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Energy Price and Greenflation in the European Union. Facts and Challenges

Piotr Misztal*

Abstract: As the environmental and climate crises intensify, accelerating the green transition has become increasingly urgent. Only recently have scientists and economists begun to examine the relationship between green monetary policy and inflation. Therefore, it is important to investigate whether monetary policy can influence the green transition while supporting price stability. Although the concept of climatflation is gaining attention in empirical research, the effects of fossilflation and greenflation remain less understood and require further study. In particular, the sensitivity of green investments to changes in interest rates is a key issue that demands additional theoretical and empirical analysis. Systematic research in these areas is essential for shaping effective monetary policy and enabling policymakers and regulators to respond more efficiently to contemporary climate and environmental challenges. The aim of research on green monetary policy is to examine how central banks in the European Union (EU) can incorporate environmental sustainability, especially climate change into their decision-making frameworks. The research focuses on identifying how monetary policy instruments can be adjusted to support the transition to a low-carbon economy while preserving traditional objectives such as price stability and financial stability. A key objective is to better understand how climate-related risks affect inflation, financial stability, and economic growth, allowing central banks to adapt interest-rate policy to these emerging conditions. The study applied research methods based on literature analysis in banking and finance as well as econometric techniques, specifically the Vector Error Correction Model (VECM). Combining these approaches enabled a comprehensive analysis of green monetary policy and its potential impact on inflation and the development of a green economy.

Keywords: green economy; monetary policy; inflation; interest rate.

JEL classification: Q48; E52; O44.

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1. INTRODUCTION

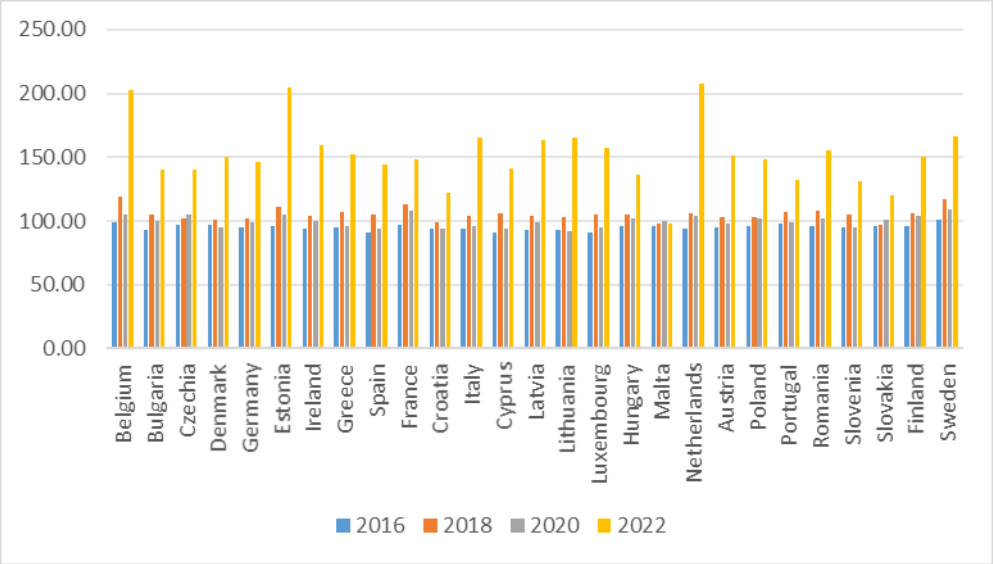
In the context of the global transition toward a low-carbon economy, new forms of inflation have emerged, shaped by both mitigation efforts and the intensifying impacts of climate change. Three interrelated but conceptually distinct inflationary phenomena are particularly relevant: greenflation, fossilflation, and climatflation. Each captures a unique mechanism through which climate-related dynamics influence price levels (see Table no. 1).

Table no. 1 – Typology of climate-related inflationary pressures

Term	Definition	Key Drivers	Examples
Greenflation	Inflation caused by increased demand and limited supply of green technologies and materials.	- High demand for critical minerals (lithium, copper, etc.) - Supply bottlenecks - Cost of environmental compliance	Rising cost of EVs due to lithium and cobalt price surges
Fossilflation	Inflation from fossil fuel price volatility and underinvestment during the energy transition.	- Reduced investment in fossil fuel infrastructure - Geopolitical shocks - Energy market imbalance	Oil and gas price spikes increase heating and transport costs
Climatflation	Inflation driven by the physical impacts of climate change disrupting economic activity.	- Extreme weather (droughts, floods, wildfires) - Agricultural and infrastructure disruption - Supply chain shocks	Drought reduces crop yields, increasing global food prices

Source: own study

The inflation rate in the EU member states has many interconnected causes, and its effects are widely felt by households, businesses and governments. In recent years, and especially after the Russian invasion of Ukraine, the prices of fossil fuels (especially gas, coal and oil) have increased dramatically. Russia was one of the main suppliers of gas to the EU, and the reduction of supplies (or complete interruption) led to shortages and increased competition for the raw material. Fluctuations in oil prices on the global market have also affected the costs of electricity production, especially in countries where oil is an important source of energy. The war in Ukraine and sanctions against Russia have affected the supply chains of energy raw materials. The EU had to look for alternative sources, which resulted in higher prices due to the need for rapid market reorganization and the construction of new infrastructure (e.g. LNG terminals). The transition to renewable energy sources (RES) under the Green Deal policy involves investments in new infrastructure, which initially increases costs. The introduction of the Emissions Trading System (ETS) also affects the increase in energy prices, as companies have to buy CO2 emission allowances, which increases the costs of energy production from fossil fuels. The lack of stability in energy production from renewable sources also increases the demand for traditional energy sources, such as gas or coal, which increases their prices. The largest increases in energy prices in the EU took place in 2022, in particular in the Netherlands, Estonia and Belgium (by over 100% compared to 2015), while the smallest growth dynamics were found in Malta and Croatia, where energy prices were similar to those in 2015 (see Figure no. 1).



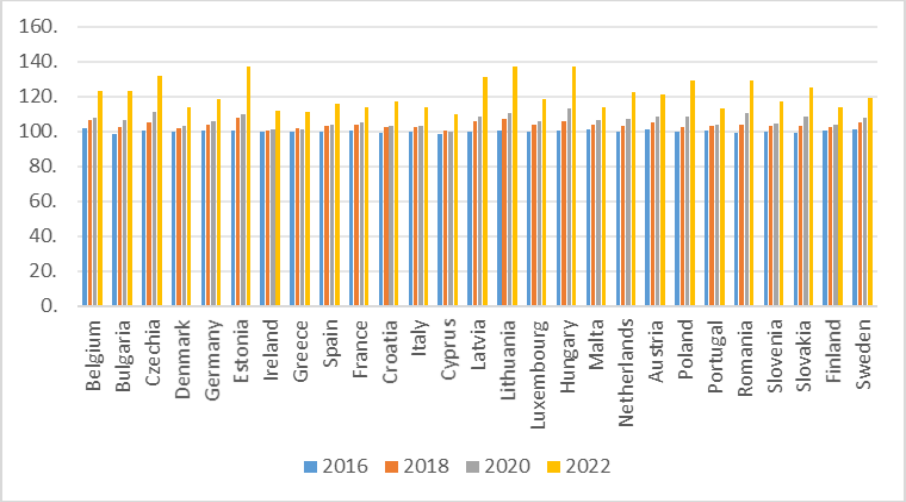
Source: author's own work based on data from Eurostat (2024)

