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CO₂ emissions inequality through the lens of developing countries

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HIGHLIGHTS

• The impacts of COVID-19 outbreak on CO₂ emission inequality are simulated.
• CO₂ emissions inequality under shared socioeconomic pathway scenarios are projected.
• The carbon implications of targeted poverty elimination measures are examined.

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ABSTRACT

There is increasing interest in CO₂ emissions inequality between and within countries, and concerns about the impacts of COVID-19 on vulnerable groups. In this study, the CO₂ emissions inequality based on the different consumption category data of disaggregated income groups in eight developing countries is analyzed with the application of input-output model. We further examine the effects of the COVID-19 outbreak on CO₂ emissions inequality based on the hypothetical extraction method, and the results reveal that the outbreak has decreased the CO₂ emissions inequality and emissions over time. However, the shared socioeconomic pathway scenario simulation results indicate that long-term CO₂ emissions inequality will persist. Targeted poverty elimination measures improve the utility of the low- and lowest-income groups and reduce CO₂ emissions inequality. Reducing the excessive consumption on the demand side as well as improving the energy efficiency and increasing the share of renewable energy in the energy consumption on the supply side will provide more informed options to achieve multiple desirable outcomes, such as poverty elimination and climate change mitigation.

1. Introduction

In December 2019, a new coronavirus emerged in Wuhan, China, which eventually causes a severe acute respiratory syndrome. The World Health Organization declared a global pandemic on 11 March 2020 [1]. The virus has spread across more than 210 nations and regions, more than four million people worldwide have been infected, and hundreds of thousands of people have died within a few months (World Health Assembly, 2020). The COVID-19 outbreak has not only seriously endangered the lives and health of people but also greatly impacted social and economic activities. People have been encouraged or mandated to maintain a social distance and to travel less often to flatten the curve, many restaurants and shops are closed, and public transportation services have been reduced or halted to prevent further spread of the virus.

Due to the complexity and high interdependence of the modern economic system, the COVID-19 outbreak has exerted major impacts on the economy and employment in many regions through the supply chain [2], which has resulted in new challenges to the governance capacity of decision-makers already struggling to identify solutions to fulfill the sustainable development goals (SDGs) proposed by the United Nations (UN) in 2015. On the one hand, the low-income groups who work in the manufacturing and services industries have been unable to return to work due to mandated isolation regulations, which jeopardizes their income and livelihood, and the gap between the rich and the poor is likely to further widen, which threatens any inequality reduction

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The synergies and trade-offs among the achievements of the different SDGs have been intensively examined and discussed by many researchers to provide consistent and effective policy suggestions to regional and national governments [3,4]. For example, multiple benefits, such as poverty elimination and environmental sustainability development, could be achieved by targeting the undernourished and by reducing overconsumption and other environmental impacts [5]. Increased educational attainment would substantially improve the adaptability to climate change impacts [6]. Poverty alleviation and sustainable economic growth impose a fundamental impact on the realization of the other SDGs [7].

Energy inequality has been considered to be a better proxy for the measurement of inequality than income inequality since it captures the service flows of durable commodities [8]. High energy inequality has been found among different income groups on both the international and intranational scales [9]. Moreover, carbon inequality has also been encountered across income groups and nations. The richest 10% of the world’s population contribute approximately 34% of the global greenhouse gas (GHG) emissions, whereas the bottom half contributes only 15% to global emissions [10]. There is carbon emissions inequality within the EU countries, and sustainable energy transformation in Central-Eastern Europe is necessary to achieve the EU climate mitigation targets [11]. Carbon inequality may be higher within developing countries with a large gap between urban and rural areas, and between high- and low-income groups. For example, the top 5% of the population contributed 17% to the total household carbon footprint in China, whereas the bottom half of the population was responsible for only one quarter [12]. In India, the ratio of CO2 emissions per capita of the top 10% of the population to the bottom 10% of the population in urban areas is 15:1, while it is approximately 9:1 in rural areas [13]. Energy/carbon inequality reflects the income disparity, consumption pattern, and associated carbon emissions across areas and households. Therefore, feasible measures to eliminate energy/carbon inequality play an important role in achieving the objectives of poverty alleviation, inequality reduction and climate change mitigation.

The input–output (IO) model has been a popular method broadly adopted to examine the carbon inequality among different households at the national and subnational levels, since it captures the indirect carbon emissions caused by the household consumption of commodities and services [14,15]. Numerous studies have indicated that indirect household carbon emissions are much higher than direct household carbon emissions [16,17]. Considering the whole supply chain, the energy utilization and environmental pollution caused by the consumption of high-income households tend to be higher than those of low-income households [18]. Household CO2 emissions will continue to increase in many emerging economies due to their increasing population and economic development [19].

