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Research Article

Analyzing the influence of structural changes on CO_2 emissions in OECD countries: Employing panel cointegration techniques

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Abstract. Structural transformations in OECD countries significantly influence carbon dioxide (CO_2) emissions, affecting economic and social dimensions. These transformations encompass changes in industrial composition, technological progress, energy consumption patterns, and policy frameworks. This research investigates the impact of such structural shifts on CO_2 emissions across a panel of 38 OECD countries between 2000 and 2021, using panel cointegration techniques to ensure robust analysis. The study confirms the presence of cross-sectional dependence among countries and establishes long-run cointegration relationships. Results from Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) models indicate that renewable energy, advancements in information and communication technology, and structural changes significantly reduce CO_2 emissions. In contrast, economic growth, reliance on non-renewable energy, and institutional quality are linked to higher emissions. However, estimates derived from Panel-Corrected Standard Errors (PCSE) and Mean Group Panel (MGP) methods differ from those of FMOLS and DOLS, underscoring potential methodological variances in evaluating these relationships. This study highlights the pivotal role of structural changes in emission reduction strategies, while also emphasizing the importance of methodological choices in policy analysis. The findings provide valuable insights for policymakers aiming to align economic growth with environmental sustainability within OECD countries. Moreover, the research stresses the necessity of incorporating structural changes into long-term climate strategies to ensure their effectiveness. Future studies could expand the analysis by integrating more recent data and exploring non-linear relationships to refine policy recommendations further.

Keywords: CO2 emissions; Structural changes; Renewable energy; Panel cointegration; OECD.

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1. Introduction

There is considerable attention given to the impact of carbon dioxide (CO2) emissions and air pollution on the environmental quality of the atmosphere. It is widely recognized that taking preventive measures, such as replacing fossil fuel-based energy with renewable energy sources, is essential for improving environmental quality, particularly in reducing pollutants like particulate matter (PM), nitrogen oxides (NOx), and sulfur dioxide (SO2) (Progiou *et al.* 2023). Addressing climate change requires urgent and coordinated efforts from stakeholders and citizens. Effective engagement hinges on building mutual trust and understanding, which is strongly influenced by citizens' positive perceptions of the involved parties. Such a relationship is pivotal for fostering active or passive participation in climate mitigation strategies (Zerva *et al.*, 2018). Concurrently, renewable energy sources (RES) contribute significantly to both energy security and environmental sustainability. By reducing dependence on imported fossil fuels, RES helps mitigate risks tied to geopolitical uncertainties and supply chain disruptions. Additionally, they play a crucial role in lowering greenhouse gas emissions and improving air quality, thereby aligning with global climate objectives and advancing sustainable energy policies (Tampakis *et al.* 2017). Together, these social and technological dimensions highlight the multifaceted approach necessary to effectively combat climate change.

In recent years, there has been increasing focus on policies and action plans aimed at reducing greenhouse gas (GHG) emissions, reflecting a global commitment to tackling climate change. Countries and regions have implemented strategies such as carbon pricing, renewable energy incentives, and emissions reduction targets to transition to low-carbon economies. These mitigation efforts are often supported by adaptation measures, such as National Adaptation Plans (NAPs), which guide countries in reducing their climate vulnerability through sector-specific actions, capacity building, and resilience investments. Key studies, such as Martín-Ortega *et al.* (2024) on improving the transparency of climate initiatives through integrated GHG mitigation strategies (Model for the Integrated Assessment of Climate Change, MITICA), Tsepi *et al.* (2024) on the decomposition analysis of CO2 emissions in

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Greece, and Sebos *et al*. (2016) on Greece's mitigation and adaptation policies, will be examined to provide context for the findings within the wider climate challenge. A comparison of these studies in the discussion section will offer valuable insights into the interplay between mitigation and adaptation strategies, contributing to a more comprehensive understanding of how coordinated climate actions can effectively address the complex challenges posed by climate change.

Papadogiannaki *et al*. (2023) have discussed that the COVID-19 pandemic, officially declared by the World Health Organization in March 2020, has profoundly impacted global health, leading to widespread infections and fatalities. Governments worldwide responded with strict measures to control the spread of the virus, including Europe's first lockdown in February 2020. These unprecedented circumstances disrupted daily life, particularly in work and education. Traditional commuting was largely replaced by remote work, virtual learning, and adherence to social distancing protocols, resulting in decreased workplace travel, reduced traffic congestion, and lower carbon emissions. The pandemic also disrupted research activities, limiting fieldwork, international collaborations, and resource accessibility. Furthermore, scientific conferences and seminars shifted to virtual formats, altering opportunities for networking and the exchange of ideas.