Figure no. 1 – The dynamics of energy price in the EU countries (2015 year=100)

The increase in fuel prices affects the costs of transport and distribution of energy. Transporting gas, oil and even coal is becoming more expensive, which additionally increases energy costs. Due to the drive for decarbonisation and withdrawal from investments in fossil fuels, there is a lack of new investments in traditional energy sources, which limits their availability and increases costs. The increase in energy prices translates into higher electricity, gas and heating bills. Households, especially those with lower incomes, experience greater financial difficulties, which leads to so-called energy poverty. Companies, particularly those in energy-intensive sectors must pay more for energy, resulting in greater production costs and a decline in worldwide competitiveness. Because energy is a basic expense in many areas of the economy, rising energy prices create an overall increase in the pricing of goods and services (greenflation). This puts further strain on households and businesses.

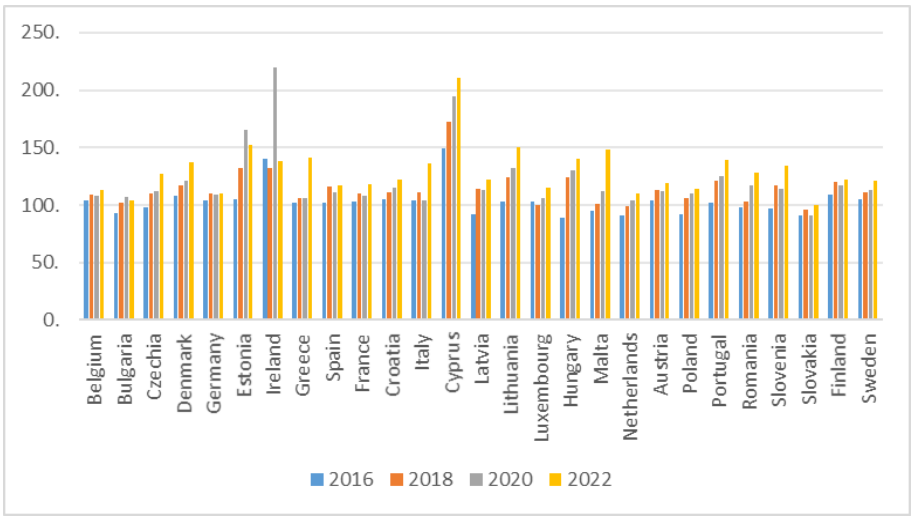
In the case of EU countries, the highest price dynamics of consumer goods and services was recorded in Lithuania, Estonia and Hungary (an increase of around 37% compared to 2015), while the lowest price dynamics was recorded in Cyprus, Italy and Ireland, where the price dynamics was around 10% compared to 2015 (see Figure no. 2).

Rising energy costs generally lead to a decline in consumption and investment. Businesses usually reduce production and investment, and consumers reduce their spending on goods and services. The lowest investment dynamics were recorded in countries where energy prices rose relatively quickly, leading to a significant acceleration in inflation. This includes countries such as Slovakia and Bulgaria, where investment volumes in 2022 were similar to those in 2015. On the other hand, the highest investment growth dynamics was revealed in Cyprus (an increase of over 100% compared to the volume in 2015) (see Figure no. 3).



Source: own study based on data from Eurostat (2024)

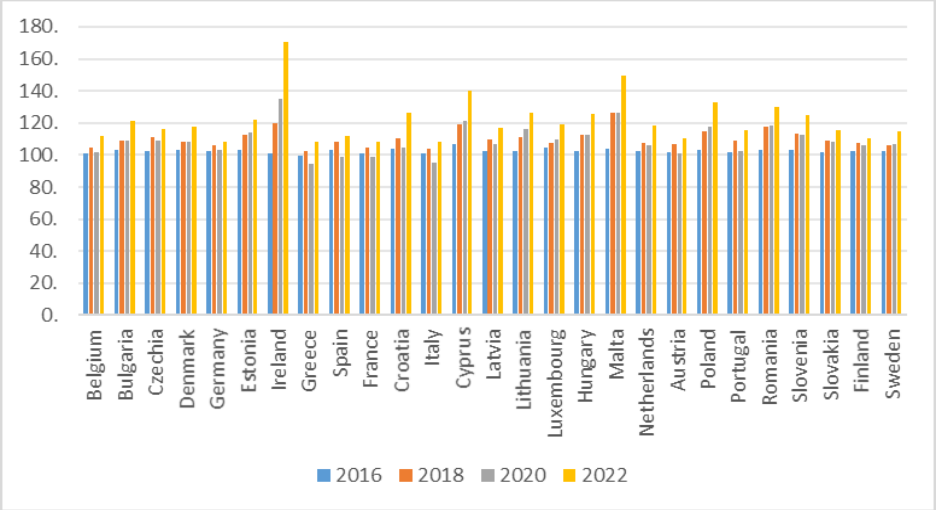
Figure no. 2 – Inflation rate in the EU countries (2015 year=100)



Source: author's own work based on data from Eurostat (2024)

Figure no. 3 – The dynamics of investments in the EU countries (2015 year=100)

The increase in energy prices, acceleration of inflation and the resulting decrease in investment and consumption dynamics led to a significant economic slowdown in the countries studied. The lowest GDP growth dynamics in 2022 were recorded in Greece, France and Italy (GDP growth of approx. 10% compared to 2015), while the highest GDP growth dynamics were recorded in Ireland (an increase of over 70% compared to 2015) (see Figure no. 4).



Source: author's own work based on data from Eurostat (2024)

Figure no. 4 – The dynamics of GDP in the EU countries (2015 year=100)

The increase in energy prices has forced EU governments to take the necessary measures to protect citizens and the economy from the worst effects of the energy crisis. Various support programs have been introduced, such as energy subsidies, price freezes or tax cuts, which, however, constitute an additional burden on state budgets. The increase in energy prices in the EU is therefore a complex phenomenon that results from both external and internal factors (political, economic and technological). The effects of this phenomenon are felt on many levels and require integrated actions to minimize its negative impact on society and the European economy.

2. LITERATURE REVIEW

2.1. Supportive studies on green monetary policies

A substantial body of literature supports the view that central banks should play an active role in mitigating climate change and accelerating the green transition. These studies emphasize the interlinkages between monetary policy, economic stability, and environmental sustainability.

Khan *et al.* (2019) explore how central banks can mitigate climate change and reduce its macroeconomic effects. Given the strong correlation between economic activity and carbon emissions, monetary policy impacts both inflation and emissions. Chen *et al.* (2021) propose modifying the Taylor rule by adding an "emission gap" target alongside inflation and output gaps. This approach allows monetary authorities to respond to deviations in carbon emissions from their target paths, effectively aligning monetary tools with environmental goals. However, Vollme (2024) notes that such integration might strain central banks' mandates by requiring them to balance multiple conflicting objectives.