Scenario analysis can compare the potential and consequences of different policies, inform decision-makers in the development and implementation of effective and feasible measures, and improve the public acceptance of these policies and measures. Shared socioeconomic pathways (SSPs) provide a scenario framework for the research community that describes five representative qualitative narratives under the possible future trends of socioeconomic and environmental development [20]. SSP1 describes a sustainable development storyline that implies low challenges for mitigation and adaptation [21]. SSP2 involves a moderate challenge to both mitigation and adaptation [22]. SSP3 is a rocky road scenario with high challenges for both mitigation and adaptation [23]. SSP4 is a road divided scenario characterized by low challenges to mitigation but high challenges to adaptation [24]. In contrast, SSP5 involves high challenges to mitigation but low challenges to adaptation [25]. The future income inequality measured by the Gini coefficient has been applied across the SSPs [26]. However, the collection of income data limits the accuracy of inequality since people tend to underreport their income. In addition, income data do not reflect the long-term resource usage of households.

Overall, a growing body of studies has investigated global and subnational energy consumption and the associated carbon emissions by considering income gap and socio-economic disparity as shown in Table 1, which is informative for decision makers to understand carbon emissions inequality and its driving factors. However, these studies have focused on historical data and have not described the current existing inequality issue, which fails to examine the impact of unexpected events on carbon inequality or consider future carbon inequality under a consensual scenario framework that comprises different socioeconomic development possibilities. Moreover, they have not provided a useful solution to better inform decision makers on how to solve carbon inequality.

Therefore, this study contributes to the body of knowledge in the following ways. First, we examine the international and intranational CO2 emissions inequalities among eight developing countries, including China, India, Russia, South Africa, Brazil, Indonesia, Mexico, and Turkey, since these countries account for 47.9% of the world’s population (World Bank, 2019) and 47.7% of the total global CO2 emissions caused by fossil fuel consumption in 2018 [27]. They also face great challenges in terms of eliminating poverty, reducing inequality and tackling climate change. More importantly, these developing countries are severely affected by the epidemic due to their fragile public health

| Table 1 | Literature review on energy/CO2 emissions inequality. |
|---------|--------------------------------------------------------|
| Indicators | Regions | Time period |
| Huiback et al. [10] | Carbon emissions | Global | 2012 |
| Oswald et al. [9] | Energy consumption | Global | 2011 |
| Bianco et al. [11] | Energy consumption and carbon emissions | EU 28 | 2008-2016 |
| Gill and Moeller [28] | GHG emissions | Germany | 2013 |
| Briza et al. [15] | Carbon emissions | the Baltic States | 1995-2011 |
| Scherer et al. [19] | Carbon emissions | BRIC and MINT countries | 2010 |
| Parikh et al. [13] | CO2 emissions | India | 2003-2004 |
| Mi et al. [12] | Carbon emissions | China | 2007, 2012 |
| Zhang et al. [14] | Carbon emissions | China | 2007, 2012 |
| Wu et al. [8] | Energy consumption | China | 2012 |
| Chen et al. [16] | Energy consumption | China | 2012 |
| Liu et al. [29] | Carbon emissions | China | 2002, 2007, 2012 |
| Feng et al. [17] | CO2 emissions | Beijing, Tianjin, Shanghai, and Chongqing | 2012 |
| Huang et al. [30] | CO2 emissions | Beijing, Tianjin, Shanghai, and Chongqing | 2007, 2012 |
systems. According to data from Johns Hopkins University, the number of infections and deaths in Brazil, India, and Mexico are among the highest in the world. Second, we simulate the short-term impact of the household consumption category changes due to the COVID-19 outbreak on the CO₂ emission reduction and inequality levels under four extreme scenarios by extracting the catering and accommodation, transportation, and clothing sectors and all of these sectors combined from the economic system with the hypothetical extraction method (HEM). Third, we provide CO₂ emissions inequality projections under the different SSP scenarios to inform decision-makers and the public of the long-term difficulties and challenges. Fourth, we simulate the effect of targeted poverty elimination measures on CO₂ emissions inequality and the associated CO₂ emissions to provide solutions to decision-makers to achieve multiple outcomes of sustainable development.

2. Methodology and data

The starting point is the IO model where the relationship among the industrial sectors in an economic system is described as:

\[ X = AX + Y = (I - A) \begin{bmatrix} X_0 \\ L \end{bmatrix} + Y = LY \]  

(1)

where \( X \) is the output, \( A \) is the direct consumption coefficient, \( Y \) is the final demand, and \( L \) is the Leontief inverse matrix.

