019a; Voigt et al., 2015).

The KOF globalization index is being employed evermore frequently to measure globalization impacts on carbon emissions for empirical analysis. By following the KOF globalization index, instead of economic globalization, some researchers argue that political globalization through international agreements, i.e., the Kyoto Protocol and the Paris Agreement, promotes multinational cooperation that reduces reliance on fossil fuels, encourages the use of renewable energy, and protects the environment (Acheampong, 2022; Grunewald and Martinez-Zarzoso, 2016). In contrast, some others believe political globalization can detrimentally affect businesses globally, encourage geo-political conflicts, and reveal institutional weaknesses that adversely transform the environment (Feng et al., 2024). The same is true for social globalization. Social globalization enables the exchange of people, information, and cultures across borders, influencing technology change and, hence, enabling reductions in carbon emissions (Fan et al., 2024; Motoshita et al., 2015; Ramzan et al., 2023). On the other hand, informational and communications technologies demand more energy to install new plants and machinery and emit more carbon emissions into the atmosphere (Razzaq et al., 2021).

While more recent research has been using both de facto and *de jure* measures of economic, social, and political globalization for carbon emissions, its findings have been as inconclusive as that without them. For example, Omoke et al. (2023) find that *de facto* aspects of trade are not important to environmental outcomes, while *de jure* aspects appear to be effective. Considering Europe only, however, Leal and Marques (2019) find that economic and political aspects of *de jure* globalization appear to enhance carbon emissions in high-income countries but reduce them in lower-income countries. Another study also found that *de jure* economic and social globalization increases carbon emissions, while political *de facto* and *de jure* are insignificant for carbon emissions (Walayat and Mehmood, 2021).

According to the Word Bank, South Asia is home to one-fourth of the world's population, with higher levels of poverty and unemployment. To reduce poverty and unemployment, however, over the past four decades, South Asian nations have prioritized economic prosperity, largely ignoring environmental concerns. During the last decade, the average growth rate of GDP in South Asia has remained above 6%, high compared to other developing regions. The concomitant surge in energy demand met by fossil fuels from 1996 to 2019 almost tripled in Bangladesh and India, doubled in Sri Lanka, and increased by 50% in Pakistan (ABDI, 2023). Jackson et al. (2022) report that this rise in energy demand has exacerbated environmental degradation. In 2022, South Asia accounted for 44% of global greenhouse gas emissions (ABDI, 2023). With such rates of change, by 2050, the average temperature in South Asia is likely to rise by two to four degrees Celsius, unleashing lethal heat waves and, hence, ice melts and floods (Woetzel et al., 2020). In South Asia, a substantial share of the population lives in coastal areas, making this region particularly vulnerable to climate change (Agarwal et al., 2021). Flooding, drought, and heat could push as many as 62 million South Asians below the threshold of extreme poverty by 2030 (Gupta, 2021). Economic costs associated with such future climate change are expected to be close to 13% of GDP (Singh et al., 2020).

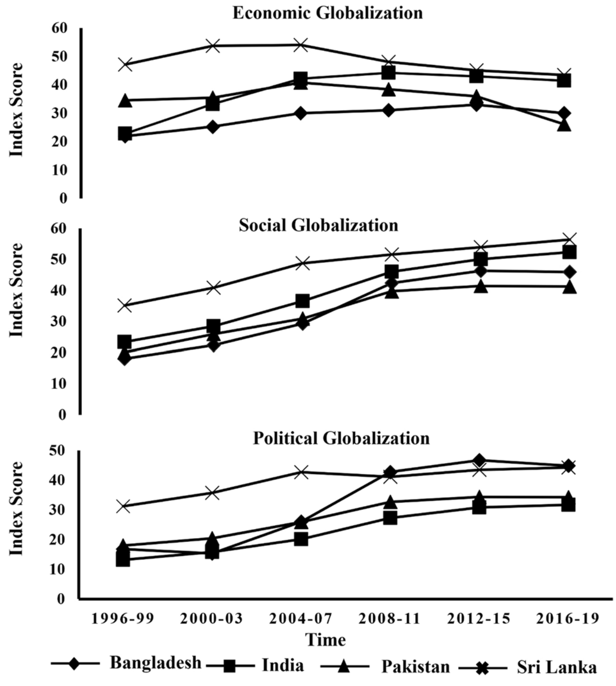

Fig. 1 Comparison of economic, social, and political globalization. This figure shows the average trend of economic, social, and political globalization in selected countries of South Asia over the period 1996–2019. A rising trend in all dimensions of globalization has been observed in Bangladesh, India, Pakistan, and Sri Lanka, except for economic globalization, which has shown a downward trend in Sri Lanka and Pakistan since 2008.

Considering these facts, controlling carbon emissions in South Asia is highly demanding. Clearly, South Asian nations should do their part in the global fight against climate change. However, they are economically challenged and, therefore, face difficulties in achieving their internationally agreed goals to reduce carbon emissions (Bhowmick et al., 2019; Tiwari et al., 2024). So, it is imperative to understand the contributing factors to climate change peculiar to South Asia, one of which is drastic rises in carbon dioxide emissions. To gain a reasonable balance between economic prosperity and environmental degradation, it is essential to gain a better understanding of disaggregated globalization's effects on carbon emissions in South Asia (Destek, 2020). For practical reasons, we analyze just four of South Asia's eight countries:[1] Pakistan, Bangladesh, India, and Sri Lanka.

In the meantime, selected South Asian countries have become more integrated with the rest of the world since joining the World Trade Organization in 1995. Figure 1 also shows a steady relative rise in the rank of their social and political globalization vis-à-vis their economic globalization. From 1996 to 2019, social globalization in Bangladesh, India, Pakistan, and Sri Lanka has increased by 152%, 153%, 137%, and 76%, respectively. Over the same period, political globalization increased by 147% in Bangladesh, 148% in India, 88% in Pakistan, and 42% in Sri Lanka. As compared to social and political globalization, the rise of economic globalization has slowed in all selected countries: Bangladesh (40%), India (99%), Pakistan (1.63%), and Sri Lanka (−2.58%). Still, empirical studies quantifying the association between globalization and carbon emissions in South Asia almost strictly focus on economic globalization (trade, foreign direct investment, and financial development) and, thus, represent a relatively narrow perspective on the panoply of globalization's effects (Acheampong, 2022). Hence, it is essential to understand interconnections among the potential effects of economic, social, and political globalization on carbon emissions to properly hypothesize how they might affect environmental quality (specifically, CO_2 emissions) in South Asia. To address this gap, we apply Gygli et al. (2019a) revised KOF globalization index with the intention of evaluating the impact of economic, social, and political globalization distinctly on carbon emissions. In so doing, we seek to get a better grasp of globalization's complexities and globalization's effects on the environment of developing countries like those in South Asia. For a comprehensive analysis, we also explore the effects of *de facto* and *de jure* measures of disaggregated globalization on carbon emissions, ensuring that the study's policy recommendations are based on robust analysis. Furthermore, these two measures are included in determining whether the change in carbon emissions is driven by the actual flow of international activities or by the regulatory and environmental policies of the nations. In this vein, we also attempt to counteract the tendency for one-sided outcomes in prior assessments (Martens et al., 2015). We investigate the following:

(1) How do economic, social, and political aspects of globalization each influence carbon emissions?
(2) Can social and political globalization mitigate carbon emissions?
(3) Are *de facto* and *de jure* aspects of globalization distinct in how they affect carbon emissions?
(4) By how much and in what ways do economic growth, energy consumption, and financial development influence carbon emissions?

Furthermore, under these disaggregated facets of globalization, each with the two measures, this study empirically evaluates the status of the pollution haven hypothesis (PHH) and the world polity theory (WPT) in South Asia. We do so by examining the relationships among disaggregated facets of globalization (economic, social, and political), their *de facto* and *de jure* measures, and carbon emissions while controlling for economic growth, energy consumption, and internal financial development across four of South Asia's eight nations from 1996 to 2019. As controls, we include economic expansion, energy use, and financial development; they are highly interlinked to globalization and carbon emissions and are critical components of environmental sustainability. Subsequently, we offer insights into the causes of rising carbon emissions in South Asia, where such policy research is largely lacking. Aligned with the study's aims and the preceding literature review, we formulate four research hypotheses:

Hypothesis 1: *Economic globalization, both de facto and de jure, increases carbon emissions and confirms the pollution haven hypothesis.*

Hypothesis 2: *Social globalization, both de facto and de jure, decreases carbon emissions.*

Hypothesis 3: *Political globalization, both de facto and de jure, decreases carbon emissions.*

Hypothesis 4: *Economic expansion enhances energy use, which increases carbon emissions.*

We find what we believe are some new and exciting outcomes for the three facets of globalization on carbon emissions in South Asia. Economic globalization increases carbon emissions, while social and political globalization reduces them. The PHH is primarily associated with the economic aspects of globalization, while WPT is associated with social and political globalization. Concerning energy sources, primary energy consumption increases CO_2 emissions, while renewable energy helps to reduce them. Conversely, economic growth (measured by GDP per capita and economic complexity index) and financial development contribute to increased CO_2 emissions in South Asia. Our research encompasses several novel aspects. First, we analyze South Asia, an environmentally risky, yet economically emerging region that is woefully understudied. We, thus, contribute further to the scant literature on the region that focuses on interconnections between globalization and the environment. Second, we examine the relationship between carbon emissions and disaggregated globalization (economic, social, and political, as well as the *de facto* and *de jure* measures of each), expanding beyond the conventional focus on trade and foreign direct investment (FDI). In this way, we learn how the facets of globalization appear to be helping or hindering the environmental quality in South Asia. Third, it is a common belief that the pollution haven hypothesis is attached to globalization in developing countries; by disaggregating globalization, we can dig more deeply into those particular facets of globalization that appear to motivate the pollution haven hypothesis. Fourth, we include both primary energy and renewable energy consumption in our analysis for better energy policy. By doing so, we can identify energy resources that are likely to influence carbon emissions in South Asia. Fifth, we evaluate the role of economic development by incorporating two proxies (GDP and economic complexity index) and financial development on carbon emissions. Finally, we use feasible generalized least squares (FGLS) for empirical analysis to test our hypotheses. By using this technique, we hope to minimize statistical objections leveled at some prior research as it accounts for parameter heterogeneity, cross-sectional dependency, and heteroscedasticity (Zakari et al., 2022). We check the robustness of our FGLS findings by also applying robust dynamic panel estimation of fully modified ordinary least squares (FMOLS). Our collection of novel contributions sheds light on policy implications regarding the evolution of globalization and environmental quality in South Asia.