The green transition requires large-scale capital reallocation. According to Bouckaert *et al.* (2021), the global economy needs an annual investment of approximately 2% of global GDP from 2010 to 2050 to achieve decarbonization. Weber *et al.* (2022) and Campiglio (2016) argue that central banks can help overcome investment barriers such as limited credit availability and poor risk-return profiles by facilitating access to green financing.

Roy (2024) further supports the strategic use of green credit to strengthen energy security and reduce reliance on fossil fuels. Empirical findings indicate a positive relationship between green credit flows and inflation control in advanced economies. However, the same effects may not materialize in developing countries due to structural constraints and weaker monetary frameworks.

Several studies highlight the disproportionate sensitivity of green investments to interest rates. Steffen and Waidelich (2022) show that rising rates impact green investments more severely than high-carbon alternatives because of their capital intensity and reliance on financial leverage. This raises concerns about monetary tightening undermining climate objectives.

Supporting this view, Voldsgaard *et al.* (2022) estimate that increasing the cost of capital from 5% to 10% raises the cost of electricity from offshore wind by 47%, rooftop solar by 60%, and large-scale solar by over 50%. In contrast, the same increase has only an 8% cost impact on natural gas energy. Ferguson and Storm (2023) confirm that renewable energy is far more sensitive to interest rate changes than fossil fuels, creating an uneven playing field during periods of monetary tightening.

Beyond interest rates, central banks are also exploring other tools. Ferrari and Nispi Landi (2020) propose implementing green quantitative easing, where central banks purchase green bonds to influence long-term yields and promote sustainable investments. DiLeo (2023) suggests that quantitative tightening might inadvertently harm the green transition by raising capital costs, especially if asset purchase programs previously favored high-emission sectors.

Several central banks have already launched green refinancing schemes. For instance, Bangladesh Bank offers concessional lending for green projects (Dikau and Ryan-Collins, 2017). Similarly, the European Central Bank (Schnabel, 2023) is considering greening its long-term refinancing operations. These tools, when aligned with collateral policy reforms – as suggested by Dafermos *et al.* (2018) – can address climate-related financial risks and promote green lending.

Innovative strategies have also been proposed, including adjusting capital reserve requirements. For example, the Central Bank of Lebanon reduced reserve requirements for green loans (Barmes and Livingstone, 2021), while the Chinese central bank offers favorable interest rates on reserves for green-lending banks. Campiglio (2016) recommends incorporating carbon certificates as part of reserve requirements and adjusting risk weights to favor low-carbon assets.

2.2. Critical perspectives on green monetary policies

Despite the potential benefits of green monetary policy, several scholars caution against its widespread adoption, pointing to institutional, macroeconomic, and structural limitations.

One major concern is the risk of mandate overreach. Critics argue that central banks are designed to focus on price and financial stability, not environmental goals. Expanding their mandate could compromise their independence and credibility. Vollme (2024) warns that

tasking central banks with climate goals may result in "policy overload," where monetary institutions are expected to deliver results traditionally achieved through fiscal or regulatory channels.

Another criticism lies in the inflationary implications of green policy tools, especially in the short term. Roy (2024) and Aguila and Wullweber (2024) note that while green investments may reduce inflation in the long run, they often trigger short-run price increases due to supply constraints in critical raw materials, commonly referred to as greenflation.

Furthermore, these inflationary effects are uneven across countries. Developing economies often face greater difficulties in implementing green monetary policies due to underdeveloped financial systems, limited credit availability, and institutional constraints. Monetary policy in these contexts may inadvertently raise inflation, as noted by Roy (2024), rather than stabilize it, thereby undermining policy effectiveness.

Another key criticism is the regressive nature of interest rate hikes. As interest rates rise, renewable projects become more expensive relative to fossil fuel investments, as shown by Ferguson and Storm (2023). High borrowing costs reduce access to financing for capital-intensive green technologies, widening the competitiveness gap between clean and dirty energy sources.

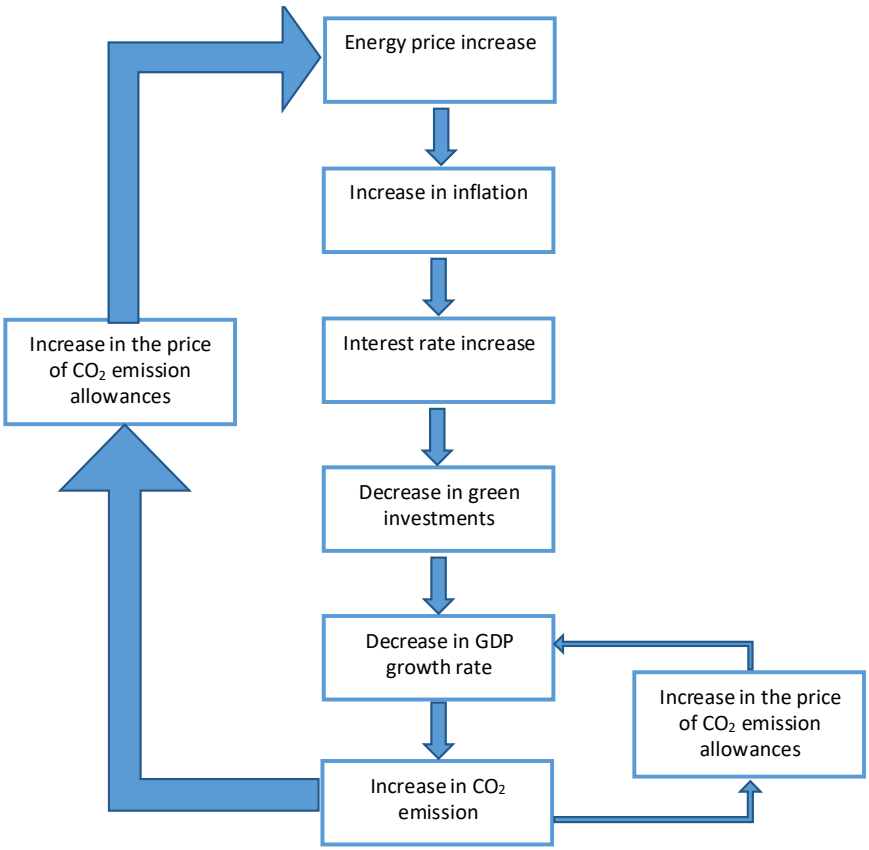
Moreover, monetary tightening affects households and governments, limiting their ability to fund or adopt green solutions. Batsaikhan and Jourdan (2021) emphasizes that higher borrowing costs discourage individuals from switching to sustainable home heating and cooling systems, while governments may find it more difficult to fund green infrastructure initiatives.

Lastly, critics are skeptical about the effectiveness of greening traditional monetary instruments. Some argue that central banks' collateral frameworks and interest rate policies are not designed to differentiate climate risks effectively. Without robust risk metrics and regulatory support, these efforts may distort market signals, misallocate credit, or foster green asset bubbles (Khan *et al.*, 2019).

These empirical studies support the view that monetary policy has a measurable impact on the pace and quality of the green transition, but they also underscore the complexity of balancing inflation control with environmental goals. The emerging consensus suggests that green monetary tools can be effective, but their design must account for macroeconomic trade-offs, financial stability concerns, and regional differences.