2.1. Hypothetical extraction method (HEM)

The HEM was first proposed by Schultz to examine the economic impact of a sector’s activity change [31], Cella [32] and Duarte et al. [33] further reformulated the HEM. The original idea of the HEM is to estimate the effect of sector \( i \) on the economy by comparing the economic production with that of a hypothetical scenario in which sector \( i \) was extracted from the economy. Based on the results, the effect of sector \( i \) on the economy can be recognized, which allows us to identify the key sectors in the economy. As global warming has received increasing attention, the HEM has been widely applied to study the CO₂ emissions linkages of the industrial sectors in different regions [34,35].

\( B_s \) is a block of the target sectors in the economy, which can include either a single sector or several sectors. \( \bar{B}_s \) are the remaining blocks.

The economy can be expressed as:

\[
\begin{bmatrix}
X_s \\
\bar{X}_s
\end{bmatrix} = \begin{bmatrix}
\Delta_{s,s} & \Delta_{s,s-} \\
\Delta_{s,s} & \Delta_{s,s-}
\end{bmatrix} \begin{bmatrix}
Y_s \\
\bar{Y}_s
\end{bmatrix}
\]

(2)

where \( X = \begin{bmatrix} X_s \\ \bar{X}_s \end{bmatrix} \) is the total output, \( Y = \begin{bmatrix} Y_s \\ \bar{Y}_s \end{bmatrix} \) is the final demand, and \( L = \begin{bmatrix} \Delta_{s,s} & \Delta_{s,s-} \\
\Delta_{s,s} & \Delta_{s,s-} \end{bmatrix} \) is the Leontief inverse matrix.

In the hypothetical economy, block \( B_s \) neither buys from nor sells to the other sectors, and the hypothetical economic relationship can be described as:

\[
\begin{bmatrix}
X'_{s} \\
\bar{X}'_{s}
\end{bmatrix} = \begin{bmatrix}
\Delta_{s,s} & 0 \\
0 & \Delta_{s,s-}
\end{bmatrix} \begin{bmatrix}
X_s \\
\bar{X}_s
\end{bmatrix} + \begin{bmatrix}
Y_s \\
\bar{Y}_s
\end{bmatrix} = \begin{bmatrix}
X''_s \\
\bar{X}''_s
\end{bmatrix}
\]

(3)

The economic impact of block \( B_s \) on the total output can be expressed as follows:

\[
X - X'' = \begin{bmatrix}
\Delta_{s,s} - (I - A_{s,i})^{-1} & \Delta_{s,s-} \\
\Delta_{s,s} & \Delta_{s,s-} - (I - A_{s,i})^{-1}
\end{bmatrix} \begin{bmatrix}
Y_s \\
\bar{Y}_s
\end{bmatrix} = \begin{bmatrix}
C_{s,s} & C_{s,s-} \\
C_{s,s} & C_{s,s-}
\end{bmatrix} \begin{bmatrix}
Y_s \\
\bar{Y}_s
\end{bmatrix}
\]

(4)

The effect of block \( S \) on CO₂ emissions can be expressed as Equation (5):

\[
F - F' = \begin{bmatrix}
f_S \\ 0 \\
0 \\ f_S
\end{bmatrix} \begin{bmatrix}
C_{s,s} & C_{s,s-} \\
C_{s,s} & C_{s,s-}
\end{bmatrix} \begin{bmatrix}
Y_s \\
\bar{Y}_s
\end{bmatrix} = \begin{bmatrix}
\Omega_{s,s} & \Omega_{s,s-} \\
\Omega_{s,s} & \Omega_{s,s-}
\end{bmatrix} \begin{bmatrix}
Y_s \\
\bar{Y}_s
\end{bmatrix}
\]

(5)

where \( f_S \) are the sectoral CO₂ emissions per output unit of blocks \( S \) and \( \bar{S} \).

2.2. Gini coefficient

The Gini coefficient and Lorenz curve are broadly used to measure inequality in economics. The Gini coefficient was developed and named after an Italian economist, and the value of the Gini coefficient ranges from zero to one [36]. A value of zero indicates that income is distributed equally across the population, while a value of one is the highest degree of income inequality. The Gini coefficient has been widely adopted to test the extent of inequality in many fields [37,38]. In this study, we use the Gini coefficient to measure CO₂ emissions inequality through Equation (6). The CO₂ emissions Lorenz curve is a useful supplement to the Gini coefficient of CO₂ emissions, and is a ranked distribution of the cumulative percentage of the population on a horizontal axis versus the cumulative percentage of CO₂ emissions distributed along a vertical axis [8].

\[
G = \sum_{i=1}^{n} D_i C_i + 2 \sum_{i=1}^{n} D_i (1 - T_i) - 1
\]

(6)

where \( G \) is the Gini coefficient of CO₂ emissions, \( D_i \) and \( C_i \) are the proportions of the population and CO₂ emissions of each group, respectively, \( T_i \) is the cumulative proportion of the CO₂ emissions of each group, and \( n \) is the number of groups. When the value of \( G \) is larger, CO₂ emissions inequality is larger.