The subsequent parts of the paper follow this structure: the section "Literature review" comprises a literature review incorporating theoretical frameworks and empirical evidence. Section "Materials and methods" outlines the materials and methods, including data, variables, model specification, and estimation framework. Section "Results" presents the descriptive and empirical findings of the study along with robustness analysis. Section "Discussion" is devoted to discussion. Finally, the section "Conclusion and policy recommendations" offers the conclusion and policy recommendations of the study, along with limitations and prospects for future research.

Literature review

This section is divided into two main parts. The first offers a concise outline of the study's theoretical framework, while the second summarizes the relevant empirical literature.

Theoretical background. Since the last quarter of the 20th century, a substantial debate has arisen about globalization and its impact on the environment. In part, this is because globalization intensified in the 1990s with the expansion of trade openness as the result of the World Trade Organization (Gill et al., 2018). Globalization has always driven economic growth. Foreign direct investment and trade openness as a factor of globalization are also contributing to increasing the scale of production and upgrading technology. The higher the degree of economic integration and trade, the greater the anticipated growth (Dahal et al., 2024). The growth and globalization nexus stimulates demands for primary energy, deforestation, natural resource extraction, transportation, and urbanization, which ultimately deteriorate environmental quality (Gyamfi et al., 2024). Traditionally, scholars have explored three hypotheses—the pollution haven hypothesis (PHH, race to the bottom hypothesis), the pollution halo hypothesis, and the environmental Kuznets curve hypothesis to evaluate globalization's environmental influences from income, scale, and composition (Acheampong, 2022; Farooq et al., 2022; Le and Le, 2023). The pollution halo hypothesis suggests that globalization enables the transfer of technology and knowledge, which enhances productivity and, thereby, improves environmental performance in the host country (Pazienza, 2019). The environmental Kuznets curve, a concept attributed to Grossman and Krueger (1991), suggests an inverted U-shaped relationship between pollution per capita and GDP per capita. The PHH contends that differences in government policies and factor abundance can spawn a comparative advantage for developing nations (Acheampong, 2022; Ozcelik et al., 2024). If environmental policies are lax and labor is cheap, production in developing nations is liable to become more pollution-intensive (Schenker et al., 2018). Stringent environmental regulations and higher labor costs increase production costs and repel foreign investment. Consequently, multinational establishments operating in developed countries, the relative wealth of which facilitates more stringent environmental laws, may opt to relocate to developing countries to reduce their total logistical costs (Doytch and Uctum, 2016). Among them, the PHH is the most common phenomenon attached to globalization in developing countries.

Empirical support for the PHH is uneven. Trade openness increases carbon emissions in high-, low- and middle-income countries (Shahbaz et al., 2017). Sun et al. (2017) validate the PHH that foreign direct investment inflow in China increased carbon emissions from 1980 to 2012. Trade openness and FDI tend to help economies expand their GDPs, but such expansion tends to enhance energy demand, thereby increasing carbon emissions (Shahbaz et al., 2019). Similarly, Sun et al. (2019) measured the effects of trade openness on carbon emissions for 49 countries, revealing that trade enhances carbon emissions across the board. Singhania and Saini (2021) conclude that more trade and FDI in developing nations appear to increase carbon emissions, *confirming the pollution haven hypothesis*. On the other hand, Wang and Zhang (2021) find a heterogenous association between trade and environmental outcomes among low- and high-income countries from 1990 to 2015 and find that trade deteriorates environmental quality in low-income countries and improves in high-income countries. One such study for Ghana from 1996 to 2016 reveals that *de facto* economic, political, and cultural facets of globalization increase carbon emissions, supporting the PHH (Acheampong, 2022). Looking at the association between FDI and environmental quality across 67 countries with different income levels, Wang et al. (2023) find environmental quality declining through to a specific income level; after attaining a threshold level of income, FDI improves environmental quality. Le and Le (2023) extended the sample to 128 countries but for a shorter period (2001–2014) and found that economic and political globalization support the PHH. They observe, however, that social globalization improves environmental quality in middle-income countries but decreases it in high- and low-income countries.

Since 1990, globalization has developed different facets. Social globalization affects carbon emissions via three pathways: the diffusion of information and communication technology, transportation, interpersonal relations, and the development of human capital. The diffusion of information, specifically via improvements in communication technology, plays a significant role in raising environmental awareness and reducing carbon emissions in the greenest economies (Ramzan et al., 2023). More awareness enables a shift in household consumption towards more environmentally friendly products, ultimately reducing carbon emissions (Fan et al., 2024; Motoshita et al., 2015). Transportation, a key component of social globalization, increases carbon emissions (Avotra and Nawaz, 2023). On the other hand, human capital development, a component of social globalization through education, reduces carbon emissions in developing countries (Jahanger et al., 2023).

Political globalization is expanding even more rapidly. It promotes international interaction and collaboration via formal and informal institutions that not only generally motivate stakeholders to engage in collective effort but, specifically, to sign agreements designed to mitigate and control greenhouse gas emissions (Frank et al., 2000; Wang et al., 2022). Earlier, Spilker (2013) found that intergovernmental organizations encourage member nations to reduce CO_2 emissions in three ways: first, by helping them to recognize and develop norms of acceptable behavior; second, to conceive achievable environmental goals; and third, to achieve environmental targets via financial encouragement or compensation. Grunewald and Martinez-Zarzoso (2016) find that international treaties on the environment bring financial support and promote energy transition in member nations. Political globalization encompasses the activities of governmental institutions, their policies, and their engagement in global agreements (Gygli et al., 2019b). Feng et al. (2024) found that political globalization helped to reduce carbon emissions in resource-rich countries from 1985 to 2020.

Drawing upon the above-noted new social and political globalization perspective, some theoretical developments capture facets of globalization. In the form of world polity theory (WPT), the organizational role and cultural perspectives, rather than economic perspectives associated with globalization, explain rises in environmental awareness and international cooperation (Meyer, 2010). WPT stipulates that environmental policy formation has arisen because people have aligned their behavior via a discourse infused with science. Schofer and Hironaka (2005) conclude that the countries heavily entrenched in world polity have significantly lower levels of CO_2 emissions, given their national product. We follow their analytical framework to evaluate the depth of world polity practiced in South Asia. Empirical study finds that the global cooperation between the 1997 Kyoto Protocol and the Paris Agreement, for instance, permitted industrialized states to achieve their goals via various flexible mechanisms like joint implementation or the Clean Development Mechanism under the Kyoto Protocol. These allow developed countries to invest in renewable energy or any other carbon reduction project to meet their carbon reduction targets (Held and Roger, 2018).

Henderson (2019) examines energy aid's impact on national CO_2 emissions in developing nations under world polity and the role of government and international norms. He uses a panel dataset of 121 countries to find that fossil-fuel energy aids enhance CO_2 emissions. Interestingly, embeddedness in international environmental regimes moderates this effect.

Givens (2017), however, analyzes the linkages of carbon intensity related to human development in developed and developing countries under WPT from 1990 to 2011 in 81 countries and found that carbon intensity only reduced in developed countries. Similarly, Sommer and Hargrove (2020) conclude that the effectiveness of national environmental governance in reducing CO_2 emissions varies by a country's position and income level in the global hierarchy under a world-systems perspective. For this, they evaluate the impact of environmental taxes on CO_2 emissions for 75 countries from 2000 to 2011. They find that the impact of environmental governance on CO_2 emissions varies across countries at different income levels and their position in the world system.

Empirical evidence

KOF Globalization index and carbon emissions. Over time, the concept of globalization has changed significantly from a strictly economic one, adding social and political perspectives due to its high-profile status in the public over the post-1989 era (Roudometof, 2021). More generally, globalization lubricates interactions among companies, peoples, and (national) governments on a global scale. Gygli et al. (2019b) provide an overview of the commonly used indexes for globalization, i.e., the Global Index, the new Globalization Index, and the Maastricht Globalization Index. Still, these indices of globalization have some limitations. Using components of the KOF globalization index, Destek (2020) investigates disaggregated globalization's effects on carbon emissions in transitional European countries. He finds that economic and social globalization induced carbon emissions from 1995 to 2015, while political globalization reduced them. Measuring globalization's effects on carbon emissions in Iran from 1981 to 2015, Khodaparast Shirazi and Khavand (2020) use all facets of the KOF globalization index. They find that economic and political globalization impedes environmental quality while social globalization improves it via increased household awareness. Similarly, Adebayo et al. (2021) also found that globalization enhanced carbon emissions in South Korea from 1980 to 2018.

Currently, *de facto* and *de jure* measures have been used to split components of the KOF index, enhancing the precision of parameters focused on the effects of globalization on carbon emissions. Leal and Marques (2019) use data from 25 European Union member countries from 1996 to 2016 and a rather sophisticated statistical approach—a Driscoll Kerry Panel ARDL with the panel-corrected standard error (PCSE) plus feasible generalized least squares (FGLS) to test robustness and conclude that *de jure* political globalization reduces carbon emissions in developed countries through their expertise in designing policies and treaties. *De facto* political globalization reduces carbon emissions in developing countries. They also find that *de jure* social globalization *intensifies* CO_2 emissions in developing countries and that in highly globalized countries, *de jure* aspects of economic globalization increase the carbon *level*. Interestingly, Leal and Marques tell us that the *de facto* aspects significantly affect carbon emissions in developing countries, but *de jure* measurements tend to wield strong effects in developed nations.

While measuring the impacts of de facto and de jure globalization, Walayat and Mehmood (2021) find that the *de jure* economic and social components of globalization are associated with environmental degradation, while political *de facto* and *de jure* components yield no statistically significant environmental effects. Similarly, focusing on West Africa from 1980 to 2018, Omoke et al. (2023) find that *de facto* trade has statistically significant negative effects on environmental quality while *de jure* trade tends to counteract them. In contrast, *de facto* and *de jure* informational globalization reduces carbon emissions. Additionally, when examining just eleven transition economies, Destek et al. (2023) detect no trade effects on environmental quality but do find that *de facto* and *de jure* financial globalization decreases CO_2 emissions.