3. METHODOLOGY

This part of the article attempts to empirically examine whether monetary policy can affect pro-ecological expenditure and, as a result, the level of carbon dioxide emissions in the economy. Therefore, the potential impact of interest rates on carbon dioxide emissions was examined by creating appropriate conditions for financing green investments, while ensuring a stable price level in the European Union economy. According to the adopted model assumption, the increase in energy prices leads to an increase in inflation, which results in an increase in interest rates in the country as a result of the appropriate reaction of the central bank to rising prices. Subsequently, rising interest rates cause a decrease in investment expenditure (including expenditure financing green investments), which results in a decrease in GDP dynamics. The decrease in real incomes means that enterprises, households and governments of individual countries are less interested in financing pro-ecological projects, which ultimately leads to an increase in carbon dioxide emissions in the economy (see Figure no. 5).



Source: author's own work

Figure no. 5 – The mechanism of price impulse transmission in the green economy

To investigate the relationship between monetary policy and the effects of pro-environmental investments, the following panel data model was used. The econometric model was proposed by (Roy, 2024).

$$E_{it} = \alpha_i + \beta_{1i} GDP_{it} + \beta_{2i} Green_{it} + \beta_{3i} IR_{it} + \beta_{4i} CPI_{it} + \varepsilon_{it} \quad (1)$$

where:

E_{it} – carbon dioxide emission level in countries i = 1, 2, ..., N in the period t = 1, 2... T;
GDP_{it} - gross domestic product in countries i = 1 , 2, ..., N in period t = 1, 2... N;
$Green_{it}$ - value of expenditures on pro-ecological purposes in countries i = 1, 2, ..., N in the period t = 1, 2... N;
IR_{it} - long-term interest rate (yield rate on 10-year Treasury bonds) in countries i = 1, 2, ..., N in period t = 1, 2... N;
CPI_{it} - , consumer price index measuring the inflation rate in countries i = 1, 2, ..., N in the period t = 1, 2... N;

B_{1i}, ..., β_{4i} - estimated parameters defining the influence of a given explanatory variable on the explained variable;
and $_{it}$ - the free term of the equation;
$\mathcal{E}_{it}$ - random error.

4. DATA AND EMPIRICAL RESULTS

It should be noted here that due to the fact that twenty EU member states belong to the euro zone, where a single monetary policy is conducted by the European Central Bank, while in the seven remaining EU countries independent monetary policies are conducted by national central banks, instead of central bank interest rates, the study uses long-term interest rates (10-year Treasury bond yields), which in fact affect the cost of long-term investments in all EU member states. An additional advantage of using 10-year Treasury bond yields is that their level depends on the level of central bank interest rates and the risk associated with the capital recipient. Therefore, the risk factor is also included in the levels of these interest rates.

In order to examine the potential impact of interest rate policy on the effects of ecological transformation, relevant statistical data for the European Union member states (27 countries) from the Eurostat statistical database were used. The data had an annual frequency and covered the period 2015-2022 (see Table no. 2).

Table no. 2 – Descriptive statistics of the data used in the panel study

Statistic	CPI	E	GDP	IR	GREEN
Mean	2.456744	7008.370000	512952.300000	1.344698	602.701200
Median	1.400000	42277.340000	210192.000000	0.830000	9.310000
Maximum	19.400000	670815.30	3953850.00	9.67	9476.29
Minimum	-1.500000	1316.118000	10221.400000	-0.510000	0.000000
Std. Dev.	3.624506	128910.8	803360.0	1.588521	1738.39
Skewness	2.364262	2.616682	2.447822	2.082040	3.525314
Kurtosis	9.049727	10.422820	8.525810	9.011546	14.352770
Jarque-Bera	528.1665	738.9396	488.2462	479.0760	1599.9280
Probability	0.000000	0.000000	0.000000	0.000000	0.000000
Sum	528.2000	19502300.0000	110000000.0000	289.1100	129580.8000
Sum Sq. Dev.	2811.328	3.56E+12	1.38E+14	540.0076	6.47E+08
Observations	215	215	215	215	215

Source: author's own work using Eviews software

The descriptive statistics presented in Table no. 1 show that among the variables used in the basic analysis, the average value of the parameter E (the amount of carbon dioxide emissions) was over 90708 thousand tons, while the standard deviation of E was over 128910 thousand tons, which means that there are huge differences in the effects of the green transformation policy conducted between the European Union countries. In turn, the average level of the long-term interest rate in the EU countries was 1.34%, and its standard deviation was almost 1.59%, which indicates that there is a significant disproportion in monetary policy activities in the EU countries. On the other hand, the average value of pro-ecological expenditure in the EU was almost EUR 603 billion, and the standard deviation was EUR 1738 billion, so also in this respect there were significant differences between the EU member states.

The calculated correlation coefficient between the variables studied indicated a strong and positive linear relationship between the amount of carbon dioxide emissions and the amount of GDP (0.91), which indicated that larger economies were accompanied by greater emissions of carbon dioxide pollutants. A relatively high positive correlation was also observed in the case of the linear relationship between the value of pro-ecological expenditures and the amount of carbon dioxide emissions (0.80), which could result from time lags between the period of making green investments and the effects of these investments. On the other hand, the correlation coefficients between the level of the interest rate and pro-ecological expenditures and between the level of the interest rate and the amount of carbon dioxide emissions were negative but relatively low, which could also indicate the occurrence of time lags between the variables studied (see Table no. 3).

Table no. 3 – Correlation coefficients between the studied variables

	CPI	E	GDP	IR	GREEN
CPI	1.00	-0.04	-0.02	0.26	-0.01
E	-0.04	1.00	0.91	-0.03	0.80
GDP	-0.02	0.91	1.00	-0.15	0.90
IR	0.26	-0.03	-0.15	1.00	-0.19
GREEN	-0.01	0.80	0.90	-0.19	1.00

Source: author's own work using Eviews software

Before the econometric analysis, a test for the presence of a unit root was performed. The general process generating panel data can be written in the following form:

$$y_{it} = \alpha_i + \delta_{i_t} + \varphi_i y_{it-1} + \theta_t + \varepsilon_{it} \quad (2)$$

This method differentiates between two individual effects (α), individual linear trends (δ), heterogeneous autoregressive parameters (φ), and heterogeneous time effects (θ). In certain cases, some of these parameters may not be heterogeneous. When testing stationarity, it's crucial to examine the parameter φ. There are various methods for determining the presence of unit roots in panel data. There are two categories of tests: first-generation and second-generation. They address the question of cross-sectional data reliance differently. First-generation tests assume no interdependence, whereas second-generation tests allow for cross-sectional dependence (Staszczyk, 2017). The Levin, Lin, and Chu y tests, Peseran and Shin tests, and Fisher's test were employed to determine the stationarity of the variables under consideration (see Table no. 4).