2.3. Scenario setting

By investigating the effect of the COVID-19 outbreak on CO₂ emissions inequality and associated CO₂ emissions, we construct four scenarios to simulate the effect of household consumption category variation on CO₂ emissions change by adopting the HEM, as indicated in Table 2. The CO₂ emissions inequality and CO₂ emissions of household consumption before the COVID-19 outbreak are adopted as the business-as-usual (BAU) scenario. The production and consumption of the catering and accommodation, transport and clothing sectors and these sectors combined are hypothetically extracted from the economic system, since the household consumption of these categories has been greatly affected by the imposed isolation measures. By comparing the results under these scenarios to the data under the BAU scenario, we can analyze the effect of the COVID-19 outbreak on the CO₂ emissions and CO₂ emissions inequality in each country.

2.4. Data

The IO table and CO₂ emissions data employed in our study are acquired from the Eora multiregional input-output (MRIO) database, which provides a time series of high-resolution IO tables with matching environmental and social satellite accounts for 190 economies [39,40].

| Table 2 | Scenario setting |
|---------|------------------|
| BAU     | Catering and accommodation |
| S1      | Catering and accommodation |
| S2      | Transport |
| S3      | Clothing |
| S4      | Catering and accommodation, transport, and clothing |
It has been adopted in other research to examine various environmental footprints on different geographical scales [41,42]. In this study, we adopt the national IO tables of China, India, Russia, South Africa, Brazil, Indonesia, Mexico, and Turkey at 2010 purchase prices for the sake of consistency for the household consumption data. The detailed household consumption data for urban higher-, middle-, low- and lowest-income households and rural higher-, middle-, low- and lowest-income households are from the World Bank. The nomenclature in this study is given in Table 3.

3. Results

3.1. International and intranational CO₂ inequalities

Based on Equation (1) and the detailed household consumption data across income groups, we can calculate the CO₂ emissions caused by household consumption at different income levels. The social average CO₂ emissions of a given nation are defined as the summation of the CO₂ emissions per capita of urban higher-, middle-, low- and lowest-income households and rural higher-, middle-, low- and lowest-income households. We compare the social average CO₂ emissions of the above eight countries, as shown in Fig. 1.

Notable CO₂ emissions inequality is observed in these developing countries. China and Russia exhibit the highest social average CO₂ emissions, which are 11–12 times higher than the social average CO₂ emissions of Brazil, which has the lowest emissions. The social average CO₂ emissions of Indonesia are ranked third, which are equivalent to the total emissions of South Africa and Turkey. India, in sixth place, exhibits twice the social average CO₂ emissions of Mexico and Brazil.

There are also very high CO₂ emissions inequalities among the different income groups within a country. The shares of the different household income CO₂ emissions are shown in Fig. 2. More than half of the CO₂ emissions are caused by the urban households in China, India, Indonesia, and South Africa, with the urban higher-income households dominating. In contrast, the rural households in Russia, Brazil, Mexico, and Turkey contribute relatively more to CO₂ emissions, especially the rural higher-income households. For example, 50.53% of the social average CO₂ emissions in India are due to its urban higher-income households. In contrast, in Turkey, the rural higher-income households account for 50.97% of the social average CO₂ emissions.

The CO₂ emissions caused by the different consumption categories for the urban and rural households at different income levels vary greatly for each country. The sources of the different household income CO₂ emissions in China are shown in Fig. 3. The energy and water sector is the dominant emission source for the Chinese urban and rural households at different income levels, followed by the transport and housing sectors. This occurs because these goods and services are energy intensive and have a coal-based energy structure in China. In contrast, the CO₂ emissions caused by consumption in the food, catering and accommodation, education and health, information and communications technology (ICT), clothing, finance, and personal care sectors are relatively lower.