Energy consumption, financial development, and carbon emissions. Climate change and global warming result from intensified carbon emissions in the atmosphere and are, thus, consequences of globalization. Globalization supports economic growth, industrialization, and development, which in turn encourages energy consumption. This is particularly a concern in developing and emerging economies where the use of fossil fuels increases carbon emissions. Heightened energy consumption poses threats to environmental sustainability and humanity worldwide (Allan et al., 2023). Hence, the electric power industry's choice of generation technologies heavily influences the sustainability of economies worldwide (Batrancea and Tulai, 2022). Generally, vintage industrial technology is less energy-efficient and consumes more energy, thereby producing more carbon emissions (Xia et al., 2022; Zafar et al., 2019). Moreover, energy prices play an essential role in decisions about energy consumption and environmental sustainability. For example, when prices of fossil fuels rise, the relative cost of renewable energy lowers, enhancing its demand through substitution effects (Assi et al., 2021; Chen et al., 2019). Renewable energy generated from water, solar, and wind power helps reduce greenhouse gas emissions substantially (Shan et al., 2021).[2] Batool et al. (2022) note that renewable energy can improve environmental quality by reducing carbon emissions in different developing countries. For sub-Saharan African countries from 1980 to 2015, Acheampong et al. (2019) found that renewable energy and foreign direct investment reduce carbon dioxide emissions, while trade openness increases them. Ahmad and Majeed (2019) get similar results for South Asia from 1990 to 2014. With a broad global view extending from 1985 through 2020, Rehman et al. (2023) find that renewable energy does little to nothing to influence carbon emissions but supports the usual theme that, through economic growth, globalization increases carbon emissions.

Financial development is a core element of sustainable economic growth. Reduced financial costs enable investment, which can intensify national economic growth and employment. Early studies find a positive role of financial development in increasing economic growth, consumption, savings, and capital accumulation (Batrancea, 2021; Huang et al., 2021; Kim et al., 2018). However, very little research probes its environmental consequences, at least in earlier studies (Qin et al., 2021). Environmentally, its influence can possibly be positive or negative. By enabling investment and enhancing industrial growth, financial development can degrade environmental quality. But, it can help reduce carbon emissions by advancing technology through investments and R&D (Shahbaz et al., 2016).

Xia et al. (2022) find that financial development is vital for achieving carbon neutrality objectives. Charfeddine and Kahia (2019) find that weak financial development in MENA countries has raised carbon emissions between 1980 and 2015. Le et al. (2020) argue that financial inclusion might well be harmful to the environmental quality of those Asian countries in which no policies or subsidies exist to manage financial efforts to help organizations and households conserve energy or otherwise adapt it to improve environmental outcomes. In a comparative analysis of the relationship between financial development and carbon emissions of eight developed (G8) and eight developing (D8) countries from 1999 to 2013, Shoaib et al. (2020) conclude that financial development enhances carbon emissions everywhere. In contrast, Zaidi et al. (2019) estimate that financial development, as measured by domestic credit to the private sector, reduced carbon emissions among Asian Pacific Economic Cooperation (APEC) member nations from 1990 to 2016 while controlling economic growth and energy intensity. Also, Renzhi and Baek (2020) found that financial inclusion decreased CO_2 emissions across a global set of 103 countries from 2004 to 2014. Similarly, financial development appears to have reduced carbon emissions in BRICS countries from 1990 to 2017 (Rafique et al., 2020).

Our review of the extant literature highlights notable research gaps. For one, there is a very noticeable lack of attention given to the relationship between globalization's effects on carbon emissions explicitly generated by South Asian nations. Moreover, key theoretical foundations are often ignored; that is, most work has concentrated strictly on the effects of *economic* globalization on CO_2 emissions with an eye toward testing for the PHH but fully neglecting the social and political dimensions of globalization. Scant literature to date investigates the interplay between the various components/dimensions of globalization and the mix of energy resources used (renewable and primary) on CO_2 emissions. Even so, the magnitude and statistical significance of the effects of economic, political, and social components of globalization on carbon emissions are inconclusive, both between and within high- and low-income nations. The implications of *de facto* versus *de jure* aspects of the components of globalization on carbon emissions for South Asia are nigh unto non-existent.

And then there are statistical issues that have not tended to be properly handled. Most existing studies carried out on global or country-specific samples employ statistical tests that neglect issues associated with data heterogeneity and cross-sectional dependency, potential sources of parametric imprecision, and bias. As a result, we endeavor to fill these gaps in our examination of the influences of the various components of globalization, not only by including *de facto* and *de jure* aspects of the components of globalization but also by controlling for the energy resource mix, financial development, economic size, and economic expansion in South Asia. Moreover, we engage using the lens of a solid theoretical treatment (pollution haven hypothesis and world polity theory) and vigorous statistical testing technique (FGLS and FMOLS).

Materials and methods

Data and variables. We employ a panel of data on four South Asian countries—Bangladesh, India, Pakistan, and Sri Lanka. Although South Asia embraces eight countries, much key data for Afghanistan, Bhutan, the Maldives, and Nepal were unavailable. The choice of the study period, 1996–2019, is also based on data availability. The data is from various outlets. Those on carbon emissions, renewable energy, GDP per capita, and financial development are from the World Bank Development Indicators (WDI) Databank.[3] Data on economic, social, and political components of globalization, as well as their *de facto* and *de jure* aspects, are from the KOF Overall Globalization Index.[4] Data on economic complexity are from the MIT Observatory of Economic Complexity.[5] Data on primary energy consumption comes from British Petroleum.[6] The natural logarithm of all variables was taken to ensure normality, address some homoscedasticity issues, and obtain parameters that are constant elasticities.

Dependent variable. The World Bank-sourced dependent variable in our analysis is carbon dioxide (CO_2) emissions in metric tons per capita. They are measured from the combustion of fossil fuels and the production of cement. It comes from the combustion of solid, liquid, and gaseous fuels in various sectors, including industry, transportation, construction, and power generation. We did ***not*** include carbon emissions from other forms of land use or land-use change (e.g., deforestation or other changes of vacant land), which are another major source of CO_2 emissions, accounting for approximately one-quarter of emissions worldwide (Shiraishi et al., 2023). Carbon emissions constitute 75% of greenhouse gas emissions and are the primary contributor to climate change and global warming (International Energy Agency, 2021). CO_2 emissions have been used in countless studies to proxy for environmental degradation. While CO_2 is important for plant photosynthesis, it regulates the Earth's greenhouse effect. A global anthropogenic greenhouse effect is generated through the combustion of fossil-fuel resources (mainly coal, natural gas, and oil), which annually releases substantial quantities of carbon emissions into the atmosphere. Only forest regrowth and rising ocean-based plankton populations can counteract the greenhouse effect. Warming oceans, a result of the greenhouse effect, are reducing rather than improving plankton populations, and global forest coverage is trending steeply downward. As a result, the planet's average temperature has been rising and continues to rise; it is also linked to greater day-to-day temperature vacillations and more extreme weather-related events (Scholz, 2011). The prior causes problems in meeting energy demands—particularly at relatively low cost—while the latter increases the costs of infrastructure and emergency services.

Independent variables. The various components of the KOF globalization Index, a widely used and accepted measure of globalization, are our primary independent variables. Dreher (2006) developed the first rendition of the index using 23 variables to form three complementary components of globalization—economic, social, and political—via principal components analysis (PCA) with rolling windows of ten years as a weight instead of calculating time-varying weights. PCA is a datareduction technique. Technically, principal components are eigenvectors of the original dataset's co-variance matrix. From them, PCA essentially derives a minimal set of latent variables that maximally explains the variance across all original variables included in this clustering-type analysis. The labeling of the latent variables—in this case, the economic, social, and political components of globalization—is determined by the nature of the set of original variables that most influence the direction of each eigenvector. An overall index can be composed of the components that result from each eigenvector of the PCA and as weighted by the normalized vector of eigenvalues of the eigenvectors.

Such latent variables, typically called "composite indicators", are not always labeled well since no "actual" measure exists against which the composite indicator can be gauged; the same goes for its components.[7] In essence, while the analyst might label PCA's result "globalization index," it might not be measuring the exact sort of globalization the analyst means to measure, and the naming of its components can be vicarious.[8] As a result, indices produced by PCA (and their components) can be overly simple and, thus, yield misleading results (Martens et al., 2015). Gygli et al. (2019b) revised Dreher's original work by following suggestions from Dreher et al. (2008) and Martens et al. (2015) in developing complementary globalization indices. In doing so, they used 43 rather than 23 variables to build two indices, one focusing on *de facto* measures and the other on *de jure* measures. Dreher's original index only focused on *de facto* globalization. However, the inclusion of both *de facto* and *de jure* aspects in the revision allows researchers to compare even more outcomes of globalization. Differences in the outcomes of *de facto* and *de jure* aspects of a globalization component highlight policies that may be strong on paper but truthless in practice (Martens et al., 2015). By disentangling trade and financial globalization within the economic component and by enabling a time-varying weighting of the variables, Gygli et al. (2019b) made the index more complete and flexible. In particular, in it, they deploy a time-varying weighting system so that the importance of variables can adjust over the years to account for the influence of globalization.

In the Supplementary file, we briefly summarize Gygli et al. (2019a) list of components used for constructing the revised version of the KOF globalization index, a composite index measuring globalization for every country in the world along the economic, social, and political dimensions and its de facto and de jure measures. Note that each element has a *de facto* and *de jure* aspect and that the two aspects of each element are given equal weighting in the overall index. It is sufficient here to report that their *economic globalization* component focuses on trade and other financial aspects of the globalization of a nation. Their *social globalization* component measures the apparent tendency for a nation's people to engage directly with their foreign equivalents, including information sharing and their tolerance toward foreign cultural influences. The component of *political globalization* is designed to measure a nation's ability and desire to cooperate politically on the international platform. For more details, of course, see Gygli et al. (2019a). The KOF globalization index ranges between 0 and 100, where 0 indicates the absence of globalization and 100 the full engagement of globalization.