Table no. 4 – Test for the occurrence of a unit root in panel data

Panel unit root test: Summary			
Series:	E		
Date:	10/04/24	Time:	19:31
Sample:	2015–2022		
Exogenous variables:	Individual effects		
User-specified lags:	1		
Newey-West automatic bandwidth selection and Bartlett kernel			
Balanced observations for each test			
Null: Unit root (assumes common unit root process)			

Method	Statistic	Prob.**	Cross-sections	Obs
Levin, Lin & Chu t*	-3.25491	0.0006	27	162
Null: Unit root (assumes individual unit root process)				
Method	Statistic	Prob.**	Cross-sections	Obs
Im, Pesaran and Shin W-stat	1.77451	0.962	27	162
ADF - Fisher Chi-square	32.7819	0.99	27	162
PP - Fisher Chi-square	48.2003	0.6966	27	189

Note:** Probabilities for Fisher tests are computed using an asymptotic Chi-square distribution. All other tests assume asymptotic normality.

Source: author's own work using Eviews software

Since the value of the p parameter is lower than the assumed significance level of 0.05, it can be stated that the variables studied do not have a common unit root, i.e. treated as homogeneous, they are stationary. The tests also indicate that some individual variables have an individual unit root, so they may not be stationary. Johansen (1988), analyzing the issues of cointegration, concluded that it is possible to study the long-term equilibrium between variables using the vector autoregression model (VAR), if this model is supplemented with the so-called error correction component, presenting the long-term relationship between non-stationary variables. This means transforming the VAR model into a vector error correction model (VECM) (Marona and Bieniek, 2013).

Therefore, due to the presence of a unit root in the case of several individual variables, the vector error correction model was used instead of the VAR model. Therefore, the next stage of the analysis was to determine the structural parameters of the model (1). To determine the optimal number of lags for the variables included in the VECM, two commonly used information criteria were applied: the Akaike Information Criterion (AIC) and the Schwarz Bayesian Information Criterion (SBIC), also referred to as the Bayesian Information Criterion (BIC). These criteria are based on a trade-off between model fit and model complexity. AIC aims to minimize the information loss by balancing goodness-of-fit (log-likelihood) with the number of estimated parameters. It is more permissive and tends to select models with more lags. SBIC/BIC, on the other hand, applies a stronger penalty for the inclusion of additional parameters, thus favoring more parsimonious models. Formally, the criteria are defined as:

$$AIC = -2ln(L) + 2k \tag{3}$$

$$SBIC = -2ln(L) + k\ ln(n) \tag{4}$$

where:

L is the likelihood of the model;

k is the number of estimated parameters;

n is the number of observations.

In the current study, a range of lag lengths was tested, and both the AIC and SBIC were computed for each specification. The criteria values were then compared across lag lengths. Although AIC and SBIC sometimes yield different suggestions, in this case, both pointed to a lag order of 2 as providing the best balance between explanatory power and model simplicity. This result implies that incorporating two lags (two years) captures the most relevant dynamic interdependencies among the variables, namely carbon emissions, green investment, interest rates, inflation, and GDP without introducing overfitting or unnecessary complexity.

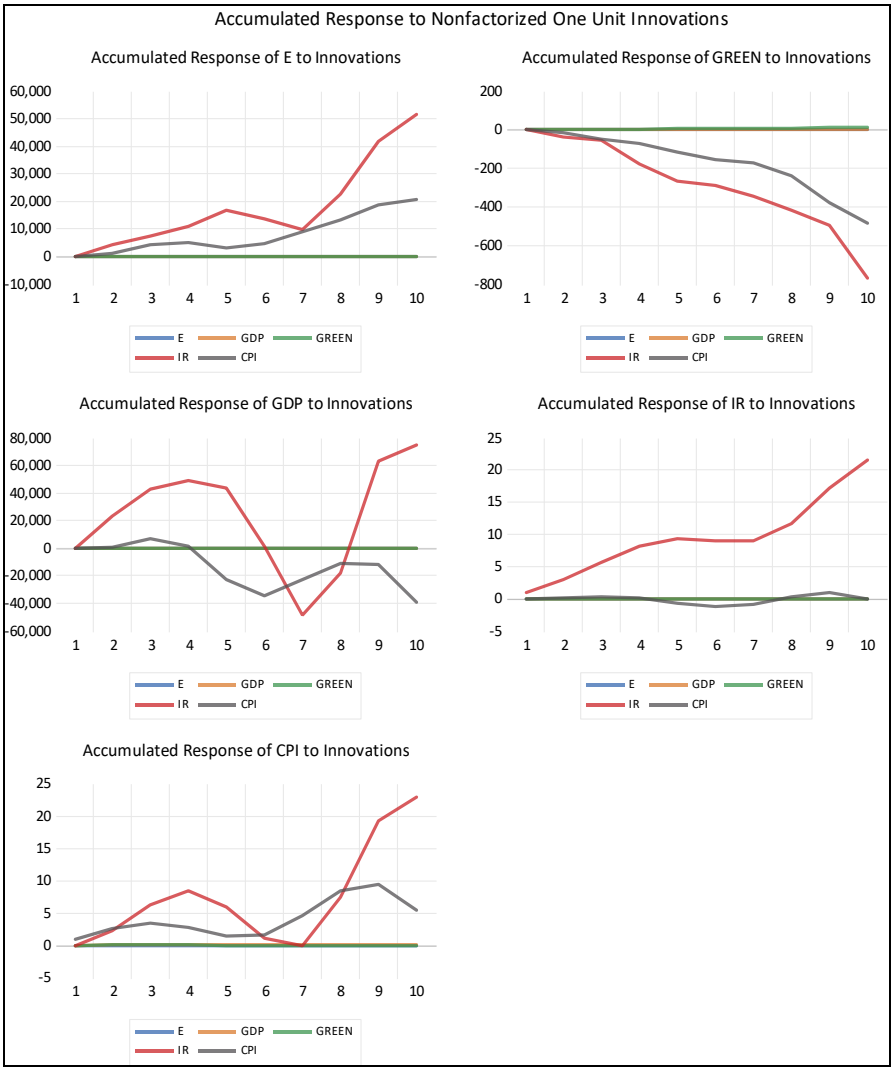
Selecting a two-period lag structure allows the model to account for the delayed effects of monetary policy and economic conditions on environmental and investment outcomes. This is particularly important in green transition dynamics, where policy impacts (such as interest rate changes) typically manifest over multiple years due to the long-term nature of infrastructure and capital investment cycles. Consequently, the VECM was specified with a two-period lag structure, as recommended by both information criteria, ensuring robust and interpretable results for the subsequent analysis. Finally, the results of the analysis are presented below (se Table no. 5).