3.2. CO₂ emission reductions under the different scenarios

Based on the HEM and scenarios settings shown in Table 2, we can calculate the CO₂ emissions of these countries under each scenario. By comparing the CO₂ emissions under the BAU and different scenarios, we can obtain the CO₂ emission reductions under each scenario. The CO₂ emission reduction levels of the eight countries under the different scenarios are shown in Fig. 4. Under S2 (the transport sector scenario) and S4 (the mixed sector scenario), a remarkable reduction effect is found in all countries since the transport sector is an emission-intensive sector in these countries. In contrast, under S1 (the catering and accommodation sector scenario) and S3 (the clothing sector scenario), the emission reduction effect in most countries is not notable, except for China and Turkey. For instance, the emission reduction level is approximately 59% in China under S1. The emission reduction level is approximately 36% in Turkey under S3. This reflects the emission-intensive characteristics and high reduction potential of the relevant sectors in China and Turkey.

The emission reductions for the different household income under the different scenarios are shown in Fig. 5. Interestingly, the reduction effect is more notable for the low- and lowest-income groups in China,
Brazil, and Indonesia under S1 (the catering and accommodation sector scenario). This occurs due to the large share of catering and accommodation consumption in the total consumption of the low- and lowest-income groups. For instance, the proportions of the catering and accommodation consumption of the urban (rural) low- and lowest-income groups are 8.1% and 8.5% (7.2% and 8.1%), respectively, in China, while these proportions are 6.2% and 7.6% (5.6% and 5.9%) for the urban (rural) higher- and middle-income groups, respectively.

It is apparent in all of these countries that the reduction effects are consistently larger for both the urban and rural higher- and middle-income households under S2 (the transport sector scenario). Therefore, advocating green and low-carbon travel options that target these middle- and higher-income households could result in considerable emission reductions.

The reduction effect greatly differs across the different income groups among these nations under S3 (the clothing sector scenario). For example, the reduction effect is more evident for the low- and lowest-income groups in India, South Africa, Brazil, and Mexico. However,
the reduction effect is more distinct for the low- and middle-income groups in China and Russia. In Turkey, the reduction effect is more notable for its urban high- and lowest-income groups under S3. These results indicate that particular reduction strategies are needed for the specific income groups in the different countries.

The reduction effect for each income group under S4 (the mixed sector scenario) is similar to that under S2 (the transport sector scenario). The reduction effect increases with the increasing income level of the different groups. However, the situation in China is more complicated, where the urban high- and middle-income groups and rural low- and lowest-income groups are responsible for more of the emission reduction.

### 3.3. CO₂ inequality under the different scenarios

Based on Equation (6), we can calculate the Gini coefficients of the CO₂ emissions under the different scenarios for each country, as given in Table 4. The Gini coefficients of the CO₂ emissions of these countries vary greatly before the COVID-19 outbreak (BAU in Table 4). South Africa exhibits the highest CO₂ emissions inequality, while Turkey and Brazil rank second and third, respectively. In contrast, India has the lowest CO₂ inequality. Affected by the COVID-19 outbreak, the Gini coefficients of the CO₂ emissions of these countries decrease to different extents (denoted as S4 in Table 4), which is mainly caused by the transportation limitations and shutdown measures (S2).

In contrast, the effects of the catering and accommodation sector extraction (S1) and clothing sector extraction (S3) on the Gini coefficient of the CO₂ emissions greatly differ among the different countries. For example, under S1, the Gini coefficient of the CO₂ emissions in China is increasing, whereas the Gini coefficient of the CO₂ emissions in India is decreasing. This occurs because the CO₂ emissions Lorenz curve of this sector is different between China and India, as shown in Fig. 6. The CO₂

### Table 4
International CO₂ emissions inequality under the different scenarios.

| Country   | BAU  | S1    | S2    | S3    | S4    |
|-----------|------|-------|-------|-------|-------|
| China     | 0.4354 | 0.4556 | 0.4141 | 0.4325 | 0.4142 |
| India     | 0.2945 | 0.293  | 0.2666 | 0.2989 | 0.2685 |
| Russia    | 0.4536 | 0.4541 | 0.3622 | 0.4546 | 0.3576 |
| South Africa | 0.6107 | 0.6105 | 0.5856 | 0.6149 | 0.5900 |
| Brazil    | 0.5397 | 0.5425 | 0.4168 | 0.544  | 0.4136 |
| Indonesia | 0.4632 | 0.4137 | 0.278  | 0.4047 | 0.2741 |
| Mexico    | 0.4152 | 0.4133 | 0.3598 | 0.4159 | 0.3547 |
| Turkey    | 0.5481 | 0.5488 | 0.5346 | 0.5474 | 0.5338 |

Fig. 4. CO₂ emission reductions under the different scenarios.