Control variables. In addition to the above core test variables, we include the gross domestic product (GDP, essentially *economic growth*), *renewable energy*'s share of all energy consumed, and percent of domestic credit lent to the private sector (*financial development*) as control variables to complete our empirical analysis of disaggregated globalization and carbon emissions. As mentioned earlier, globalization is inextricably intertwined with economic growth and, through energy use, carbon emissions. While financial development is intrinsic to both economic and social globalization, it is also fundamental to the adoption of renewable energy. In this regard, its rising presence can increase carbon emissions (Charfeddine and Kahia, 2019) or decrease carbon emissions (Shahbaz et al., 2016). Inasmuch as it is primarily composed of solar, wind, and hydropower and not biomass-related technologies, renewable energy should reduce carbon emissions (Rehman et al., 2023). South Asia has been making substantial strides toward enhancing domestic financial development and renewable energy shares. Understanding the impacts of carbon emissions on economic growth, renewable energy, and financial development, along with the various components of globalization, is paramount to developing policies that can monitor and control environmental quality in South Asia. See Table 1 for more details.

Model specifications. This study aims to measure the impact on carbon emissions by nation of six main aspects of globalization—i.e., the three components of globalization (economic, social, and political), each with two different aspects, i.e., *de facto* and *de jure*—while controlling for the nation's economic growth, the share of its energy use supplied via renewable resources, and its domestically supported financial development. As discussed in the literature review, while one dimension of globalization can be associated directly with degrading environmental quality, another can be inversely associated and, thus, improve it. In this vein, using the various aspects of globalization for each of its three main components should enable a deeper, more fundamental understanding of globalization's multifarious effects on carbon emissions (Acheampong, 2022; Gygli et al., 2019b; Martens et al., 2015; Shahbaz et al., 2018).

We propose three models (A, B, and C) to analyze globalization's effects on South Asia's ambient environmental quality. In model A, we analyze just the effects of globalization's three components—economic, social, and political—consolidating across the *de facto* and *de jure* aspects. In models B and C, we separately incorporate the *de facto* and *de jure* aspects of the components. That is, model B only implements the *de facto* measures and model C the *de jure* measures. In this way, we supply a more comprehensive and robust analysis than has been undertaken prior in evaluations using the KOF Globalization Index. The approach also avoids obtaining results that might be spurious, distorted, or biased due to the application of a single measure, which is some combination of the various components and/or aspects. By breaking out the components and their aspects into different models, we avoid multicollinearity problems. That is, many of the aspects of globalization are highly correlated, such that mutual inclusion in a model would induce variance inflation and, hence, parametric bias. Mathematically, we can summarize this debate in the following equations to better understand the relationship among the variables.

Model-A

$$\ln CO_{2it} = \alpha + \beta_1 \ln GDP_{it} + \beta_2 \ln \text{RE}_{it} + \beta_{3t} \ln FD_{it} + \beta_4 \ln EG_{it} + \varepsilon_{it} \quad (1)$$

$$\ln CO_{2it} = \alpha + \beta_1 \ln GDP_{it} + \beta_2 \ln \text{RE}_{it} + \beta_{3t} \ln FD_{it} + \beta_4 \ln SG_{it} + \varepsilon_{it} \quad (2)$$

$$\ln CO_{2it} = \alpha + \beta_1 \ln GDP_{it} + \beta_2 \ln \text{RE}_{it} + \beta_{3t} \ln FD_{it} + \beta_4 \ln PG_{it} + \varepsilon_{it} \quad (3)$$

Model-B

$$\ln CO_{2it} = \alpha + \beta_1 \ln GDP_{it} + \beta_2 \ln RE_{it} + \beta_{3t} \ln FD_{it} + \beta_4 \ln EGdf_{it} + \varepsilon_{it} \quad (4)$$

$$\ln CO_{2it} = \alpha + \beta_1 \ln GDP_{it} + \beta_2 \ln RE_{it} + \beta_{3t} \ln FD_{it} + \beta_4 \ln SGdf_{it} + \varepsilon_{it} \quad (5)$$

$$\ln CO_{2it} = \alpha + \beta_1 \ln GDP_{it} + \beta_2 \ln RE_{it} + \beta_{3t} \ln FD_{it} + \beta_4 \ln PGdf_{it} + \varepsilon_{it} \quad (6)$$

Model-C

$$\ln CO_{2it} = \alpha + \beta_1 \ln GDP_{it} + \beta_2 \ln RE_{it} + \beta_{3t} \ln FD_{it} + \beta_4 \ln EGdj_{it} + \varepsilon_{it} \quad (7)$$

$$\ln CO_{2it} = \alpha + \beta_1 \ln GDP_{it} + \beta_2 \ln RE_{it} + \beta_{3t} \ln FD_{it} + \beta_4 \ln SGdj_{it} + \varepsilon_{it} \quad (8)$$

$$\ln CO_{2it} = \alpha + \beta_1 \ln GDP_{it} + \beta_2 \ln RE_{it} + \beta_{3t} \ln FD_{it} + \beta_4 \ln PGdj_{it} + \varepsilon_{it} \quad (9)$$

Here, $\ln CO_{2it}$ is the natural logarithm of carbon dioxide emissions per capita as a dependent variable, subscript i stands for the selected four countries of South Asia and t specifies the time from 1996 to 2019. α is a fixed term; $\beta_1, \beta_2, \beta_3$, and β_4 are the slope coefficients of respective variables in each model and ε denotes the error stochastic term in the model.

Robustness analysis. We further explore the robustness of our fundamental findings by altering the set of control variables and employing a different functional form. First, we respecify our model by replacing renewable energy mix and economic growth with primary energy consumption per capita and economic complexity index, respectively. Second, we apply a different estimation technique, as explained in robustness estimation. Primary energy consumption is relatively elevated in South Asia due to the energy intensity of its industry mix (Jain and Goswami, 2021). Compared to nations outside of the region, South Asian nations are energy-intensive across all residential, industrial, and service sectors but with low energy equity (Shakya et al., 2022). Leaning on this body of work, we acknowledge that South Asia's energy sector heavily relies on fossil fuels, so the *energy consumption* variable is expected to exacerbate carbon emissions (Adeleye et al., 2023; Khan et al., 2022) and perform a role that opposes that of *renewable energy* that it replaces.

Alternatively, a nation's economic complexity reflects its industry mix and the sophistication of its export specialization(s) (Mealy and Teytelboym, 2020). The economic complexity index has gained considerable footing among policymakers as a reliable indicator of a nation's economic advancement, as it essentially embodies a country's economic progress by considering export variety, product complexity, ability, knowledge, and ubiquity (Hidalgo and Hausmann, 2009). Balsalobre-Lorente et al. (2022) assert that there is a relationship between economic complexity and CO_2 emissions. Given the higher energy consumption in the economic complex system, gaining a better understanding of economic complexity's effects on energy consumption, globalization, and, thus, carbon emissions are therefore pivotal to the goals of our research.

Estimation framework

Cross-sectional dependency and slope heterogeneity test. Prior research suggests that the dataset we use is likely affected by cross-sectional dependency and slope heterogeneity. In this modern era of globalization, the interdependency among nations is increasing for economic, financial, political, and environmental goals. The panel data results will be biased and unreliable in the presence of cross-sectional dependency (CSD) and slope heterogeneity (Campello et al., 2019; Hussain et al., 2020). To check for cross-sectional dependency among the selected South Asian countries, we use three tests: the Breusch-Pagan LM test (Breusch and Pagan, 1980), the Pesaran Scale LM test (Pesaran et al., 2008), and the Pesaran cross-sectional dependence test (Pesaran, 2004). For slope heterogeneity, we apply the Blomquist and Westerlund (2013) slope heterogeneity test, which is efficient in handling heteroskedastic and autocorrelated data.

Stationarity and co-integration test. For example, in the case of cross-sectional dependency and slope heterogeneity, if time series variables are not stationary, then the statistical procedure yields inconsistent results. For stationarity of the variables, we employ five tests: Im-Pesaran-Shin (Im et al., 2003), Augmented Dickey-Fuller (1979), and PP-Fisher (1970) tests, fall under first-generation unit-root tests, and cross-sectional augmented Im-Pesaran-Shin (CIPS) and the cross-sectional augmented Dickey-Fuller (CADF) tests belong to second-generation unit-root tests. The second-generation CIPS and CADF unit-root test proposed by Pesaran (2007) are commonly used tests for stationarity in the presence of cross-sectional dependency. Additionally, as we use a panel of the data, the stationarity of time series can be an issue, so it is critical to assess co-integration among the variables. For co-integration, this study applied two tests, i.e., the Kao co-integration test (Kao, 1999) and the Pedroni co-integration test (Pedroni, 1999).

Pre-model estimation tests. To identify a suitable estimation technique, we applied various pre-model estimation tests, including assessments for heteroskedasticity, autocorrelation, panel-specific autocorrelation, and multicollinearity within the data. To address serial correlation, we used the Bias-corrected $Q(p)$ test and the heteroskedasticity-robust (HR) test (Born and Breitung, 2016). The $Q(p)$ test assesses serial correlation up to order p, while the HR test examines only first-order serial correlation in the data. Additionally, the Hausman test was used to decide between random and fixed effects. The choice of a fixed effect enabled us to use both the $Q(p)$ test and the HR test.

The modified Wald test (Baum, 2001) was used for heteroskedasticity, and the Wooldridge test (Wooldridge, 2010) was used for first-order autocorrelation.

Model estimation: feasible generalized least square (FGLS). Since heteroskedasticity, cross-sectional, and serial correlation exist in our data, we followed Leal and Marques (2019) and employed the feasible generalized least squares (FGLS) estimator. FGLS is more efficient (having lower standard deviations) than the ordinary least squares (OLS) estimator in the presence of cross-sectional dependency (Bai et al., 2021). Parks (1967) first proposed the FGLS approach, using it to estimate the parameters of a linear regression model in the presence of heteroskedasticity and serial and cross-sectional correlation. FGLS is a suitable long-run estimation technique for balanced panel data, providing unbiased and consistent results, and directly addressing the issues of cross-sectional dependency, serial correlation, and heteroskedasticity in the estimation (Bai et al., 2021; Zakari et al., 2022). Ordinary panel data estimators (OLS, fixed effects, random effects, and weighted least squares) face an issue of causal interpretations of the estimated coefficient when the coefficient of the error term is not unique and the variables are co-integrated (Lin and Omoju, 2017). FGLS estimators are consistent and asymptotically more efficient than OLS as they give less weight to observations considered to be noisier. It is important to know that FGLS only produces efficient, consistent, and valid estimates when the temporal component of the panel (T) is greater than the count of cross-sectional units (N) (Hoechle, 2007; Nuță et al., 2024). However, the FGLS estimator is criticized for its underestimation of standard errors because it assumes the parameters of error terms are known. It is still consistent to estimate panel data in small N and large T, as in the case of our study ($T = 24 > N = 04$) (Mumuni and Mwimba, 2023).