Table no. 5 – VECM model estimation results

Error Correction:	**D(E)**	**D(GDP)**	**D(GREEN)**	**D(IR)**	**D(CPI)**
COINTEQ1	-0.0020	0.0640	0.0002	0.0000	0.0000
	0.0020	0.0097	0.0001	0.0000	0.0000
	[-0.97753]	[6.57273]	[2.68058]	[-2.52057]	[-2.12392]
D(E(-1))	0.0332	1.1885	-0.0011	0.0000	0.0000
	0.0973	0.4746	0.0029	0.0000	0.0000
	[0.34071]	[2.50418]	[-0.39067]	[-0.59070]	[-0.23755]
D(E(-2))	-0.3698	-1.5131	-0.0015	0.0000	-0.0001
	0.0990	0.4829	0.0030	0.0000	0.0000
	[-3.73497]	[-3.13348]	[-0.51200]	[-2.79832]	[-2.38621]
D(GDP(-1))	-0.2160	-0.7724	0.0021	0.0000	0.0000
	0.0265	0.1292	0.0008	0.0000	0.0000
	[-8.15730]	[-5.97996]	[2.66252]	[1.77357]	[0.72128]
D(GDP(-2))	-0.1260	-0.5874	-0.0028	0.0000	0.0000
	0.0365	0.1779	0.0011	0.0000	0.0000
	[-3.45588]	[-3.30258]	[-2.59104]	[0.03169]	[0.35137]
D(GREEN(-1))	0.8009	-24.3543	-0.0055	0.0003	0.0007
	0.2477	0.1208	0.0742	0.0003	0.0009
	[0.32332]	[-2.01587]	[-0.07440]	[1.03276]	[0.79480]
D(GREEN(-2))	12.9610	-5.8487	0.1205	0.0000	-0.0003
	0.2614	0.1275	0.0783	0.0003	0.0010
	[4.95786]	[-0.45871]	[1.53809]	[0.06402]	[-0.27363]
D(IR(-1))	4307.6549	23756.0889	-37.6591	0.8975	2.1499
	0.1412	0.6889	0.4232	0.1514	0.5233
	[3.04998]	[3.44863]	[-0.88983]	[5.92722]	[4.10863]
D(IR(-2))	-2595.0389	-13504.6688	51.8913	-0.4992	-1.3697
	0.1463	0.7137	0.4385	0.1569	0.5421
	[-1.77352]	[-1.89232]	[1.18351]	[-3.18194]	[-2.52666]
D(CPI(-1))	824.3765	5425,1204	-4.9847	0.1482	0.4073
	0.5138	0.2506	0.1540	0.0551	0.1904
	[1.60447]	[2.16487]	[-0.32376]	[2.69122]	[2.13957]
D(CPI(-2))	930.3182	4674.6714	10.8868	-0.3551	-1.4975
	0.6403	0.3123	0.1919	0.0686	0.2372
	[1.45298]	[1.49691]	[0.56743]	[-5.17344]	[-6.31289]
C	38.9195	36324.9814	49.0916	0.0460	1.4087
	0, 118 7	0, 5801	0, 3564	0.1275	0.4407
	[0.03272]	[6.26096]	[1.37724]	[0.36038]	[3.19645]
R-squared	0.6811	0.6259	0.5191	0.5981	0.5387
Adj. R-squared	0.6518	0.5916	0.4750	0.5612	0.4964

Source: author's own work using Eviews software

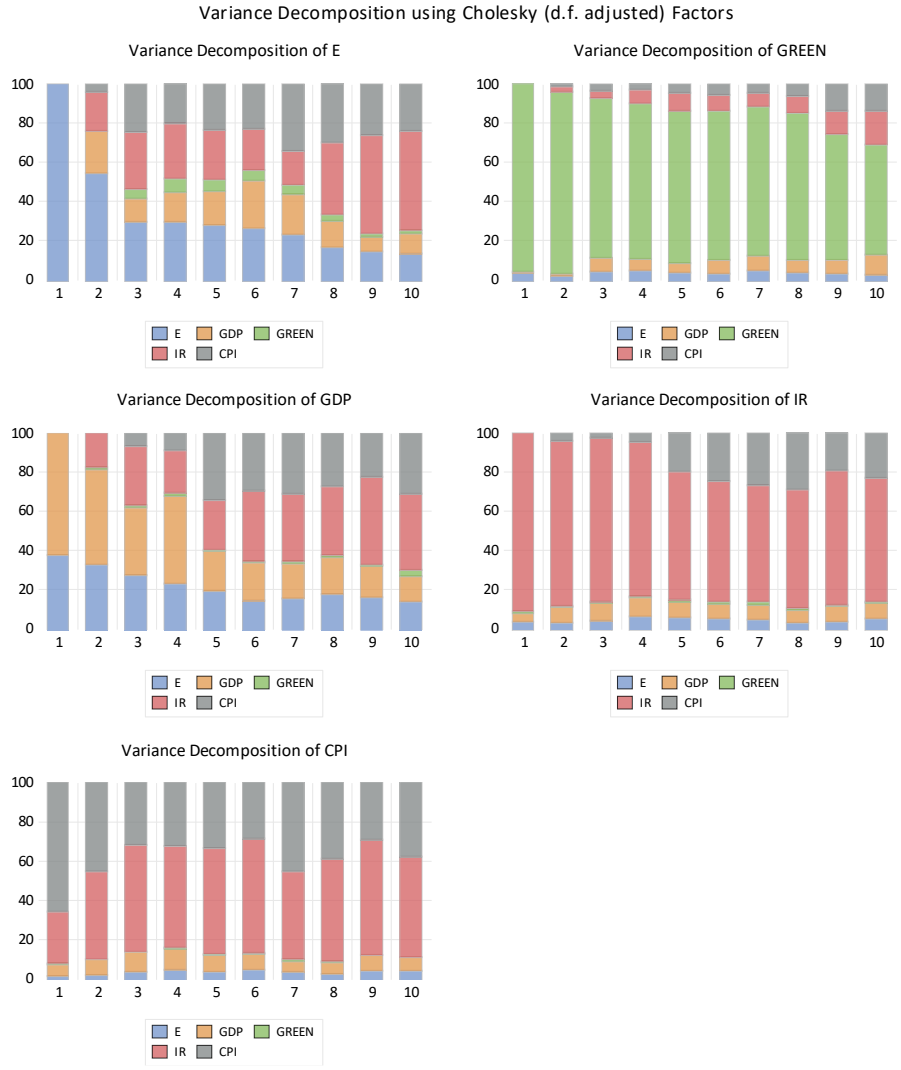
According to the data presented in Table no. 5, in the period under review there was a negative impact of the long-term interest rate lagged by two years on carbon dioxide emissions in the EU countries. This meant that the increase in the interest rate, through the increase in costs and consequently the decrease in the volume of green investments, contributed to the increase in carbon dioxide emissions in the EU economy. The negative impact of lagged inflation on the effects of the green transformation was also revealed, as the rising prices of goods and services could significantly limit the investment possibilities of households, enterprises and the government in the green economy.



Source: author's own work using Eviews software

Figure no. 6 – Impulse response function

The impulse response function, on the other hand, illustrates the time lines that show how variables react to unexpected events or shocks in a dynamic system. In general, the impulse response captures the reaction of any dynamic system when confronted with an external shock. An impulse in the form of an increase in the long-term interest rate caused a gradual increase in carbon dioxide emissions during the next 7 years following the shock, and then a sharp increase in CO_2 emissions in the following years. On the other hand, a shock increase in the long-term interest rate by one unit led to a sharp decline in expenditure on financing green investments within 10 years from the moment of the change in the interest rate (see Figure no. 6).



Source: author's own work using Eviews software

Figure no. 7 – Variance decomposition

The last stage of the analysis is the decomposition of the variance of the residual component of variables (the amount of carbon dioxide emissions and expenditures on pro-ecological investments), in order to estimate the impact of changes in the long-term interest rate on changes in individual variables. Based on the data presented in Figure no. 6, it can be seen that changes in the long-term interest rate explained a significant part of the changes in carbon dioxide emissions. About 50 % of the changes in carbon dioxide emissions were explained by changes in the interest rate during the 10th year from the change in the size of the issue. However, in a much lower m the extent to which changes in the long-term interest rate were explained by changes in expenditure on financing green investments. Namely, almost 20% of changes in expenditure on financing pro-ecological investments could be explained by changes in the long-term interest rate 10 years after the change in these expenditures (see Figure no. 7).