Fig. 5. CO₂ emission reductions for different household income.
emissions Lorenz curve of the catering and accommodation sector in China is steeper than its total CO$_2$ emissions Lorenz curve, which implies that this sector could decrease the Gini coefficient of CO$_2$ emissions. Therefore, the Gini coefficient of CO$_2$ emissions in China increased after extracting the catering and accommodation sector. In contrast, the CO$_2$ emissions Lorenz curve of the catering and accommodation sector in India is less steep than its total CO$_2$ emissions Lorenz curve, which indicates that this sector could increase the Gini coefficient of its CO$_2$ emissions. Therefore, the Gini coefficient of the CO$_2$ emissions in India decreased after extracting the catering and accommodation sector.

3.4. CO$_2$ inequality under the various SSP scenarios

Based on the Gini coefficients of the household expenditures and the CO$_2$ emissions under the BAU and four simulated hypothetical extraction scenarios, we can obtain their linear relationship for the eight countries. The regression results are shown in Fig. 7. The degree of fitting for each model indicates that the projection of the Gini coefficient of the CO$_2$ emissions based on each model is feasible. The Gini coefficient of the CO$_2$ emissions of each country under the different SSPs until 2100 are shown in Fig. 8.

A long-standing international CO$_2$ emissions inequality is observed even under the sustainable development scenario (SSP1). The CO$_2$ emissions inequalities in Russia and Turkey remain stagnant until the end of this century. The Gini coefficients of the CO$_2$ emissions of South Africa exhibit a slight downward trend. In contrast, the Gini coefficients of the CO$_2$ emissions of China, Mexico, India, Brazil, and Indonesia exhibit a notable downward trend.

Under SSP2, the CO$_2$ emissions inequality in South Africa, Turkey and Brazil remains constant for a long time. The CO$_2$ emissions inequality in China, Mexico and Indonesia could be greatly improved. In contrast, the Gini coefficients of the CO$_2$ emissions of Russia and India exhibit a rising trend, which indicates an aggravating CO$_2$ emissions inequality.
Under SSP3, the CO₂ emissions inequality in all countries will be exacerbated, including China and Indonesia. The Gini coefficients of the CO₂ emissions of Mexico exhibit a U-shaped curve, which declines initially but rises after 2066. The Gini coefficients of the CO₂ emissions of Russia, Turkey, and India present a steep increasing trend.

Under SSP4, the international CO₂ emissions inequality is more disparate among these countries, which implies the necessity for these nations to implement effective measures to avoid a more polarized world.

Under SSP5, the CO₂ emissions inequalities in China, Mexico, Indonesia, and Brazil could be suitably managed by the end of this century. The Gini coefficients of the CO₂ emissions of South Africa and India also exhibit a downward trend. In contrast, the Gini coefficients of the CO₂ emissions of Russia and Turkey still reveal an increasing trend.

3.5. The effect of targeted poverty elimination on CO₂ inequality

Since the Gini coefficient of the total CO₂ emissions of each country could mask the inequality disparity in a specific consumption category, we further assess the CO₂ inequality of the different income groups in each consumption category, which provides us more information and details on the disaggregated consumption inequality. As shown in Fig. 9, there are large distinctions between the Gini coefficients of the CO₂ emissions in the disaggregated consumption categories for each country. The detailed Gini coefficients of CO₂ emissions in each consumption category across countries are provided in the supplementary materials. The CO₂ emissions inequality in the food consumption category is the lowest in China, India, Russia, South Africa, Brazil, Indonesia, and Mexico, since food is a life necessity for people of all incomes. In contrast, the consumption category with the highest CO₂ emissions...
inequality varies among these countries. For example, the consumption categories with the highest CO₂ emissions inequality in China, India, Russia, South Africa, and Turkey are the clothing, housing, personal care, finance, and transport sectors, respectively. In addition, the CO₂ emissions inequality in certain consumption categories is higher than the total CO₂ emissions inequality in each country, which enables the provision of specific measures to reduce inequality by targeting these consumption categories with high CO₂ emissions inequality.

Targeted poverty elimination is aimed at increasing the consumption of the low- and lowest-income groups in the categories with a higher inequality than the total CO₂ emissions inequality to the corresponding level of the middle-income group in each country instead of increasing the overall consumption of the low- and lowest-income groups to the level of the middle-income group. The effect of targeted poverty elimination measures on CO₂ emissions inequality is shown in Fig. 10. We find that CO₂ emissions inequality is improved to varying extents in all countries over the BAU scenario baseline. The Gini coefficient of the CO₂ emissions in India after targeted poverty elimination is greatly reduced from 0.2945 to 0.0322. This is related to the larger proportion of the low- and lowest-income groups in the total population of India. The above result reflects the enormous potential of targeted poverty elimination in terms of CO₂ inequality reduction.