Robustness estimation: fully modified ordinary least square (FMOLS). Furthermore, to test the robustness of our FGLS results, we apply a fully modified ordinary least squares (FMOLS) which also corrects the issue of endogeneity, heterogeneity, and cross-sectional dependency. To measure the long-run relationship among the variables, Pedroni (1999) proposed fully modified ordinary least squares as an alternative to Park (1967) FGLS models, at least insofar as it can confirm the main findings obtained through FGLS. FMOLS handles the issue of small sample bias and serial correlation effectively associated with traditional OLS estimates (Zakari et al., 2022). FMOLS produces dependable, long-run estimates for small samples. FMOLS used a nonparametric approach to solve the issue of endogeneity and long-run serial correlation via different lags, leads, and kernels in co-integrated and cross-sectional, dependent data (Doğan et al., 2022).

Causality tests. In the hope of identifying causal relationships among study variables, again following Leal and Marques (2019), we apply Dumitrescu and Hurlin's (2012) causality test. Knowing relationships are causal rather than spurious or indirect is critical when formulating any policy related to these variables (Chi et al., 2021). The Dumitrescu-Hurlin test is appropriate in the context of panel data studies when the time dimension is greater than or equal to the number of cross-sectional units, and it is more efficient than other Granger's causality tests (Li et al., 2021). This test is particularly true in the presence of cross-sectional dependency and slope heterogeneity in small and balanced panel datasets (Dumitrescu and Hurlin, 2012; Li et al., 2021). A Z-bar statistic is estimated under the null hypothesis of no causal relationship among the variables against an alternative hypothesis of causality.

Results

Descriptive results. Supplementary Table S1 online presents the summary statistics for all variables considered in this study, including mean, median, maximum, minimum, and standard deviation. The values of skewness and kurtosis are also given in Table S1. The dataset consists of a total of 96 observations. Variability in the time series is captured by the standard deviation, with carbon emissions showing the highest dispersion, followed by GDP, *de jure* political globalization, and *de facto* globalization. Skewness values indicate that most variables are moderately skewed to the left, except for GDP, which is skewed to the right. Moreover, three variables exhibit kurtosis values exceeding 3.0, indicating a leptokurtic distribution, while others display a platykurtic distribution. The Jarque-Bera test, which is used to evaluate normality, reveals statistically significant values at the 1% level in a two-tailed test for most variables, suggesting a non-normal distribution. Supplementary Table S2 online, presents the pairwise correlation matrix values, demonstrating a positive relationship among per capita GDP, financial development, economic, social, and political globalization (both de facto and de jure measures), and carbon emissions. Conversely, a negative association is observed between renewable energy and carbon emissions. The correlation matrix results in Table S2, along with the value of the mean-variance inflation factor (VIF) in Table 5, confirm the absence of collinearity and multicollinearity in the data. Notably, all correlation values on the principal diagonal equal 1, while all other values are below 0.70. Strong correlations are observed between economic, social, and political globalization, as well as their de facto and de jure measures in the correlation matrix. To mitigate multicollinearity concerns, these variables are separately included in their respective models for estimation.

Table 1 Detail of variables.

Variable	Description	Data Source
CO_2	Carbon dioxide emissions (metric tons per capita)	World Development Indicators
GDP	Gross domestic product per capita (constant at 2015 US$)	WDI
RE	Renewable energy (% of total energy consumption)	WDI
FD	Financial development (% of domestic credit to the private sector).	WDI
EG	Economic globalization	KOF Swiss Economic Institute
SG	Social globalization	KOF Swiss Economic Institute
PG	Political globalization	KOF Swiss Economic Institute
EGdf	*De facto* economic globalization	KOF Swiss Economic Institute
SGdf	*De facto* social globalization	KOF Swiss Economic Institute
PGdf	*De facto* political globalization	KOF Swiss Economic Institute
EGdj	*De jure* economic globalization	KOF Swiss Economic Institute
SGdj	*De jure* social globalization	KOF Swiss Economic Institute
PGdj	*De jure* political globalization	KOF Swiss Economic Institute
EC	Primary energy consumption (Gigajoule per capita)	British Petroleum
ECI	Economic complexity index	MIT Observatory of Economic Complexity

Data Source link: https://databank.worldbank.org/reports.aspx?source=world-development-indicators; https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html; https://www.media.mit.edu/projects/oec-new/overview/; https://oec.world/en; www.bp.com

Empirical results. Empirical results begin with the cross-sectional dependency test and slope heterogeneity test. The results of three cross-sectional dependency tests—Breusch-Pagan LM test, Pesaran's Scaled LM test, and Pesaran's CD test—in Table 2 reject the null hypothesis of no cross-sectional dependency, supporting the alternative hypothesis of cross-sectional dependency in the data. The existence of cross-sectional dependency suggests that any economic or financial shock in one sample country could spill over to other sample countries. The results in the lower part of Table 2 reject the null hypothesis of slope homogeneity and accept the alternative hypothesis of slope heterogeneity in the data. Table 3 displays the results of IPS, ADF, PP-Fisher, CADF, and CIPS unit-root tests, which show that all the variables are stationary at the first difference. The results of the Kao and Pedroni co-integration tests, shown in Table 4, indicate that both Pedroni and Kao co-integration tests are statistically significant at 1% and 5% confidence levels, confirming the existence of long-run associations among all considered variables. Table 5 presents detailed outcomes of all the pre-model estimation tests. The results show that the HR test is significant, confirming first-order serial correlation for most variables. Additionally, the Hausman test rejects random effects in favor of fixed effects. The fixed-effects model allowed us to use the $Q(p)$ test and the HR test. The modified Wald test confirms the presence of heteroskedasticity, and the Wooldridge test detects first-order autocorrelation. Table 5 provides detailed results of these tests.

The empirical findings from Models A, B, and C, obtained via FGLS, are summarized in Table 6. The parameters of the variables and their standard deviations, shown in parentheses, are reported. Equation 1 of Model A reveals a statistically significant and positive association between economic globalization and carbon emissions. Economic globalization contributes to increased carbon emissions in South Asia, supporting H1. Specifically, a 1% rise in economic globalization corresponds to a 0.16% increase in carbon dioxide emissions. Equations 2 and 3 of Model A demonstrate statistically significant, negative associations for social and political globalization, respectively, with a 1% rise in social and political globalization leading to reductions of 0.10% and 0.49% in carbon emissions, respectively. Model B focuses solely on de facto aspects of economic, social, and political globalization. The results show statistically significant parameters for de facto economic, social, and political globalization in Eqs. 4, 5, and 6. On average, a 1% increase in de facto economic globalization results in a 0.25% rise in carbon emissions (Eq. 4). In contrast, as in Model A, increases in de facto social and political globalization lead to reductions of 0.15% and 0.58% in carbon emissions, respectively (see Eqs. 5 and 6). Model C examines the parameters of the de jure aspects of globalization components, but only the parameters for social and political aspects are statistically different from zero; the parameters for economic globalization are not. Equations 8 and 9 in Model C indicate that a 1% change in de jure social and political globalization corresponds to reductions in carbon emissions by 0.24% and 0.12%, respectively. The study also finds that GDP per capita, financial development, and renewable energy have statistically significant effects on carbon emissions in all equations. However, the slope coefficient for financial development is insignificant in Eq. 4 when interacting with de facto economic globalization, implying that financial development has no impact on carbon emissions in the context of de facto economic globalization. As expected, positive economic growth

Table 2 Cross-sectional dependency test and slope heterogeneity test.

Test	Statistic	Probability
Model A (economic, social, and political globalization)		
Breusch-Pagan LM	21.88***	0.00
Pesaran-Scaled LM	4.58***	0.00
Pesaran CD	1.90**	0.06
Model B (de facto economic, social, and political globalization)		
Breusch-Pagan LM	13.42***	0.00
Pesaran-Scaled LM	2.14***	0.00
Pesaran CD	1.90**	0.05
Model C (de jure economic, social, and political globalization)		
Breusch-Pagan LM	30.63***	0.00
Pesaran-Scaled LM	7.11***	0.00
Pesaran CD	−1.38	0.17
Slope heterogeneity test-Heteroscedasticity, autocorrelation consistent (HAC)		
	Statistics	*P*-value
Δ	2.73***	0.00
$\Delta_{adjusted}$	4.22***	0.00

Note: ***, ** statistically significant at 1% and 5% level of confidence.

Table 3 Results of unit-root tests.