Productive capacities were first systematically presented by UNCTAD (2006), as the productive resources, entrepreneurial skills, and production linkages that collectively determine a country's ability to produce goods and services and achieve growth and development. The link between productive capacity and the goal of sustainable development with environmental concerns was first highlighted at the Fourth United Nations Conference on LDCs, held in Turkey in 2011, and subsequently at major international conferences such as UNCTAD XIV, held in Nairobi in 2016. The latest version of the Productive Capacities Index (PCI) covers the period 2000-2022 and 194 economies. This index takes into account the complex multidimensional nature of productive capacity and reflects the overall productive economic structure of an economy (UNCTAD 2023). Inspired by the definition of productive capacity, the PCI reflects three pillars: resources, entrepreneurial skills, and production linkages. Using PCA methods, the PCI is a set of 42 indicators grouped into 8 categories: information and communication technologies (ICT), natural capital, human capital, energy, transport, the private sector, institutions (INS) and structural change. This last group deserves particular attention. However, the relationship between structural change, which reflects the composition effect, and environmental quality is justified by the impact on pollution of changes in sectoral structures, for example from an agricultural structure to a more advanced economic structure including industrial and technological sectors (Dinda, 2004). In addition, economic activities have different pollution intensities, reflecting this composition effect, according to Antweiler *et al*. (2001). Empirically, this structural change is generally considered to be a determinant of environmental quality. Several indicators have been used as proxies to assess its impact, which are integrated into a composite indicator developed by UNCTAD. To better reflect the structural change, UNCTAD used PCA methods and mobilized the following four variables: export concentration index, gross fixed capital formation, industrial ratio and economic complexity index to develop a Structural Change Index (SCI). In fact, to the best of our knowledge, the SCI, in the form presented by the calculation of the IPC, has not yet been used in research on environmental quality impacts, except in the article by Oluc *et al*. (2023). On the other hand, the four variables that make up the SCI are widely used in environmental economics: (1) Economic complexity index: According to Hidalgo (2021), economic complexity, using fine-grained data on economic activities, characterizes detailed economic structures and provides a quantitative basis for industrial policy efforts. Theoretically, the relationship between economic complexity and environmental quality is justified by the impact of the composition and structure of the economy. Empirically, studies have been inspired by the measure of economic complexity proposed by the seminal project of Hidalgo and Hausmann (2009). They propose the use of economic complexity as a means of improving the measurement of economic structure. Thus, these empirical studies linking economic complexity and carbon emissions are relatively recent, but also mixed. (Majeed *et al*. 2022; Aluko *et al*. 2023; Can and Gozgor, 2017; Taghvaee *et al*. 2022; Padhan *et al*. 2023). (2) The export concentration index: The relationship between trade and environmental quality originated with Grossman and Krueger (1991), who analyzed the environmental impact of trade agreements. According to Copeland and Taylor (2004), this relationship between trade and environmental quality is justified by the factor endowment hypothesis. More recent empirical studies use export concentration/diversification instead of trade openness, reflecting the structural change associated with trade in an economy. (Apergis *et al*., 2018 ; Olasehinde-Williams *et al*., 2023 ; Bashir *et al*., 2020 ; Iqbal *et al*., 2021 ; Wang *et al*., 2020). (3) Gross fixed capital formation: The traditional approach of the Solow model of economic growth emphasizes the importance of capital accumulation as a key and determinant driver of growth, which consequently affects environmental quality (Jin and Kim, 2018; Petrović and Lobanov, 2020; Chen and Wang, 2020; Li *et al*., 2023; Saqib *et al*., 2023). The impact of capital accumulation on pollution is controversial and depends mainly on increased production and structural effects, the latter also depends on the financing of capital for polluting or environmentally friendly activities. (4) The industrial ratio: The industrial sector is generally recognized as a major economic activity with significant potential to influence the distribution of CO2 emissions. Indeed, different types of economic activity, including industry, have different pollution intensities, in particular capital-intensive industries, which are considered to be energy-intensive (Antweiler *et al*., 2001). To investigate this structural effect on CO2 emissions, empirical studies generally use industrial value added. (Fujii and Managi, 2013; Ben Jebli *et al*., 2020; Kahia and Ben Jebli, 2021; Basty and Ghachem, 2023).

In OECD countries, the relationship between the PCI, SCI, and CO2 emissions reflects how economic transitions and capacities influence environmental outcomes. High PCI scores, often above 70, signify strong infrastructure and innovation, contributing to reduced emissions intensity through energy-efficient practices and technological advancements. The SCI measures structural shifts, with transitions toward service-based economies generally associated with lower emissions, whereas industrial expansion can elevate them. On average, CO2 emissions in OECD nations range from 8 to 12 metric tons per capita, with service-oriented economies typically reporting lower values (UNCTAD, 2023). This study fills a significant gap in the literature by examining the SCI and its impact on CO2 emissions within the context of OECD countries. Understanding the SCI in developed economies is particularly relevant as these countries are undergoing structural shifts from industrial to service-based economies, which have different implications for emissions. This novel approach offers insights into how these transitions affect environmental sustainability in industrialized nations, contributing to discussions on sustainable economic transformation in the context of global emissions reduction targets.

In light of the above motivations, the objective of this study is to investigate the impact of SCI and other control variables, namely, ICT, INS, GDP, renewable energy (RE) and non-renewable energy (NRE), on carbon emissions across OECD countries spanning the period from 1999 to 2021. Although the main purpose of introducing the SCI, and indeed the PCI, was to respond to the request made by Member States at the XIV UNCTAD Conference in Nairobi to promote productive capacity in developing countries, this study is, to our knowledge, the first of its kind to empirically estimate the role of the SCI in CO2 emissions in developed countries, and more specifically in OECD countries.

The study introduces various panel cointegration techniques. Specifically, it employs panel cointegration methods to analyze a panel dataset consisting of G20 countries. To our knowledge, there is no empirical study investigating the dynamic influence of SCI on environmental quality especially for the selected counties using cointegration approaches. The paper presents a novel application of panel cointegration techniques to a dataset comprising G20 countries, offering a robust and flexible framework for examining inter-country relationships. The key contributions of the study are as follows: (i) the introduction of multiple panel cointegration methods, which enhance the reliability and versatility of the empirical analysis; (ii) the improved capacity to accurately estimate relationships and coefficients, particularly in small to medium-sized samples, leading to more precise results; (iii) A comprehensive analytical approach that provides new insights into the interrelations among G20 countries, which may not be fully captured by traditional methods; (v) The selection of G20 countries is crucial because they play a major role in the global economy, accounting for a significant portion of global GDP, trade, and investment. The varied economic structures and policies within this group offer valuable insights into the dynamics between countries. Furthermore, the G20 countries have a considerable influence on global policy, particularly in areas like trade and climate change, making them key for exploring international cooperation and tackling global issues.

The structure of our study is as follows: A review of the theoretical and empirical literature on the topic is presented in the second section. The study data, descriptive statistics and methodology are presented in the third section. The results and discussion are presented in section 4. Finally, the conclusions and policy recommendations are discussed in the last section.

2. Literature review

UNCTAD has recently provided data on the SCI, emphasizing the limited research connecting it to environmental quality. In a recent study, Oluc *et al.* (2023) utilized this index to demonstrate that structural transformation is a key driver of rising CO2 emissions in middle-income countries (MICs). Their findings reveal a significant tension between environmental quality and efforts to achieve structural transformation in these economies. The authors suggest that MICs undergoing rapid industrialization should accelerate structural adjustments and adopt a sustainable development trajectory. Employing moment quantile regression (MMQR) and bootstrapped simultaneous quantile regression (BSQR), the study examines the long-term impacts of structural transformation, institutional quality, population density, and natural resource rents on CO2 emissions across 94 MICs from 2000 to 2018. The analysis shows that structural change, economic growth, natural resource extraction, and urbanization negatively affect environmental quality, whereas institutional quality is the only factor with a positive impact.