The left number in brackets represents the Gini coefficient of the CO₂ emissions under the BAU scenario, and the right number denotes the Gini coefficient of the CO₂ emissions under the targeted poverty elimination scenario.

The CO₂ implications of targeted poverty elimination are further examined, as shown in Fig. 11a. The total CO₂ emissions increase 155 Mt after targeted poverty elimination due to increased consumption. The CO₂ emissions increments in Indonesia are the largest (63.5 Mt), followed by those in Russia (34.1 Mt), China (25.2 Mt), India (13.8 Mt), and South Africa (11.2 Mt). This occurs due to the large consumption gap between the low- and lowest-income groups and the middle-income group in these countries. However, this result also indicates the carbon-rich characteristics of the respective consumption categories in each country. The contributions of the different income groups to the observed CO₂ emissions increments are different in each country. For example, the rural low- and lowest-income groups in Indonesia contribute more to its CO₂ emissions increment, at 33.6% and 37.7%, respectively (Fig. 11b), since the carbon-intensive transport consumption of the rural low- and lowest-income groups is more than twice that of the corresponding urban income groups after targeted poverty elimination. In China, the CO₂ emissions increments of the urban low- and lowest-income groups are slightly larger than those of the rural low- and lowest-income groups (Fig. 11d) since there is no notable consumption difference between them in the targeted categories. By comparison, the contributions of the different income groups to CO₂ emissions differ greatly in Turkey (Fig. 11c). This occurs because the consumption of the urban low- and lowest-income groups in the targeted categories is much higher than the consumption of the urban middle-income group, such as in the food, housing, energy and water, and personal care sectors, which could offset the carbon implication of the consumption increase of the rural low- and lowest-income groups. These results emphasize the positive impact of consumption reduction on CO₂ emission reduction.

4. Conclusions and discussion

In this study, the CO₂ emissions inequality based on the consumption data of different categories among various disaggregated income groups is analyzed with the application of the input–output model. The results reveal that a substantial CO₂ emissions inequality occurs across the studied developing countries due to their different economic development levels and consumption patterns. The gap in the CO₂ emissions per capita between the extremely wealthy developed countries and economically impoverished developing countries could be even larger. For example, the CO₂ emissions per capita in China and India are much smaller than that in the USA and fall short of the world average level [13,43]. Evidence shows that there is a positive correlation between income per capita and CO₂ emissions per capita [10]. The poor tend to increase their consumption in carbon-intensive categories as they move into the middle class [44]. The rising middle and wealthy classes have become the major driving forces of CO₂ emissions increase [45]. Therefore, more attention should be paid to the potential CO₂ emissions increase and deteriorating CO₂ inequality associated with the rapid urbanization process and household income increase in developing countries [37]. In addition, a notable CO₂ emissions inequality is
observed among the different income groups across the varying consumption categories within a given country, which provides the opportunity for targeted poverty elimination.

Four extreme scenarios indicate that the COVID-19 epidemic has temporarily abated the CO\textsubscript{2} emissions inequality among the different income groups and has reduced global CO\textsubscript{2} emissions, which has mainly occurred because of the reduction effect of the transport sector due to the implemented lockdown measures. Recent studies have also confirmed that temporary global CO\textsubscript{2} emission and regional air pollution reductions have occurred due to the lockdown measures \cite{46,47}, which indicates the high reduction potential of the transport sector. However, this may be only a temporary achievement with regard to reducing inequality and tackling climate change considering the hundreds of thousands of deaths, global economic recession and increased unemployment due to the spillover effect through the supply chain. The results of a recent study show that the pandemic could cause $2.1 trillion of global income losses and 147 million full-time equivalent of job losses due to the world-wide ripple effects of the economically worst-hit sectors, such as transport, tourism, retail and wholesale, and service sectors \cite{48}. Moreover, complexities and uncertainties occur in the process of climate change mitigation. For example, global CO\textsubscript{2} emissions notably increased after the global financial crisis from 2008 to 2009 as the world economy recovered \cite{49}. Therefore, it is of great concern that global CO\textsubscript{2} emissions may substantially rebound due to rapidly increasing consumption after the end of the epidemic.