Variable	IPS		ADF		PP-Fisher		CADF		CIPS	
	Level	1st Diff.	Level	1st Diff.	Level	1st Diff.	Level	1st Diff.	Level	1st Diff.
ln CO_2	1.86	3.16***	1.44	24.03**	1.74	48.27***	−1.36	−3.90***	−1.37	−3.93**
ln GDP	3.73	−1.55**	1,08	15.65**	0.33	22.76**	−1.76	−3.56***	−1.76	−3.56**
ln RE	4.13	−2.80***	0.27	21.82**	0.16	37.53***	−1.13	−4.10***	−1.33	−4.10**
lnDCTPS	−0.07	−2.40**	7.20	19.51**	5.92	39.31***	−0.1.43	−2.73***	−1.43	−3.74***
ln EG	−0.81	−3.48***	9.70	26.83**	1.93	32.98***	−2.10	−3.30***	−2.00	−4.06**
ln SG	−1.33**	−1.86**	18.63**	15.97**	29.12***	34.42***	−2.76**	−3.98***	−3.79	−5.10***
ln PG	−0.17	−2.43**	6.82	22.73**	6.38*	24.20**	−1.89	−2.48**	−2.48	−3.91**
ln EGdf	−1.10	−7.36***	10.61	57.10***	11.00	57.18***	−2.70**	−2.64**	−2.78	−4.31**
ln SGdf	−1.16	−3.45***	12.72	24.25**	13.55	46.38***	−2.79**	−4.36***	−3.69	−4.86***
ln PGdf	0.64	3.31***	3.78	27.65***	3.50	26.12**	−2.28	−3.56***	−2.31	−4.75**
ln EGdj	−1.38**	4.22***	12.34	32.91***	9.91	29.16**	−1.76	−3.35***	−1.58	−4.07**
ln SGdj	−2.40**	2.37**	18.91**	24.64**	38.60***	35.56***	−2.61**	−3.20***	−3.74	−4.83*
ln PGdj	−1.01	2.08**	11.45	21.18**	8.92	22.50**	−2.16	−2.98**	−2.16	−2.98*
LEC	−2.82	−4.54***	16.87**	53.43***	0.58	61.73***	−1.93	−4.52***	−2.11	−3.14***
ECI	−2.07**	−4.23***	1.62	36.93**	13.10	53.34**	−2.22	−5.13***	−2.34	−2.79**

Note: ***, **, * show values are statistically significant at 1%, 5%, and 10% levels.

and financial development are associated with increased carbon emissions, while renewable energy use reduces carbon emissions in South Asia. These results confirm our Hypothesis 4. Thus, these results showed that economic, social, and political globalization have varying effects on CO_2 emissions. Economic globalization increases carbon emissions, while enhanced social and political globalization reduces them in South Asia, supporting our first three hypotheses, H1, H2, and H3. Furthermore, it does not matter whether we apply de facto or de jure aspects of globalization or consolidate them by component. This suggests that at least when examining their effects on carbon emissions, both de facto and de jure aspects of globalization's components are equally important in practice and policy enforcement.

Table 4 Co-integration tests.

Model A: Economic, social, and political globalization			
Pedroni test		**Kao test**	
	***t*-statistics**		***t*-statistics**
MPP	1.69**	MDF	−2.67***
PP	−1.30**	DF	−2.62***
ADF	−0.91	ADF	−2.46***
		UAMDF	−4.38***
		UADF	−3.14***
Model B: De facto economic, social, and political globalization			
MPP	1.82**	MDF	−4.68***
PP	−0.89	DF	−3.04***
ADF	−0.82	ADF	−2.69***
		UAMDF	−4.63***
		UADF	−3.03***
Model C: De jure Economic, Social, and Political Globalization			
MPP	1.52**	MDF	−4.68***
PP	−1.73**	DF	−3.04***
ADF	−1.33***	ADF	−2.69***
		UAMDF	−4.63***
		UADF	−3.03***

MPP Modified Phillips-Perron, *PP* Phillips-Perron, and ADF stands for Augmented Dickey-Fuller, *MDF* modified Dickey-Fuller, *DF* Dickey-Fuller, *UAMDF* unadjusted modified Dickey-Fuller, *UADF* unadjusted Dickey-Fuller.
Note: ***, ** values are significant at the 1% and 5% significance levels. MPP stands for Modified Phillips-Perron, PP stands for Phillips-Perron, and ADF stands for Augmented Dickey-Fuller. MDF stands for modified Dickey-Fuller, DF is Dickey-Fuller, UAMDF is Unadjusted Modified Dickey-Fuller, and UADF is Unadjusted Dickey-Fuller.

Robustness analysis. When we employed fully modified ordinary least squares (FMOLS) as an alternative estimation technique for robustness, the results in Table 7 reassuringly verify our core FGLS findings in Table 6. That is, the direction and statistical significance of all parameters were intact, although the size of some parameters changed somewhat. First, all parameters in the FMOLS replication of the FGLS are now statistically significant from zero. Second, the de jure economic component of Model C becomes significant and takes a slightly higher positive value in magnitude, specifically 0.45 in Table 7, rather than 0.30. The same is true for the parameter for financial development (ln DCPTS) in Model B of Eq. 4, which has a value of 0.15 rather than 0.10 in Table 6. Economic globalization, both de facto and de jure, is associated with increased carbon emissions, while social and political globalization is linked to reductions in carbon emissions. Furthermore, the findings indicate that economic growth and financial development drive CO_2 emissions upward, whereas renewable energy mitigates them.

Similarly, Supplementary Tables S3 and S4 online, display the results of the robustness analysis when we add economic complexity and renewable energy to the model, along with disaggregated globalization and its de facto and de jure measures. These results also verify the baseline findings in Table 6. The signs and statistical significance of economic, social, and political globalization remain intact, although the parameter magnitudes are slightly lower. However, the parameters for de facto and de jure political globalization are not statistically significantly different from zero. Tables S3 and S4 show that energy consumption is a statistically substantial and dominant factor in carbon emissions. Economic complexity also has a statistically significant and positive impact on carbon emissions in all models, as GDP does in Table 6

Dumitrescu-Hurlin causality. The outcomes of the panel causality test, shown in Table 8, reveal several noteworthy

Table 5 Pre-model estimation tests.

	Serial correlation		
	Q(*p*) test	**HR test**	**Panel**
Ln CO_2	18.15*** (0.00)	−2.63*** (0.00)	Balance
In GDP	18.54*** (0.00)	−4.02*** (0.00)	Balance
In RE	41.14*** (0.00)	−2.24** (0.02)	Balance
In DCTPS	606.70*** (0.00)	1.24 (0.22)	Balance
In EG	12.19*** (0.00)	0.03 (0.90)	Balance
In SG	193.45*** (0.00)	−5.73*** (0.00)	Balance
In PG	48.35*** (0.00)	−2.17*** (0.00)	Balance
In EGdf	13.24*** (0.00)	0.26*** (0.00)	Balance
In SGdf	62.35*** (0.00)	−8.54 (0.80)	Balance
In PGdf	116.71*** (0.00)	−2.24** (0.03)	Balance
In EGdJ	27.05*** (0.00)	−2.10** (0.04)	Balance
In SGdj	71.14*** (0.00)	−3.07*** (0.00)	Balance
In PGdj	9.82*** (0.00)	0.07 (0.90)	Balance
Other specification tests			
	Model A	**Model B**	**Model C**
Hausman tests FE vs. RE	417.84**	10621.48***	55.42***
Modified Wald test for group-wise heteroscedasticity	20.41**	11.86**	78.17**
Wooldridge test for autocorrelation	3.71**	5.42***	3.15**
Mean VIF for multicollinearity	4.24	4.97	2.77

Note: *** and ** represent two-tailed *t-tests* that are significant at 1% and 5% levels of confidence.

Table 6 Results of feasible generalized least squares (FGLS) estimates (CO_2 emissions per capita is a dependent variable).

	Model A			Model B			Model C		
	Eq-1	Eq-2	Eq-3	Eq-4	Eq-5	Eq-6	Eq-7	Eq-8	Eq-9
ln GDP	0.16*** (0.04)	0.31*** (0.02)	0.53*** (0.07)	0.10** (0.05)	0.09* (0.05)	0.65*** (0.08)	0.23*** (0.03)	0.30*** (0.03)	0.29*** (0.04)
ln RE	−1.01*** (0.07)	−0.85*** (0.03)	−1.10*** (0.03)	−1.04* (0.06)	−0.65*** (0.08)	−1.02*** (0.01)	−0.90*** (0.06)	−0.80*** (0.06)	−0.94** (0.09)
ln DCTPS	0.06*** (0.02)	0.15*** (0.01)	0.20*** (0.04)	0.01 (0.03)	0.13*** (0.03)	0.08** (0.03)	0.12*** (0.01)	0.21*** (0.05)	0.16*** (0.03)
ln EG	0.16* (0.09)								
ln SG		−0.10*** (0.02)							
ln PG			−0.49*** (0.09)						
ln EGdf				0.25** (0.10)					
ln SGdf					−0.15** (0.07)				
ln PGdf						−0.58*** (0.10)			
ln EGdj							0.30 (0.06)		
ln SGdj								−0.24** (0.07)	
ln PGdj									−0.12** (0.05)

Note: The signs ***, **, and * show significant slopes at 1%, 5%, and 10% significance levels.

Table 7 Results of fully modified ordinary least squares (FMOLS) estimate (CO_2 is a dependent variable).

	Model A			Model B			Model C		
Variables	Eq-1	Eq-2	Eq-3	Eq-4	Eq-5	Eq-6	Eq-7	Eq-8	Eq-9
ln GDP	0.03*** (0.01)	0.60*** (0.03)	0.80*** (0.01)	0.07*** (0.01)	0.60*** (0.03)	1.01*** (0.01)	0.14** (0.01)	0.40*** (0.01)	0.48*** (0.02)
ln RE	−0.78*** (0.02)	−0.26*** (0.05)	−0.87*** (0.01)	−0.65*** (0.01)	−0.21*** (0.05)	−0.88*** (0.01)	−0.67*** (0.01)	−0.54*** (0.01)	−0.68*** (0.01)
ln DCTPS	0.13*** (0.01)	0.07*** (0.01)	0.30*** (0.01)	0.15*** (0.01)	0.07** (0.02)	0.09*** (0.01)	0.21*** (0.01)	0.43*** (0.05)	0.35*** (0.02)
ln EG	0.86* (0.03)								
ln SG		−0.13*** (0.04)							
ln PG			−0.80*** (0.04)						
ln EGdf				0.71*** (0.01)					
ln SGdf					−0.10*** (0.01)				
ln PGdf						−1.02*** (0.03)			
ln EGdj							0.45*** (0.04)		
ln SGdj								−0.45*** (0.08)	
ln PGdj									−0.30*** (0.01)
R^2	0.46	0.95	0.58	0.44	0.93	0.63	0.40	0.95	0.68
Adjusted R^2	0.44	0.94	0.57	0.42	0.90	0.61	0.38	0.93	0.66

***, **, and * denote statistical significance at 1%, 5%, and 10% levels of confidence. The panel method is pooled estimation with a heterogenous long-run coefficient. The sandwich method is used to compute coefficient co-variance, and long-run co-variance is computed using Bartlett kernel Newley-West fixed bandwidth.