The variables used to construct the SCI are widely used in the environmental quality literature as follows:

a) The relationship between economic complexity and CO2 emissions

The theoretical connection between economic complexity and carbon emissions centers on how an economy's composition and structure influence its environmental impact (Dinda, 2004). Inspired by the economic complexity metric developed by Hidalgo and Hausmann (2009), recent empirical studies provide mixed findings on this relationship. Some research identifies a positive association between economic complexity and carbon emissions. For instance, Majeed *et al.* (2022) analyze long-term data from 1971 to 2018, finding that increasing complexity exacerbates emissions in OECD nations. Similarly, Aluko *et al.* (2022) studied 35 OECD countries (1998–2017), where fixed-effects models suggest that greater complexity leads to environmental degradation, though this relationship may weaken at higher income levels.

Conversely, other studies suggest that economic complexity can mitigate emissions. Romero and Gramkow (2021) show that a 0.1 increase in complexity corresponds to a 2% reduction in greenhouse gas intensity across 67 countries between 1976 and 2012, highlighting the role of advanced, less-polluting technologies. Can and Gozgor (2017), focusing on France (1964–2014), found that greater complexity had a long-term mitigating effect on emissions while testing the Environmental Kuznets Curve (EKC) hypothesis. Similarly, Taghvaee *et al.* (2022) confirm the EKC hypothesis in OECD countries (1971–2016), finding that complexity first increases emissions before eventually reducing them. Padhan *et al.* (2023) support this negative U-shaped relationship, showing that higher economic complexity ultimately lowers emissions in OECD countries (1970–2015) using GMM and bootstrap quantile regression methods.

(b) Industrial structure and its impact on CO2 emissions

The characteristics of an industrial structure significantly influence emissions, as pollution intensity varies across sectors (Antweiler *et al.*, 2001). Empirical studies often use industrial value-added as a proxy to examine this structural effect. For instance, Kahia and Ben Jebli (2021) analyze data from 1980 to 2014 for ten leading industrialized countries, finding that industrial growth generally dampens emissions. However, country-specific results indicate reductions in Denmark and Norway but increases in Chile, France, and Sweden. Similarly, Ben Jebli *et al.* (2020) examine 102 countries (1990–2015), finding that industrial value-added positively influences emissions in low- and middle-income countries, while its effect in high-income countries is negligible. On a global scale, both industrial growth and renewable energy consumption are associated with emission reductions. Basty and Ghachem (2023) explore non-linear relationships between innovation and carbon emissions in 32 OECD countries (2015–2020), identifying at least two inflection points in this dynamic. Their findings underscore the critical role of manufacturing value-added in reducing emissions, further emphasizing the importance of structural adjustments for sustainable development.

To answer the question "Which industry is greener? Fujii and Managi (2013) conducted an empirical study that aims to analyze the relationship between CO2 emissions of different industries and economic growth in OECD countries from 1970 to 2005. They mobilize the share of each industry in GDP as a control variable, to capture the effects of the standard EKC determinants technique. The EKC relationship was observed in only 3 of the 10 sectors analyzed, namely (1) wood and wood products, (2) paper, pulp and printing, and (3) construction. These three sectors therefore proved to be more environmentally friendly than the other sectors analysed. An EKC that is not confirmed at the national level or the level of the industry as a whole in the different countries indicates that structural changes are not sufficient to reduce emissions and prevent the increase in CO2 emissions resulting from economic growth.

(c) Export concentration and its relationship with CO2 emissions

Since the influential work of Grossman and Krueger (1991), numerous studies have identified international trade, often measured by trade openness, as a significant factor influencing environmental quality. More recently, export diversification has been examined not only as an indicator of trade activity but also as a proxy for structural economic

Table 1
Literature summary on structural change and Environmental quality.

Authors	Sample/period	Variables	Main Findings
		a) Economic complexity and CO2 relationship	
Majeed *et al.* (2022)	OECD countries (1971-2018)	Economic complexity, carbon emissions	Positive impact of economic complexity on carbon emissions in the long run.
Aluko *et al.* (2022)	35 OECD countries (1998-2017)	Economic complexity, carbon emissions	Positive relationship between economic complexity and environmental degradation
Romero and Gramkow (2021)	67 countries (1976-2012)	Economic complexity, GHG emission intensity	0.1 increase in economic complexity leads to a 2% decrease in GHG emission intensity.
Can and Gozgor (2017)	France (1964-2014)	GDP per capita, economic complexity, CO2 emissions	Economic complexity has a mitigating effect on CO2 emissions in the long run.
Taghvaee *et al.* (2022)	OECD countries (1971-2016)	Economic complexity, CO2 emissions	Economic complexity is positively associated with CO2 emissions.
Padhan *et al.* (2023)	OECD countries (1970-2015)	Economic complexity, carbon emissions	Negative U-shaped relationship between economic complexity and CO2 emissions.
		b) Industrial ratio and CO2 relationship	
Kahia and Ben Jebli (2021)	10 leading industrial countries (1980-2014)	CO2 emissions, GDP, Industrial growth	Industrial growth reduces emissions in the global panel.
Ben Jebli *et al.* (2020)	102 countries (1990-2015)	CO2 emissions, Industrial value-added	Industrial value-added reduces CO2 emissions.
Basty and Ghachem (2023)	32 OECD member countries (2015-2020)	carbon emissions, manufacturing value added	Manufacturing value added plays a crucial role in reducing carbon emissions.
Fujii and Managi (2013)	OECD countries (1970-2005)	CO2 emissions, Industry share in GDP	the EKC relationship is confirmed in greener sectors and not confirmed at the national or industrial level in other sectors.
		c) Export concentration index and CO2 relationship	
Bashir *et al.* (2020)	29 OECD countries (1990-2015)	Carbon intensity, Export diversification, energy efficiency	Export diversification reduces CO2 emissions. Institutional factors mediate energy intensity.
Apergis et al. (2018)	19 Developed Country (DC) (1962-2011)	CO2 emissions, Export Concentration	A higher concentration of exported products reduces CO2 emissions.
Iqbal *et al.* (2021)	37 OECD countries (1970-2019)	CO2 emissions, Export diversification,	Export diversification has a positive impact on CO2 emissions in OECD countries.
Olasehinde-Williams *et al.* (2023)	30 North countries (1980-2014)	Energy demand, CO2 emissions, Export diversification	Export diversification has a negative and significant effect on energy demand and CO2 emissions.
Umer Shahzad *et al* (2020)	63 DC and LDC (1971-2014)	CO2 emissions, Export diversification, GDP	Export diversification hurts CO2 emissions, particularly in DC.
Lu Wang *et al.* (2020)	G7 countries (1990-2017)	CO2 emissions, Export diversification, ecological innovation	Export diversification increases CO2 emissions, but the effect weakens with increased environmental innovation.
		d) Gross fixed capital formation and CO2 relationship	
Li *et al.* (2023)	G-20 countries (1992-2018)	GFCF, R and NR energy, ecological footprints	GFCF has a positive and significant effect on ecological footprints.
Jin and Kim (2018)	30 OECD countries and 32 non-OECD countries (1990-2013)	GFCF, coal consumption, CO2 emissions	Only the non-OECD group exhibits a long-term relationship between coal consumption and GFCF.
Saqib *et al.* (2023)	32 OECD countries (1996-2020)	GFCF, CO2 emissions	In less developed countries, GFCF tends to increase CO2 emissions and reduce them In wealthier countries.
Chen and Wang (2020)	21 European Union countries (1970-2010)	Natural and manufacturing capital, GDP, CO2 emissions	Manufacturing capital hurts CO2 emissions when considering overall energy consumption and natural capital.
Petrović and Lobanov (2020)	16 OECD countries (1981-2014)	GFCF, CO2 emissions	GFCF has a positive and significant impact on CO2 emissions but the extent of this impact differs between countries.