In addition, the long-term impacts of the pandemic on household consumption behavior and the associated environmental footprint and inequality remain complicated and unclear. There are considerable differences in response to the crisis between high-income households and low- and middle-income families, which differently contribute to the environmental footprint. For instance, people may reduce non-essential trips to reduce the risk of infection under the normalization of epidemic prevention and control. People may passively shift towards a green lifestyle and sustainable behaviors, such as bicycle sharing and remote working, which helps reduce pollution emissions from commuting, and relieves the overburdened public transport pressure, and reduces the inequality in travel consumption. However, fears of the pandemic help to increase car sales. Wealthier households may buy private vehicles to avoid taking public transport, which may stimulate fossil-fuel consumption and aggravate CO\textsubscript{2} emissions inequality. The scenario simulation results of shared socioeconomic pathways indicate that CO\textsubscript{2} emissions inequality will persist for a long time, and many countries may fail to eliminate their CO\textsubscript{2} emissions inequality, even under the most ideal economic and social development scenario, which implies that a worldwide reduction in CO\textsubscript{2} emissions inequality remains out of reach.

Through targeted poverty elimination, CO\textsubscript{2} emissions inequality could be reduced in these countries, especially in India. Compared to the effect of increasing the consumption level of the low- and lowest-income groups in all the categories to match the consumption level of the middle-income groups \cite{50}, the carbon implications in this study are more moderate since we only improve the consumption level of the low- and lowest-income groups in the specific consumption categories that have greater inequality than the aggregate level. In Turkey, reducing the consumption in specific categories of the urban low- and lowest-income groups offsets the CO\textsubscript{2} emissions increases caused by the poverty alleviation measures targeted at the rural low- and lowest-income groups. Therefore, decreasing the unnecessary consumption of the middle- and high-income groups can be regarded as an important measure to reduce carbon inequality and carbon emissions. However, this may be not favorable for decision makers and government officials who hope to stimulate economic growth and create jobs by encouraging consumption. Therefore, integrated and feasible strategies need to be developed and customized according to the situation of each country to achieve multiple outcomes, such as steady economic growth, climate change mitigation, and social inequality elimination. For example, reducing income inequality has a positive impact in the fight against environmental deterioration in China and Turkey, while redistributing income may not be effective to improve environmental degradation in India \cite{51,52}.

Based on the above results, we provide certain policy suggestions to decision makers who are fighting to overcome the impacts of the COVID-19 outbreak and pursuing sustainable development across multiple fields. First, it is critical to consider the synergies and trade-offs among different strategies, whether formulating policies in response to the outbreak or establishing long-term plans for sustainable development.
Integrated and forward-looking schemes are crucial to accelerate the sustainable transformation of developing countries that face multiple challenges. Second, the reduction in CO₂ emissions and improvement of the welfare of poor people can be realized by controlling consumption in key categories in developing countries, for example, by levying a fuel consumption tax in the transportation sector and via cash transfers to low-income groups [53]. Third, it is very important to accelerate the transition towards green consumption patterns to control the CO₂ emissions on the demand side, which can be started by promoting low-carbon lifestyles that target higher- and middle-income groups. Fourth, supply-side structural reform and production efficiency improvement play fundamental roles in the fulfillment of SDGs. An improvement of energy efficiency and the increase in the share of renewable energy in energy consumption could be effective ways to achieve multiple outcomes. For example, a recent study has shown that solar photovoltaic interventions have reduced rural poverty in China [54].

There are certain shortcomings in this study that need to be clarified. First, the results of this study are based on the assumption that the lockdown measures last for one year. A complete lockdown did not occur, and the lockdown will probably not last for one year; moreover, certain countries, such as China, have restored normal production and life activities after their outbreak was effectively controlled. In addition, the epidemic has stimulated the rapid development of the digital economy, such as online education and online shopping, which could have a significant impact on the economy and the environment. Although these issues are interesting, they are not the focus of this study. The aim of this study is to inform decision makers regarding the impacts under the most extreme scenarios. Second, the Gini coefficients of the CO₂ emissions under the shared socioeconomic pathways scenarios that are smaller than zero were adjusted to 0.01. Although the specific values of the Gini coefficients of CO₂ emissions may be numerically inaccurate, this study captures their future trends under different socioeconomic development scenarios and provides insights into internal carbon dioxide emissions inequalities by comparing the results under the different scenarios. Third, compared to Guan et al. [2], we cannot provide the global economic losses and environmental impacts through world-wide supply chains due to the lockdown measures in a certain country or multiple economies, since single input–output tables are adopted in this study, and we focused on the CO₂ emissions inequality due to the lockdown measures. Similarly, we do not consider in the current study the effect of the epidemic on technology progress and production structure reform although the reduction effect of technology progress could be significant [55]. The impact of the epidemic is worthy of further investigation from both the supply and the demand side with the support of integrated modeling and the big data of human behaviors [56,57].

CRediT authorship contribution statement

Rui Huang: Data curation. Lixin Tian: Supervision, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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