Table 8 Results of Dumitrescu-Hurlin panel causality test.

H_0	*W*-Stat.	*Z*-bar-stat.	*p*-value	Result
ln GDP⇏ ln CO_2**	2.54	1.67	0.09	Uni-directional
ln CO_2⇏ GDP	1.06	−0.05	0.95	
ln DCTPS⇏ ln CO_2***	3.41	2.69	0.00	
ln CO_2⇏ ln DCTPS	2.32	1.42	0.15	Uni-directional
ln PG⇏ ln CO_2***	4.66	4.14	3.E-05	
ln CO_2⇏ ln PG***	5.06	4.61	4.E-06	Bidirectional
ln SG⇏ ln CO_2***	4.86	4.38	1.E-05	
ln CO_2⇏ ln SG	1.76	0.76	0.44	Uni-directional
ln PG⇏ ln EG**	2.74	1.91	0.05	
ln EG⇏ ln PG***	11.49	12.12	0.00	Bidirectional
ln SG⇏ ln EG	1.95	0.98	0.32	
ln EG⇏ ln SG***	10.09	10.48	0.00	Uni-directional
ln SG⇏ ln PG***	3.65	2.96	0.00	
ln PG⇏ ln SG	0.99	−0.13	0.89	Uni-directional

Note: ***and ** denote statistical significance at the 1% and 5% confidence levels with a two-tailed test.

associations. There appears to be bidirectional causal linkages between *ln PG* and *ln* CO_2. It indicates that political globalization granger causes carbon emissions, and carbon emissions granger causes political globalization. Rising carbon emissions have induced South Asia to engage in greater political globalization, and greater political globalization affects carbon emissions. A bidirectional causality between political and economic globalization implies that both political and economic globalization granger cause each other. We also find a uni-directional causality between each of *ln GDP*, *ln DCTPS*, and *ln SG* with *ln* CO_2, i.e., that GDP per capita, financial development, and social globalization granger cause carbon emissions. This means any policy change related to economic growth, financial development, social globalization, and political globalization tends to cause significant changes in carbon emissions. In contrast, any policy targeting CO_2 emissions does not affect economic growth, financial development, and social globalization but does influence political globalization in these countries. There also appears to be uni-directional causality from social to political globalization, as well as between economic and social globalization, suggesting influences run from economic to social to political globalization and are amplified by the bidirectional influence between economic and political globalization.

Discussion

Results revealed that economic globalization increases carbon emissions in the four selected South Asian countries. This result confirms the pollution haven hypothesis that the region's environmental and labor policies, which are weaker in the area than in the developed world, encourage polluting establishments that export to foreign nations to locate in the region to reduce overall costs. If the world is pointing out that economic globalization degrades environmental quality, our findings parallel those from other panel data studies for South Asia (Khan et al., 2022; Mehmood and Tariq, 2020), for other developing countries (Le and Le, 2023), and even for Europe (Destek, 2020; Leal and Marques, 2019). However, we failed to verify the results of Doytch and Uctum (2016), who contend that economic globalization can encourage environmental sustainability via technology transfer. There is a historical basis for why economic globalization deteriorates environmental quality in South Asia. First, to achieve higher economic growth, increase foreign reserves, and reduce poverty, the South Asian region has attracted foreign direct investment since the 1990s. Abundant natural resources, geo-political position, low-cost labor, and relaxed environmental policies attract foreign investors. FDI has tended to be directed to electric power plants, infrastructure development, manufacturing, chemicals, steel, and cement plants (ESCAP UN, 2021), all of which are among the most-polluting sectors worldwide and damage the environmental quality in South Asia as well (Manocha, 2024).

Second, due to the debt incurred, South Asian economies have reduced tariffs and other trade-related taxes as well as signed various free-trade agreements—both regional and international—to encourage exports. As a result, the shares of textiles and agricultural products in total exports have been rising in all four study countries, given their comparative advantage in what are essentially somewhat dirty industries (ESCAP UN, 2021). Production in these industries requires motor fuels, electricity, and/or fertilizer. Given electricity's continued reliance on fossil fuels within the region, increasing exports necessarily degrades South Asia's environmental quality (Khan et al., 2022; Shakeel and Ahmed, 2021). Third, in South Asia, economic globalization has led to massive infrastructure development, including roads, ports, and industrial zones. Although these developments are necessary for economic growth, they often lead to habitat destruction, increased energy consumption, deforestation, and higher emissions during both the construction and operation phases (Sattar et al., 2022). To make the region more environmentally sustainable, the governments of South Asia need to ensure that trade and FDI policies align with their promises of carbon neutrality in the not-too-distant future. Moreover, these countries need to revise their energy preferences, shifting from fossil fuels to renewable energy resources.

Political globalization reduces carbon emissions in South Asia, an innovative finding of our study that is consistent with the findings for other regions of the world where political globalization brings environmental sustainability (Destek, 2020; Leal and Marques, 2019; Shahbaz et al., 2019). Indeed, this finding differs only from those of Le and Le, (2023), who found that political globalization in developing nations (only) encourages carbon emissions. Since South Asia is becoming more politically integrated both internally and more broadly on the international stage, our region-specific findings are reassuring. International organizations have been encouraging member nations to improve environmental quality by increasing the share of electricity produced via wind-, solar- and hydro-based energy resources, replacing fossil fuels, and improving the region's energy security (Grunewald and Martinez-Zarzoso, 2016). By actively engaging in international treaties, governments of developing countries can negotiate for financial and technical assistance to protect their environment (Held and Roger, 2018). South Asia has joined in

UN peace missions and international treaties that focus on the global environment, i.e., the Kyoto Protocol, Sustainable Development Goals, the Paris Agreement, and the adoption of shared environmental standards. For instance, South Asian countries have committed to Nationally Determined Contributions (NDCs) to fulfill the Paris Agreement, aiming to reduce carbon emissions through renewable energy targets and increased energy efficiency. Likewise, these countries are adhering to international standards for environmental management systems like ISO 14001, which helps industries reduce waste, energy consumption, and carbon emissions. Moreover, South Asian countries have benefited from the Montreal Protocol (which reduces substances that deplete the ozone layer), international funding, regional cooperation, and technology transfers to phase out harmful substances, indirectly reducing their carbon footprint.

Another innovative finding from our study is that social globalization also reduces carbon emissions. This means that all subsections of social globalization (informational, interpersonal, and cultural globalization) contribute to environmental sustainability. This parallels the findings of Le and Le (2023) and Ozcan and Apergis (2018), who assert a positive role of social globalization in reducing carbon emissions. The findings of Salahuddin et al. (2016) oppose ours, contending that social globalization increases carbon emissions. Their sample of countries, however, include OECD nations, which are more globalized, developed, and richer than those in South Asia. Social globalization improves environmental quality in South Asia because, over the last two decades, access to information and communication technologies, and the internet in South Asia has skyrocketed, enabling interpersonal interactions and environmental awareness among the region's inhabitants and helping in reducing carbon emissions (Batool et al., 2022). Also, the region's social globalization score has benefited from the region's gains in human capital development and human rights, which has reduced gender disparity in South Asia (Gyamfi et al., 2024). These factors appear to also promote improved environmental quality, albeit indirectly. International cooperation and knowledge sharing, fostered by global networks and social media, promote sustainable agricultural practices (such as organic farming and precision agriculture) and renewable energy adoption in South Asia. Multinational corporations operating in South Asia, such as Unilever and Tata, often implement global sustainability standards in their operations, reducing emissions in their supply chains. These outcomes of social and political globalization very first validated the concept of world polity theory in South Asia, which was completely missing in the literature

We also find that economic growth is associated with rising carbon emissions in South Asia in all models. This outcome is not surprising, as numerous prior studies have gotten similar results (Agarwal et al., 2021; Batool et al., 2022; Rahman et al., 2020), unless the growth shifts from high- to low-polluting industries or unless the energy resource mix moves toward non-polluting renewable alternatives, a rise in economic activity must lead to an increase in carbon emissions released to the atmosphere. To reduce unemployment and poverty, South Asian nations are focusing on economic growth and industrialization, both of which heavily rely on fossil fuels, thereby leading to increased carbon emissions (Thakur and Jayaram, 2024). Moreover, South Asian nations are among the most populous in the world: higher population and economic growth increase the consumption and production of goods, which in turn emits more carbon (Rehman and Rehman, 2022). Economic growth also drives urbanization and transportation, further increasing carbon emissions in the region (Gyamfi et al., 2024).

Likewise, results in Table 6 highlight that financial development measured domestic credit to the private sector increases carbon emissions in South Asia. Our findings that domestically supplied financial development increases carbon emissions in South Asia are like those of Zakaria and Bibi (2019) as well as Le et al. (2020) for Asia more generally. Charfeddine and Kahia (2019) for MENA countries, and Wang et al. (2020) even for G7 countries. However, they diverge from the findings of Zaidi et al. (2019) on OECD countries and Rafique et al. (2020) on BRICS countries, who report that financial development appears to reduce carbon emissions. Given these empirical findings, we opine that financial development ultimately reduces environmental quality in South Asia due to the financial sector's fragile nature as it focuses on the wealthiest households and most prominent businesses for lending. It, therefore, advances credit to traditional "winner" industries, which are dirty, i.e., transportation services, textile manufacturing, fossil-fuel power generation and transmission, and agriculture. The other reason is that the financial sector in South Asia is very small and thus insufficient to fund many environmentally friendly projects and high-tech, fuel-efficient industries. To bring environmental sustainability, governments of these nations should find a way to nudge financial institutions to diversify their interests toward resource-efficient technologies, green energy, and export industries that pollute less.

The results of all models in Table 6 also highlight that the use of renewable energy reduces carbon emissions in South Asia. This positive role of renewable energy towards environmental quality is also examined in sub-Saharan African countries (Acheampong et al., 2019) and in South Asian countries (Ahmad and Majeed, 2019). The use of renewable energy shifts from fossil fuels to clean renewable energy resources enables countries to achieve net carbon emissions targets relatively quickly (Breyer et al., 2023). The share of solar energy in total renewable energy is high in South Asia due to the rich sunbelt. As the price of solar photovoltaics continues to decline compared to fossil fuels, households, and businesses naturally shifted to clean and renewable energy in South Asia. Clearly, if funding becomes available, government investment in solar and wind power and subsidies to enterprises could accelerate the shift. Considering these findings, reaching environmental sustainability in South Asia demands a better, more comprehensive approach to effectively reducing carbon emissions. Thus, these significant interrelationships among economic, social, and political globalization resonate with the world polity theory, which envisions a global community that fosters cooperation to combat environmental degradation.