Therefore, based on the research conducted, it can be concluded that monetary policy can indeed contribute to the energy transformation and meeting environmental challenges without threatening price stability, through cheaper financing of green projects at lower interest rates. Since external financing costs are the main factor determining the costs of investment in green projects, lower interest rates can contribute to falling energy prices. In the case of renewable energy sources, which are to replace fossil fuels, lowering their financing costs, and thus their prices, will reduce the inflationary effect resulting from the continued dependence of economies on non-renewable resources. Moreover, higher investment usually encourages innovation, stimulating efficiency growth, which can reduce costs and, consequently, prices. Moreover, green investments can contribute to mitigating climate change and adapting the economy to its effects, thereby reducing inflationary environmental and climate shocks and increasing resilience to risks related to changes in climate conditions.

5. CONCLUSION

Climate change is decreasing central banks' ability to conduct effective monetary policy by raising energy prices and increasing investment risk. Price shocks can be either transitory or lasting. Climate change hazards are split into two categories: physical risk and transformation risk. Physical climate change risk refers to the likelihood of an increase in the frequency and severity of negative supply shocks (e.g., capital stock erosion, supply chain disruptions) and demand shocks (e.g., deterioration of household and corporate balance sheets, resulting in reduced consumption and investment). While monetary policy can usually handle demand shocks, supply shocks are more difficult to eliminate because they force central banks to choose between stabilizing inflation and stabilizing production variations. The increased frequency and severity of negative supply shocks makes it more difficult for central banks to accurately anticipate potential output, the output gap, and, as a result, inflation. Changes in established weather patterns, in particular, may increase inflation volatility, for example, by affecting food and energy prices.

Transition risk emerges as a result of changes in economic policy to meet the new demands of a low-emission economy (also known as the green economy). The shift to a low-emission economy necessitates the implementation of several climate laws, significant technological advancement, investment in green technology, and significant socioeconomic changes. While this transition opens up chances for innovation, investment, and potential green growth, it also introduces hazards connected with economic upheaval. Changes in climate policy, technology, or market attitude can cause inefficient resource allocation in the

economy, necessitating the revaluation of some financial assets. Climate-related changes in predicted earnings and costs, in particular, can have a detrimental impact on banks' and other financial institutions' ability to repay debt and provide collateral to borrowers, as well as enhance the credit risk they face. The rate at which such asset revaluations occur is unknown, but their consequences can be considerable for financial institution safety and soundness, as well as the economy's financial stability.

Greenflation and green monetary policy are two sides of the same coin in the global shift to a sustainable economy. Greenflation describes the inflationary pressures caused by green policies and shifting market dynamics, whereas green monetary policy refers to central banks' efforts to control these transitions and promote environmental sustainability. The challenge is to balance inflationary pressures, maintain economic stability, and direct the economy towards long-term environmental goals. Policymakers must connect green policies with appropriate risk management to ensure that the most vulnerable groups are not disproportionately affected by these changes.

However, several limitations of research results must be acknowledged. First, the analysis omits other potentially influential macroeconomic variables, such as exchange rates, government fiscal spending, technological innovation, and environmental regulation, which may also shape the dynamics of green investment and emissions. Second, while the study includes all 27 EU countries, it does not explicitly account for structural differences among them, such as disparities in energy mix, financial system development, or institutional capacity, which could influence the effectiveness of monetary transmission mechanisms. Third, the use of the Vector Error Correction Model (VECM), while appropriate for capturing long-run equilibrium relationships, imposes certain restrictions on the data structure and may not fully capture non-linearities, asymmetric effects, or policy regime shifts that are characteristic of real-world green transitions.

Future research could address these limitations by incorporating additional control variables, employing non-linear or threshold models, and exploring cross-country heterogeneity through interaction terms or multi-level modeling. A more granular understanding of country-specific contexts and the interplay between monetary and fiscal tools would further enrich the policy implications of green monetary frameworks in the EU and beyond.

6. COMMENTS

The influence of climate policy on inflation is difficult to assess since it is dependent on the employment of inflation-control measures and the amount to which fiscal policy supports central bank efforts. As the scope of climate policy in the European Union expands to cover previously excluded industries, the pressure on inflation will make it more difficult for EU national central banks, as well as the European Central Bank in the case of eurozone states, to deal with climate-related shocks. According to the International Monetary Fund, two criteria are required to alleviate fears that the current high-inflation environment will damage the ability to manage inflation while not further damaging the economy.

To avoid major economic implications, the shift must be carefully planned and executed. However, if the shift is too sluggish, the institutions in charge of these processes will need to intervene in an abrupt and disorderly manner. However, if it is too rapid, it may have major ramifications for the economy's ability to respond to new conditions, as well as central banks'

ability to manage the monetary policy trade-off. The continuance of climate policy in the European Union is expected to contribute to a 13.5% annual increase in energy prices in a disorderly scenario, whereas a carefully managed transition would increase energy prices by 3.5% per year (Drudi *et al.*, 2021). Second, the credibility of the monetary policy is critical to keeping inflation expectations stable in the medium term. This may make it more difficult to accomplish more ambitious plans for decreasing carbon dioxide emissions and implementing climate policy, since an overly quick energy transition could dramatically increase green inflation in EU countries.

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Access to Housing and Economic Growth in the European Union

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Abstract: The European Union is facing what some identify as a housing crisis characterized by rising housing prices and rents and a dearth of affordable housing. Beyond its concerning direct effects on household well-being, the housing crisis may also pose long-term risks to macroeconomic performance. Escalating housing prices and rents can result in resource misallocation and shortages of highly skilled labor in key places, as well as increasing inequality, which could ultimately slow growth. An empirical assessment is conducted to examine the relationship between housing affordability pressures – proxied by the share of housing expenditure in household final consumption – and economic growth in the European Union, using data from 21 member states spanning the period from 2000 to 2019. We estimate a growth regression with country and time fixed effects and alternative inference approaches, and include a comprehensive set of control variables selected from prior literature. In this macro panel, inference is sensitive to the covariance estimator; we therefore report Driscoll-Kraay and country-clustered inference and focus on the sign, magnitude, and robustness of the estimated association. Under Driscoll-Kraay inference, a 10% relative increase (e.g., 20% to 22%) in the housing expenditure share is associated with about 0.3 percentage points lower annual real GDP growth (with similar results for real GDP per capita). These findings are consistent with the view that rising housing cost burdens may weigh on growth, but they should not be interpreted as causal effects.

Keywords: Housing Affordability; Economic Growth; European Union.

JEL classification: C33; O18; O47.