Table 2
Descriptive statistics

Variable	Mean	Std. dev.	Min	Max
CO2	342.6758	890.5054	2.5	6015.571
GDP	$1.17*10^{12}$	$2.78*10^{12}$	$1.1*10^{10}$	$2.05*10^{13}$
RE	.6458111	1.48859	.000014	12.17161
NRE	5.130183	13.22725	.0307661	86.40927
ICT	60.47548	12.85648	19.3	86.1
INS	80.70012	13.19855	40.8	100
STR	73.76041	14.5843	20.1	100

CO2= carbon dioxide emissions (metric tons); GDP= gross domestic product (constant 2015 USD); RE= renewable energy; NRE= non-renewable energy; ICT= information and communication technology; INS= Institutional index; STR= structural change index.

change. Its impact on environmental quality reflects both the composition effect of trade and the factor endowment hypothesis, which posits that wealthier nations with abundant capital tend to specialize in exporting pollution-intensive goods and services (Copeland and Taylor, 2004).

Empirical studies exploring the link between export concentration or diversification and CO2 emissions have produced mixed findings. For instance, Apergis *et al.* (2018) analyzed the effect of export concentration on emissions in 19 advanced economies (1962–2011) using the ARDL method. Their results supported the EKC hypothesis, showing an inverted U-shaped relationship between per capita income and environmental degradation, alongside a reduction in emissions associated with higher export concentration. Similarly, Olasehinde-Williams *et al.* (2023) investigated the impact of export diversification on energy demand and pollution across 30 Northern countries (1980–2014), finding that structural changes induced by diversification increased energy consumption and emissions initially. However, over time, diversification fostered investments in new industries and improved products, particularly energy-efficient goods, ultimately mitigating energy use and climate impacts. Bashir *et al.* (2020) examined 29 advanced economies (1990–2015), focusing on export diversification's influence on carbon intensity. Their findings showed that diversification reduces emissions by lowering carbon intensity, with institutional factors playing a mediating role. Conversely, other studies highlight the adverse effects of export diversification. For example, Iqbal *et al.* (2021) used the AMG method to evaluate long-term effects in 37 high-income countries (1970–2019), showing that diversification positively correlates with emissions. Similarly, Wang *et al.* (2020) analyzed G7 nations (1990–2017) using the CS-ARDL approach, finding that a 1% rise in export diversification increased emissions by 0.546% in the short term and 0.783% in the long term. However, their results also revealed that environmental innovation reduces the adverse effects of diversification on emissions, demonstrating a moderating role in this dynamic. Mania (2020) investigated the relationship between export diversification and CO2 emissions in the context of the EKC hypothesis covering 98 developed and developing countries during 1995–2013. Employing both short-term (System GMM) and long-term (PMG) estimation techniques, the findings confirm the validity of the EKC hypothesis. Moreover, export diversification is found to exert a positive influence on CO2 emissions, indicating that structural shifts in export composition can have significant environmental implications depending on the stage of economic development and diversification strategies. Khan *et al.* (2021) examined the effects of export diversification and the composite risk index on CO2 emissions in RCEP countries from 1987 to 2017. The results highlight that reducing the composite risk index, promoting renewable energy, and advancing environmental technologies can significantly lower CO2 emissions in the long run. Conversely, export diversification consistently increases emissions.

(d) Gross fixed capital formation and CO2 emissions relationship

The relationship between gross fixed capital formation and CO2 emissions has been extensively studied using various econometric techniques, yielding diverse and sometimes contradictory results. Petrović and Lobanov (2020) found a significant positive long-term impact of capital formation on CO2 emissions across 16 OECD countries. A 1% increase in this investment raises emissions by 0.05% to 0.15%, depending on the country, primarily due to the dominance of energy-intensive sectors. Although technological advancements associated with these investments can enhance productivity, they do not always improve energy efficiency. Similarly, Li *et al.* (2023), using the CS-ARDL method, analyzed the effects of renewable and non-renewable energy alongside capital investment on the ecological footprint of G20 nations (1992–2018). Their findings reveal that such investments significantly increase the ecological footprint, with a 1% rise leading to increases of 0.299% in the short term and 0.119% in the long term, reflecting its dual role in driving economic growth and environmental degradation.

In contrast, Jin and Kim (2018), employing the FMOLS approach, examined the long-term effects of fixed capital investment on energy consumption and CO2 emissions in 30 OECD and 32 non-OECD countries (1990–2013). Their results show that this type of investment only significantly influences energy use—and consequently emissions—in non-OECD nations, where a 1% increase leads to a 0.442-unit rise in energy consumption. Conversely, Chen and Wang (2020) analyzed 21 European countries (1970–2010) and emphasized the need to consider energy and natural capital in production functions. Their findings suggest that human and manufacturing capital reduce CO2 emissions when these factors are included, revealing potential biases in conventional models that omit them.