Conclusion and policy recommendations

Conclusion. Globalization has driven economic growth, industrialization, and energy consumption in South Asia. This, in turn, has increased greenhouse gases, particularly carbon emissions. South Asian nations currently face significant challenges from the release of greenhouse gases, which pose substantial long-term risks in the form of heat waves, floods, ice melting, health issues, economic loss, and poverty. Reducing carbon emissions (the main contributor to GHGs) has become increasingly complex, particularly in developing countries like those in South Asia.

Theoretically, the environmental effects of globalization are ambiguous. Globalization encourages external cooperation and intervention to address factors that science suggests influence carbon emissions. Numerous studies on the determinants of environmental sustainability have attracted scholars and policymakers from around the world to this subject area. Every nation and region has unique economic, social, and political characteristics that can influence environmental quality. Moreover, the economic, social, and political components of globalization affect carbon emissions differently. Therefore, we do not generalize the findings of these studies. Additionally, no research to date has focused on the impacts of disaggregated globalization and de facto and de jure measures on carbon emissions in South Asia. We decided to study how economic, social, and political globalization, in both actual and legal forms, affects carbon emissions in South Asia, along with economic growth, primary energy use, renewable energy use, and financial development. Data availability limited our analysis to the period from 1996 to 2019 and to just four of South Asia's eight countries: Bangladesh, India, Pakistan, and Sri Lanka. We found cross-sectional dependency and slope heterogeneity in the data. All variables are stationary and co-integrated. Pre-estimation tests show that the data is heteroskedastic, serially correlated, and exhibits panel-specific autocorrelation. We applied feasible generalized least squares (FGLS) to test our estimates. The robustness of these results was confirmed by applying an alternative estimation technique (FMOLS) as well as alternative control variables (energy consumption and economic complexity). Finally, we applied the DH-causality test to measure causal relationships among the variables.

Despite focusing on South Asia and examining more aspects of globalization (breaking its three main components into either direct evidence or the reach of government rules), we confirm a central finding of most related work: economic globalization increases carbon emissions and, in our case, specifically in South Asia. Rising foreign direct investment in infrastructure and power sector development appears to have led to higher carbon emissions. Additionally, due to the abundant factors of production (labor and natural resources), South Asian countries have comparative advantages in highly polluting industries like textiles and agriculture, which rely on fossil fuels, the burning of which leads to increased carbon emissions.

We uniquely find that social and political globalization improves environmental quality in South Asia. Social globalization—encompassing informational, interpersonal, and cultural proximity—reduces carbon emissions in South Asia through various mechanisms: the diffusion of sustainable practices, enhanced public awareness, and the adoption of global environmental norms. Similarly, political globalization reduces carbon emissions in South Asia via different channels: the incorporation of international environmental agreements, the influence of global governance institutions, and the adoption of shared environmental standards. We, thus, confirm that the pollution haven hypothesis is specific to economic globalization in South Asia and not to the other two components of globalization. We also find that world polity theory is attached to social and political globalization. For South Asia, we also find that both *de facto* and *de jure* measures produce similar effects on carbon emissions, which shows there is no difference between policy perspectives and their practical implications.

Our causality tests confirm that, in South Asia, social and political globalization each affects CO_2 emissions and vice versa. This set of self-reinforcing ties between social and political globalization and carbon emissions needs further investigation since it offers much hope for South Asia's future toward sustainability. Furthermore, social globalization affects political globalization, and political globalization affects economic globalization. This economic-social-political globalization causal pathway further underscores the pivotal role of social and political globalization in diminishing carbon emissions and fostering environmental sustainability through economic change in South Asia. We, therefore, conclude that social and political globalization are critical to reducing carbon emissions in South Asia.

Policy recommendations. Our findings suggest that to mitigate the adverse impacts of economic globalization on carbon emissions, South Asian countries should enact legislation mandating that both domestic and foreign firms adopt environmentally sustainable technologies in their production processes and adhere to environmental regulations. Furthermore, to the extent possible, South Asian nations should avoid encouraging foreign investment in energy sectors, minerals, and related infrastructure unless it substantially enhances productivity. Instead, future foreign direct investments should be directed toward information and communication technologies, green technology, sustainable cities and transportation, and renewable energy. To achieve this, governments could provide financial assistance and incentives to large international technological companies to invest in the digital media, information and communication technology, and renewable energy sectors. To promote trade sustainability, South Asian countries should diversify their basket of goods, increase the proportion of service trade, and reduce reliance on the agricultural and manufacturing sectors.

Recognizing the positive influence of social globalization on environmental sustainability, policymakers should actively promote social globalization in South Asia. This includes sharing ideas through the internet and social media, as human interaction helps strengthen social globalization. Recent campaigns against the use of plastic bags, as well as climate strikes in South Asia, are direct results of social globalization. To achieve future environmental sustainability in South Asia, time is needed to develop tourism, human capital, and the integration of information and communication technology into production. Similarly, to enhance political globalization for environmental sustainability, South Asian countries should foster transnational cooperation and ensure the effective implementation of all existing environmental agreements, particularly the SDGs and the Paris Agreement. South Asian countries should leverage existing forums and engage in new ones. Likewise, developed countries must set aside their political biases and provide financial and technical assistance to the most affected countries in South Asia.

South Asian countries should reduce their reliance on fossil fuels and prioritize the promotion of renewable energy sources in their energy mix. To achieve this, governments should financially support companies involved in producing and importing clean energy. Reducing subsidies on fossil fuels can also promote energy efficiency in South Asia. Regional trade can play a significant role in developing the infrastructure required for renewable energy by reducing transportation costs and encouraging the adoption of green energy solutions. Existing regional agreements, such as the South Asian Association for Regional Cooperation (SAARC), should be aligned with environmental requirements. Financial services in South Asia should also prioritize supporting greener and cleaner initiatives. Banks and financial institutions should allocate funds for clean energy projects and energy-efficient technologies in their credit portfolios. Increasing access to mobile banking, especially for women in rural areas, can significantly contribute to reducing carbon emissions.

Limitations and future research. Our work is innovative in that it focuses on South Asia, a region highly vulnerable to climate change. It employs advanced econometric techniques and current theory to examine the relationships between different aspects of globalization and carbon emissions. However, several limitations need to be acknowledged. First, data availability restricted our analysis to just four of South Asia's eight countries. While our study's geographic scope included the region's three largest nations plus Sri Lanka, a comprehensive analysis should include the remaining four: Afghanistan, Bhutan, the Maldives, and Nepal. It would also be beneficial to expand our analysis to encompass all MENA nations, non-MENA nations in Africa, countries in the Pacific and Southeast Asia, and smaller nations in Latin America (Brazil, Mexico, Colombia, and Chile currently receive significant attention). Second, our analysis, ending in 2019, did not account for structural breaks and industry shifts that occurred following the COVID-19 pandemic. Exogenous or endogenous structural breaks are highly reliable measures for capturing events and shifts in specific series over time. The pandemic's effects have been far-reaching, particularly concerning supply chains, which have become more regional and less extensive, at least temporarily. Many nations worldwide have sought ways to become more self-reliant on commodities, leading to temporary supply shortages. Third, we only examine carbon emissions as an indicator of environmental quality. While CO_2 emissions are critical and a strong indicator of greenhouse gas (GHG) emissions, other pollutants like particulate matter, sulfur oxides, nitrogen oxides, lead, microplastics, and mercury releases are also harmful to humans and ecological systems. Additionally, water quality and availability are prime concerns, particularly in South Asia. Fourth, future research could evaluate the effects of subsections of KOF economic, social, and political globalization on carbon emissions for a more comprehensive analysis. More work remains to be done.

Data availability

The datasets used and analyzed in the current study are available in the supplementary file, and these datasets have been derived from the following public-domain open-access resources: https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html, https://databank.worldbank.org/reports.aspx?source=World-Development-Indicators, https://www.media.mit.edu/projects/oec-new/overview/, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/energy-economics/statistical-review/bp-stats-review-2022-full-report.

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Notes

1 There is a consensus that South Asia consists of eight countries—Afghanistan, Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, and Sri Lanka—in which a quarter of the world's population resides. We dropped one of South Asia's nations from our study—Bhutan which is essentially a pollution-free. We drop three others—Nepal, Maldives, and Afghanistan—because no or little data are available for them, at least for the set of variables we examine.

2 Note renewable energy includes biomass, like straw, wood, charcoal, sorghum, sugarcane, and seed crops, some of which can be liquified. While these are potentially sustainable energy resources, they are burned and, hence, emit carbon.

3 Accessible in April 2024 at https://databank.worldbank.org/source/world-development-indicators.

4 Accessible in April 2024 at https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html.

5 Accessible in April 2024 at https://oec.world/en.

6 Accessible in April 2014 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/energy-economics/statistical-review/bp-stats-review-2022-full-report.

7 This is because PCA is a data-reduction technique from which components emerge as linear combinations of all variables that maximally explain the variance of all variables included in the exercise. Thus, the key to such indices is the analyst's choice of variables, which must cover all aspects of the target latent variable s/he is trying to estimate—in Dreher's (2006) case "globalization." Moreover, the variables included in the analysis should be orthogonal (noncollinear) to avoid over-emphasis on the characteristics of the target latent variable. The relative importance of the principal components of the index emerges from the eigenvalues of the co-variance matrix of the variable set. The components themselves are eigenvectors of the co-variance matrix of the variables.

8 Analysts typically apply intuition, labeling the components based on commonalities among the variables with coefficients in the relevant eigenvector that have large absolute values.

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Author contributions

MA contributed to the study's conception and design, writing the initial draft, revision, data collection, and quantitative analysis. LY contributed to the study's design, revision, review, and editing of the draft, as well as supervision of the overall work. MLL contributed to study conception, organization, drafting, editing, and critical evaluation.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

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Additional information

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Correspondence and requests for materials should be addressed to Musarat Abbas.