Finally, Saqib *et al.* (2023) employed panel quantile regression to study the impact of fixed capital investment on CO2 emissions in 32 OECD countries (1996–2020). Their results indicate a reduction in emissions, attributed to sustained investment in environmental infrastructure and protection programs in recent years. This demonstrates the evolving role of capital formation as a mechanism for balancing economic and environmental objectives. Table 1 presents the summary of the literature review on structural change and Environmental quality.

3. Data, Descriptive statistics and Methodology

3.1. Data

The database is structured annually, encompassing information regarding OECD member nations from 2000 to 2021, sourced from various outlets. Specifically, data relating to gross domestic product (GDP), measured in constant 2015 USD, has been retrieved from the online database of the World Bank (2024). Conversely, information concerning carbon dioxide (CO2) emissions (metric tons) and the consumption of renewable and non-renewable energy (RE, NRE) (measured in Quadrillum BTU) has been sourced from the Energy Information Administration (EIA, 2024). Additionally, data concerning structural changes (STR), information and communication technology (ICT) and institutional quality (INS) indexes have been obtained from the United Nations Conference on Trade and Development (UNCTAD, 2024). Our panel is selected to maximize the number of observations based on their availability. The sample comprises 38 OECD countries, namely: Australia, Austria, Belgium, Canada, Chile, Colombia, Costa Rica, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Iceland, Israel, Italy, Japan, Korea Republic of (South Korea), Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, and United States.

3.2. Descriptive statistics

This section conducts a descriptive analysis of the collected data to examine the empirical objective of the study. Accordingly, we will delineate the maximum and minimum values, as well as the mean, of various indicators for the selected OECD countries over the period 2000-2021. Table 2 presents the descriptive statistics for the analysis variables.

The United States exhibited the highest level of CO_2 emissions, recording 6015.57 MM tonnes in 2007. Conversely, the lowest level of CO_2 emissions was observed in Iceland over various years within the selected period. The United States recorded the highest level of real GDP, reaching $2.05*10^{13}$ constant 2015 USD in 2021. Similarly, in line with CO_2 emissions, Iceland exhibited the lowest level of real GDP, with $1.1*10^{10}$ in 2000. Additionally, Australia demonstrated significantly higher consumption of renewable energy, totaling 0.175 Quadrillion BTU (QBTU), while non-renewable energy consumption peaked at 86.41 QBTU in 2007 in the United States. Luxembourg exhibited the highest value of the ICT index, reaching 86.1 in 2021, whereas Colombia had the lowest value, standing at 19.3 in 2000. Regarding the institutional quality index, Finland achieved its peak level in 2000 with a value of 100, while Colombia registered the lowest level at 40.8 in 2003. Regarding the statistics of the structural change index, the highest index was recorded in the United States in 2000, with a value of 100, while the lowest index value was recorded in Israel in 2004, reaching 20.4.

3.3. Methodology

The study aims to investigate the impact of structural changes on CO_2 emissions within a panel composed of 38 OECD countries spanning the period 2000-2021. Several control variables are integrated into the specified model such as real GDP, renewable and non-renewable energy consumption, ICT and institutional quality indexes. The integration of these control variables enables better control over factors that may influence the relationship between the variables of interest, thereby enhancing the accuracy and validity of the results. The importance of ICT and institutional quality in addressing CO2 emissions deserves careful consideration. ICT plays a critical role by enabling the adoption of energy-efficient technologies and promoting sustainable economic practices, which are essential for reducing emissions. Meanwhile, institutional quality fosters effective governance, regulatory enforcement, and resource management, all of which are fundamental to tackling environmental issues. In OECD countries, these elements are particularly significant as they leverage advanced technology and robust institutions to achieve sustainable structural transformations and long-term environmental goals.

The study applied the panel cointegration techniques to discuss the dynamic relationship between the variables under investigation. Cointegration techniques provide a robust approach to analyzing long-term relationships among variables, considering both dynamic aspects and non-stationarities of time series data, rendering them invaluable tools in economic and financial analysis.

Various tests of panel cointegration approaches are employed in our study and can be summarized in four steps: (1) checking for the cross-sectional dependence (CD) degree; (2) testing the integration order of the analysis variables using either the first of the second generation panel unit root tests (PURT); (3) panel cointegration tests are applied to check for the presence of a long-run relationship between the variables; (4) long-run estimates are established using several techniques of estimations.

The empirical framework is represented by Equation (1), which relates CO_2 emissions (CO_{2it}) to various factors including real GDP (GDP_{it}), renewable energy (RE_{it}), non-renewable energy (NRE_{it}), information and communication technology (ICT_{it}), institutional quality (INS_{it}), and structural change (STR_{it}) denoted by f.

$$CO_{2it} = f(GDP_{it}, RE_{it}, NRE_{it}, ICT_{it}, INS_{it}, STR_{it}) \quad (1)$$

Taking the logarithmic transformation of Equation (1) yields Equation (2), expressed as follows:

$$lnCO_{2it} = \alpha_0 + \alpha_1 lnGDP_{it} + \alpha_2 lnRE_{it} + \alpha_3 lnNRE_{it} + \alpha_4 lnICT_{it} + \alpha_5 lnINS_{it} + \alpha_6 lnICT_{it} + \varepsilon_{it} \quad (2)$$

Where $ln(.)$ indicates the natural logarithmic form; $i = 1, \dots N$ and $t = 1, \dots, T$ indicate the country and period, respectively; ε_{it} is the error term; α_0 denotes the specific fixed effect; $(\alpha_1 \alpha_2 \alpha_3 \alpha_4 \alpha_5 \alpha_6)$ denotes the vector of long-run estimated coefficients.

4. Results and Discussion

The initial step of our empirical study involves testing the degree of dependence among individuals using various tests, such as the Breusch-Pagan Chi-square, Pesaran LM Normal, Pesaran CD Normal, Friedman Chi-square, and Frees Q tests. The objective of evaluating interdependence among individuals in empirical research is to determine how closely the observed data points are linked or influenced by each other, which is vital for modelling and predicting variable behavior. If there is a high and statistically significant degree of dependence among countries, then second-generation unit root tests such as Pesaran's (2007) Cross-Sectionally Augmented IPS (CIPS) test will be utilized. In contrast, if this is not the case, we will focus

Table 3
Cross-sectional Dependence Test Results

Test	Statistic		d.f.	Prob.
Breusch-Pagan Chi-square	6827.507		703	0.0000***
Pearson LM Normal	163.3347			0.0000***
Pearson CD Normal	2.324852			0.0201**
Friedman Chi-square	117.7311		21	0.0000***
Frees Q	6.988217			
Asymptotic critical values	1%	0.222533		
	5%	0.153662		
	10%	0.117399		
Frees (1995) Q distribution				

"***" and "**" indicate statistical significance at the 1% and 5%, respectively.

on first-generation unit root tests such as the Augmented Dickey-Fuller (ADF, 1979) and Phillips and Perron (PP, 1988). All of these tests are based on the null hypothesis of no cross-sectional dependence in residuals, while the alternative hypothesis posits the presence of cross-sectional dependence across countries. Breusch and Pagan (1980), introduced a Lagrange Multiplier (LM) statistic, which remains valid as the number of individuals (N) is fixed and the number of periods (T) tends to infinity. Based on the Khi-deux distribution, the LM statistic is employed to identify heteroscedasticity within regression models. The Pesaran LM Normal test and the Pesaran CD Normal test are both utilized to assess the normality assumption regarding the residuals in linear regression models. They aim to determine whether the residuals follow a normal distribution or adhere to a standard normal distribution, respectively (Pesaran, 2004). The Friedman (1937) Chi-square test is a non-parametric test that serves to identify significant differences in variable distributions among multiple related groups. Finally, frees (1995, 2004) provided a Q distribution specifically designed to evaluate the presence of heteroscedasticity.

The results of these tests are documented in Table 3. The diagnostic tests for CD provide robust insights into the presence of interdependencies across the dataset. The Breusch-Pagan Chi-square and Pearson LM Normal tests are highly significant (prob. < 0.01), indicating strong evidence of cross-sectional

Table 4
Panel Unit Root Test Results

PP							
At Level	lnCO2	lnGDP	lnRE	lnNRE	lnICT	lnINS	lnSTR
t-Stat	0.2837	1.0000	0.1300	0.3656	0.9987	0.4058	0.6198
Prob.	0.8121	1.0000	0.7719	0.9143	0.9987	0.3258	0.8188
At 1st Diff							
	d(lnCO2)	d(lnGDP)	d(lnRE)	d(lnNRE)	d(lnICT)	d(lnINS)	d(lnSTR)
t-Stat	0.0000	0.0001	0.0001	0.0000	0.0055	0.0014	0.0000
Prob.	0.0036***	0.0004***	0.0000***	0.0089***	0.0003***	0.0020***	0.0236**
ADF							
At Level	lnCO2	lnGDP	lnRE	lnNRE	lnICT	lnINS	lnSTR
t-Stat	0.3286	0.9997	0.2310	0.4082	0.9903	0.4058	0.6546
Prob.	0.7940	0.9997	0.6911	0.9015	0.9965	0.3117	0.8304
At 1st Diff							
	d(lnCO2)	d(lnGDP)	d(lnRE)	d(lnNRE)	d(lnICT)	d(lnINS)	d(lnSTR)
t-Stat	0.0000	0.0008	0.0000	0.0000	0.0029	0.0001	0.0000
Prob.	0.0005***	0.0042***	0.0000***	0.0010***	0.0003***	0.0083***	0.0013***
CIPS							
At Level	lnCO2	lnGDP	lnRE	lnNRE	lnICT	lnINS	lnSTR
Z-t bar stat	2.765	2.074	-0.217	3.022	-0.677	-0.765	-1.003
Prob.	0.997	0.981	0.414	0.999	0.249	0.222	0.158
At 1st Diff							
	d(lnCO2)	d(lnGDP)	d(lnRE)	d(lnNRE)	d(lnICT)	d(lnINS)	d(lnSTR)
Z-t bar stat	-19.687	-9.294	-19.067	18.782	-10.859	-14.947	-14.409
Prob.	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***

"***" and "**" indicate statistical significance at the 1% and 5%, respectively.

Table 5
Panel Cointegration Tests Results

Pedroni cointegration tests				
Alternative hypothesis: common AR coefs. (within-dimension)				
			Weighted	
	Statistic	Prob.	Statistic	Prob.
Panel v-Statistic	-1.480614	0.9306	-3.076739	0.9990
Panel rho-Statistic	4.186395	1.0000	5.077279	1.0000
Panel PP-Statistic	-7.022183	0.0000***	-6.317251	0.0000***
Panel ADF-Statistic	-7.032669	0.0000***	-6.313966	0.0000***
Alternative hypothesis: individual AR coefs. (between-dimension)				
	Statistic	Prob.		
Group rho-Statistic	6.823357	1.0000		
Group PP-Statistic	-8.638774	0.0000***		
Group ADF-Statistic	-6.426895	0.0000***		
Westerlund cointegration test				
	Statistic p-value	Prob.		
Variance ratio	-1.5593	0.0595*		
Kao cointegration test				
	t-Statistic	Prob.		
ADF	-9.901994	0.0000***		

"***" and "*" indicate statistical significance at the 1% and 10%, respectively

dependence. Similarly, the Friedman Chi-square test confirms the presence of interrelations, while the Pearson CD Normal test is significant at the 5% level, further validating these dependencies. Frees' Q statistic suggests critical thresholds for assessing the strength of CSD, underscoring its importance in econometric modelling, especially for panels with interlinked variables. Consequently, the level of interdependence among countries is deemed significant, prompting the adoption of the second PURT.

To assess the order of integration of each variable, three PURTs are employed: the Augmented Dickey-Fuller (ADF, 1979) and Phillips-Perron (PP, 1988) tests, representing first-generation tests, and the Cross-Sectionally Augmented IPS (CIPS; Pesran, 2007) test, considered a second-generation test. Both ADF and PP tests hold significance in panel data analysis, as non-stationarity can result in spurious regression and render statistical inference unreliable. The CIPS test is specifically developed for panel data, It employs an augmented IPS statistic approach to address cross-sectional dependence. The outcomes from these tests are reported in Table 4.

Table 4 summarizes the stationarity tests for variables (lnCO2, lnGDP, lnRE, lnNRE, lnICT, lnINS, and lnSTR) using PP, ADF, and CIPS methods. At their levels, most variables exhibit non-stationarity (high p-values). However, after differencing, all variables become stationary with significance at 1% and 5% levels, confirming integration of order one (I(1)). This validation is crucial for cointegration analysis. Variables like ICT and institutional quality show strong stationarity after differencing, underlining their importance in understanding structural changes and their influence on CO2 emissions. Consequently, it is evident that the variables are integrated of order one, denoted as I(1) and the cointegration can be tested.

To investigate the presence of long-term relationships among CO2 emissions, real GDP, renewable and non-renewable energy, ICT, institutional quality, and structural change, the analysis employed three cointegration tests. The first test was developed by Pedroni (2001, 2004) who introduced seven tests, categorized into two sets. The first set encompasses four-panel statistics (v, rho, PP, and ADF), examining the within-dimension, while the second set comprises three group statistics (rho, PP, ADF), analyzing the between-dimension. All these tests assume the null hypothesis of no long-term cointegration among the variables when CO_2 is defined as the dependent variable. Unlike Pedroni's test, the second cointegration test was devised by Kao (1999), who takes into account the scenario where the cointegration vectors are presumed to be homogeneous across individuals. This test relies on a variant of the ADF distribution. The third test, developed by Westerlund (2005), introduces a variance ratio statistic based on the null hypothesis of no cointegration.

The results of the cointegration tests are presented in Table 5. The Pedroni cointegration test reveals evidence of a long-term relationship among the variables under study. For the within-dimension results, the panel PP- and ADF-statistics are significant at the 1% level, confirming cointegration, while the panel v- and rho-statistics are insignificant, suggesting some divergence. Similarly, the between-dimension results highlight that the group PP- and ADF-statistics are highly significant, further supporting the cointegration hypothesis.

The Kao test strongly validates cointegration with a significant ADF statistic, reflecting consistent long-run associations across the dataset. Westerlund's variance ratio test shows marginal significance at the 10% level, indicating potential variability in long-run dynamics. These findings collectively imply that despite certain inconsistencies in individual test components, the overall results robustly affirm long-term equilibrium relationships among the variables. The statistical significance underscores the robustness of these relationships, particularly in explaining structural dynamics relevant to long-run economic and environmental interactions.

Now given that the long-run cointegration is established, the coefficient related to the long-run equation can be then

Table 6
FMOLS-DOLS Long-run Estimates

	FMOLS			DOLS		
Variable	Coefficient	t-Statistic	Prob.	Coefficient	t-Statistic	Prob.
lnGDP	0.168091	183.0450	0.0000***	0.145472	182.0455	0.0000***
lnRE	-0.047371	-109.5571	0.0000***	-0.036777	-94.54396	0.0000***
lnNRE	0.877375	1146.651	0.0000***	0.910867	1307.267	0.0000***
lnICT	-0.054494	-19.23619	0.0000***	-0.120615	-88.23121	0.0000***
lnINS	0.111065	34.55002	0.0000***	-0.016647	-6.961036	0.0000***
lnSTR	-0.132458	-27.15707	0.0000***	0.231586	77.15595	0.0000***

"***" indicates statistical significance at the 1%.

estimated using various approaches of estimation such as the fully modified OLS (FMOLS), the dynamic OLS (DOLS), the Panel-Corrected Standard Errors (PCSE), and Mean Group estimator (MGP) approaches. Evidence supports the assertion that the FMOLS and the DOLS methodologies, pioneered by Pedroni (2001, 2004), surpass the OLS in efficacy due to their ability to address endogeneity and serial correlation concerns.

The PCSE estimator developed by Beck and Katz (1995), stems from its capacity to tackle issues related to serial correlation and heteroscedasticity encountered in panel data analysis. Through the correction of standard errors for both within-group correlation and heteroscedasticity, the PCSE estimator yields parameter estimates that are more dependable and efficient in comparison to conventional OLS estimation. Finally, Pesaran and Smith (1995), introduced the MGE which is qualified as a method that combines the advantages of both pooled OLS and fixed effects estimators. This approach enables the estimation of individual-specific parameters while simultaneously pooling information across individuals. By employing natural logarithmic transformations, the interpretation of all long-term parameter estimates is articulated in terms of elasticities. All estimations for FMOLS, DOLS, PCSE, and MGE are presented in Tables 6 and 7, respectively.

According to the results presented in Table 6, the estimates obtained from FMOLS and DOLS exhibit a high degree of similarity in terms of the sign, coefficient, and level of significance. All estimated coefficients are statistically significant at the 1% level. For instance, the FMOLS estimates indicate that real GDP, non-renewable energy, and institutional quality have a positive influence on CO2 emissions, while renewable energy, ICT, and structural changes are associated with decreased CO_2 emissions in the long run. A 1% increase in real GDP results in a 0.16% increase in CO_2 emissions, a 1% increase in non-renewable energy leads to a 0.87% increase in emissions, and a 1% increase in institutional quality is associated with a 0.11% increase in CO_2 emissions in the long run. The finding of a positive impact of GDP and non-renewable energy consumption on CO2 emissions is consistent with studies such as Shahbaz *et al.* (2013) and Liu *et al.* (2023), which highlight the scale effects of economic growth on environmental degradation, particularly in economies reliant on non-renewable energy sources. Also, the findings of the negative impact of institutional quality and renewable energy consumption on CO2 emissions is consistent to that of Haldat and Sethi (2021) for the case of developing countries. Essentially, any shifts in economic activities, particularly those heavily dependent on fossil fuel-intensive processes like manufacturing, trade, and transportation, will likely worsen pollution levels in the chosen OECD nations. Also, the outcomes revealed that institutional quality contributes an increase in CO2 emissions in OECD countries. This finding can be explained by the fact that institutional quality may have investment portfolios that include companies or projects with high carbon emissions, such as those in the energy or transportation sectors. These investments can indirectly contribute to CO2 emissions through the activities of the invested companies.

Additionally, according to FMOLS, a 1% rise in renewable energy is associated with a 0.04% decrease in CO_2 emissions, a 1% increase in ICT leads to a 0.05% reduction in CO_2 emissions, and a 1% increase in structural changes results in a 0.13% decrease in CO_2 emissions. The observed relationship between ICT advancements and a reduction in CO_2 emissions aligns with the findings of Islam *et al.* (2023), who investigated GCC countries using cointegration methodologies. Similarly, Adebayo *et al.* (2023), employing the NARDL approach for Turkey, identified that a positive shock in structural change results in a decline in CO_2 emissions, a result consistent with the outcomes of this study. In other words, it is particularly noteworthy that there is a significant relationship between structural changes and the growth of CO2 emissions, as the

Table 7
Panel Corrected Standard Errors (PCSE) and Mean Group Estimator (MGE) estimation

	PCSEs			MGE		
Variable	Coefficient	z-statistic	Prob.	Coefficient	z-statistic	Prob.
lnGDP	-0.01786	-5.30	0.0000***	-0.10445	-2.99	0.003***
lnRE	-0.00230	-2.21	0.027**	-0.00778	-0.55	0.582
lnNRE	1.0171	435.19	0.0000***	1.04677	44.50	0.000***
lnICT	-0.00837	-1.25	0.211	-0.07982	1.94	0.052*
lnINS	0.11419	10.60	0.0000***	0.05270	0.86	0.389
lnSTR	-0.06365	-6.10	0.0000***	-0.11187	-2.17	0.030***

"***", "**" and "*" indicate statistical significance at the 1%, 5% and 10%, respectively.

estimated coefficients represent the most significant part of the discussion regarding long-term pollution rates. Next, we encounter the share of information and communication technologies, followed by clean energies. Structural changes in OECD countries lead to a transition towards more sustainable and environmentally friendly economic activities, resulting in reduced CO_2 emissions. This phenomenon can be explained by several factors. Firstly, structural changes often entail shifts towards cleaner and more efficient technologies across various industries. For instance, advancements in renewable energy technologies such as solar and wind power enable industries to reduce their reliance on fossil fuels, thereby leading to a reduction in CO_2 emissions. Secondly, structural changes may involve increased investment in research and development of environmentally friendly technologies and practices. This investment stimulates innovations in energy efficiency, waste reduction, and sustainable resource management, ultimately resulting in reduced CO_2 emissions.

In contrast to the findings of FMOLS and DOLS, the results from PCSE and MGE estimations suggest that economic growth is linked to decreased CO_2 emissions in the long run. According to the PCSE estimator, a 1% increase in real GDP leads to a decrease in emissions by 0.01%. The impact of renewable energy on CO_2 emissions remains modest and negative, with a significant coefficient observed solely from the PCSE estimation. Specifically, a 1% increase in the consumption of renewable energy is associated with a decrease in CO_2 emissions by 0.002%. Interestingly, all estimation methods concur that the estimated coefficient of structural change will lead to a decrease in CO2 emissions in the long run. To the best of our knowledge, the objective of the current study is novel and has not been previously explored. This finding can be explained by several causes: (i) Structural changes in the selected OECD countries might coincide with government initiatives aimed at fostering environmental sustainability. These initiatives may encompass regulations mandating reductions in emissions, subsidies for renewable energy initiatives, or incentives encouraging businesses to embrace cleaner technologies; (ii) also, In OECD countries, structural changes could signify changes in consumer preferences towards environmentally friendly products and services. With an increasing demand for sustainable options, industries might adjust by adopting greener practices to cater to consumer needs, consequently diminishing their carbon footprint.

5. Conclusion and policy recommendations

This study fills a gap by investigating the dynamic impact of SCI on environmental quality using panel cointegration methods for G20 countries. Key contributions include the application of advanced techniques to enhance analysis reliability, improved estimation of relationships with small to medium-sized samples, and new insights into G20 interrelations. The selection of G20 countries is vital due to their significant global economic role and influence on international policy, making them crucial for studying global cooperation and addressing challenges.

This study examines the influence of structural change on CO2 emissions in 38 OECD countries from 2000 to 2021, offering new perspectives on the interplay between economic transformation and environmental sustainability. Based on UNCTAD's definition of productive capacity, three primary variables SCI, ICT, and institutional quality were selected to represent the pillars of productive capacity: resources, entrepreneurial skills, and production linkages. The study utilizes the recently introduced SCI by UNCTAD (2023) to analyze production linkages and broader compositional effects within economies. This represents the first empirical investigation into the role of structural change in reducing carbon emissions in developed countries.

The findings indicate cross-sectional dependence and cointegration among the variables, with results from FMOLS, MGP, and PCSE methodologies, excluding DOLS, highlighting the significant impact of structural change on reducing carbon emissions in OECD countries. In line with established theories, renewable energy and ICT are found to reduce emissions, while economic growth and non-renewable energy consumption contribute to higher emissions. Although institutional quality generally fosters economic growth, it also presents a trade-off by exacerbating scale effects on CO2 emissions, highlighting its complex influence on environmental quality.

The study offers several policy recommendations. The observed relationship between economic growth and increased emissions emphasizes the need for sustainable, low-carbon growth strategies. Policymakers should prioritize investments in renewable energy and reduce dependency on fossil fuels, especially in manufacturing sectors. Governance and institutional frameworks must be reoriented to align economic growth with sustainability goals. ICT is identified as a critical enabler of environmental improvements, facilitating remote work, smart cities, and clean technological innovations.

Given the important role of SCI in reducing emissions, policymakers should establish robust monitoring and evaluation systems to track progress in SCI-driven policies and emissions reductions. Strengthening international cooperation among OECD countries is critical for sharing knowledge, fostering joint green technology ventures, and harmonizing environmental standards.

Future research should build on these findings by exploring the EKC hypothesis in relation to SCI. Furthermore, the indirect pathways linking structural change to environmental quality, such as globalization and institutional frameworks, should be explored in greater depth. A deeper understanding of these dynamics will enable policymakers to design more effective interventions that balance economic growth with environmental preservation.

The SCI is a useful tool for tracking economic structural shifts, but it has notable limitations: (i) it overlooks qualitative factors such as technological innovation, human capital development, and industrial upgrading, which are essential for a deeper understanding of economic transformation; (ii) it fails to consider the environmental and social impacts of structural changes, including issues like pollution, resource depletion, and employment shifts, all of which are critical for sustainable development.

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