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1. INTRODUCTION

The European Union is experiencing what has been increasingly recognized as a housing crisis, prompting institutions such as the European Parliament to establish a dedicated committee (the Special Committee on the Housing Crisis in the European Union - https://www.europarl.europa.eu/committees/en/hous/home/) to address the issue. This housing crisis is characterized by rising housing prices and rents and a dearth of affordable housing – see European Parliament (2024) and Kuiper and Carbonell (2024). Between 2015 and 2023, house prices in the EU rose on average by 48%, and rents rose by 18% on average over a similar period (2010-2022), outpacing inflation. According to the OECD (2020), housing expenditures constitute the largest component of household spending, with their relative share increasing over the past two decades. This trend has disproportionately impacted lower-income households, who have experienced a marked rise in the proportion of their income allocated to housing costs.

Given these economic dynamics, the prospect of ample access to housing, which could be broadly defined as the degree to which individuals or households can obtain and maintain adequate, secure, and affordable housing that meets their needs (OECD, 2021), is increasingly jeopardized. In our empirical analysis we focus on housing affordability pressures, proxied by the (log) share of housing expenditure in household final consumption. According to the United Nations Human Settlements Programme (UN-Habitat) 'Access to housing is a precondition for access to employment, education, health, and social services.' (https://unhabitat.org/topic/housing) This statement is used as broad motivation; our empirical proxy captures affordability pressures via the household housing expenditure share rather than "access" in a broader sense. The former in turn have been identified in the literature as key drivers of economic growth – see, e.g., Mankiw *et al.* (1992), Beraldo *et al.* (2009), Bloom *et al.* (2018) and D'Andrea (2022)– namely by increasing labour force and human capital availability, the latter an essential ingredient for final goods production and innovation activities that increase productivity and lead to faster growth (Nelson and Phelps, 1966; Lucas, 1988; Romer, 1990b; Benhabib and Spiegel, 2005). Housing affordability constraints due to excessive house price increases have been shown by Aizenman *et al.* (2019) to sap economic growth due to the associated diversion of investment to the housing sector, reducing funding available for investment by other more productive sectors. The latter is documented by Chakraborty *et al.* (2018) that show that banks operating in robust housing markets exhibit a tendency to increase mortgage lending while concurrently decreasing lending to firms. Anthony (2023) posits that the limited availability of affordable housing is a salient factor in firms' location decisions, driven in part by the need to maintain worker satisfaction. Furthermore, housing-related dissatisfaction is argued to negatively impact firm competitiveness through reduced productivity and increased employee turnover. The former will in turn limit economic growth. Yet another mechanism of transmission refers to inequality. Ioannides and Ngai (2025) argue that housing cost burdens and reduced affordability can drive inequality due to increasing housing costs and concentration of housing capital. According to their review of the literature, research shows that housing demand is income- and price-inelastic, leading lower-income households to spend a growing share of their income on housing, leaving less for other needs and for investment. Also, housing is unevenly distributed in many OECD countries and thus rising property values disproportionately benefit those who already own homes, further increasing inequality.

Although there is no consensus in the literature, the former may impede growth due to reduced physical and human capital accumulation associated with social-political instability, the demand for higher social spending and the consequent need for higher taxation to finance it, which distorts economic decisions namely in terms of labour supply decisions and savings and investment, or imperfect credit markets – see Bagchi and Svejnar (2015), Islam and McGillivray (2020), and Balcilar *et al.* (2021).

Recent empirical research has delved into various issues of access to housing and its implications for economic growth. Aizenman *et al.* (2019) and Asadov *et al.* (2023) investigate the link between house price dynamics and economic growth for 19 countries (both OECD and non-OECD) from the first quarter of 1975 to the third quarter of 2013 in the first case and using quarterly data from 17 OECD countries from 1970 to 2019 in the second case. Aizenman *et al.* (2019) conclude that house prices are linked to economic growth and can either hinder or support growth, depending on the severity of the changes in prices and overall market conditions. In Asadov *et al.* (2023), on the other hand, the main takeaway is that the net contribution of house price return to growth is negligible. Anthony (2023) looks at the influence through housing cost-burdened households focusing on the 100 largest metropolitan statistical areas in the USA and arrives at a statistically significant negative effect on economic growth.

This paper explores this link in the context of the housing sector in the EU by analyzing the relationship between housing affordability pressures and economic growth using data for 21 member states observed over the period 2000–2019. Affordability pressures are proxied by the share of housing expenditure in household final consumption. Our contribution is threefold. First, we provide cross-country evidence for EU member states using a nationally aggregated measure that captures the budgetary weight of housing costs and has comparatively broad coverage over time. Second, we explicitly situate the empirical exercise in an EU policy context and account for institutional and housing-policy dimensions by including government effectiveness and public social housing expenditure among the controls. Third, we implement a panel-data growth regression with country and time fixed effects and Driscoll-Kraay standard errors and complement inference with diagnostic testing and robustness checks tailored to the panel's cross-sectional dependence and serial correlation features. Given the small N and T typical of macro panels, inference can be sensitive to the covariance estimator; we therefore benchmark inference across alternative estimators in Table no. A2 (Driscoll–Kraay, country clustering, and a wild cluster bootstrap).

With this study we aim to contribute to the discussion on the macroeconomic implications of the ongoing housing crisis in the EU by providing evidence at the aggregate national economy level and focusing on long-run macroeconomic performance. While the analysis identifies associations rather than causal effects, the evidence may help inform policy discussions on which constraints are most strongly correlated with growth outcomes. As Castañeda *et al.* (2018) explain, setting policy priorities is a challenge for governments due to the need to achieve multiple objectives simultaneously, the complexity of the policy landscape, implementation inefficiencies, and the interrelated nature of policy issues.

The structure of the paper is as follows. Section 2 gives some context and reviews prior empirical studies on the relationship between the housing sector and economic growth. In Section 3, we present our empirical strategy and describe the data used. Section 4 contains the main results regarding the relationship between housing affordability pressures and growth. Section 5 offers concluding remarks and outlines potential avenues for future research.

2. BACKGROUND

Economic growth depends directly on the accumulation of physical and human capital alongside technological progress. While neoclassical models treat technology as exogenous (Solow, 1956; Mankiw *et al.*, 1992), endogenous growth theory posits that growth is driven by the deliberate creation of ideas (Romer, 1990a; Jones, 1995), and capital accumulation (Romer, 1986; Lucas, 1988). In this framework, housing affordability pressures—and, more broadly, constraints on access to adequate housing—may be associated with growth by shaping the availability and allocation of labour, physical capital, and human capital. In what follows we use "access" as broad motivation, but our operational concept is housing affordability pressures, proxied by the housing expenditure share of household final consumption. Regarding labor, home value shocks can trigger wealth effects that reduce labor supply, as shown for the cases of Japan, China and the USA, respectively by Hamaaki and Iwata (2025), Li *et al.* (2020) and Begley and Chan (2018). High costs may also restrict geographical mobility and the efficient matching of talent (Glaeser *et al.*, 2006; Hsieh and Moretti, 2019; Causa and Pichelmann, 2020). This misalignment is particularly acute for low-skilled labor (Ganong and Shoag, 2017) and can lead to increased turnover and diminished productivity among skilled professionals (Hsieh and Moretti, 2019; Anthony, 2023). Furthermore, higher housing-cost burdens can trigger a misallocation of physical capital that can hinder economic growth; overvalued property sectors often divert investment away from more innovative, productive industries (Miao *et al.*, 2015). Finally, because housing is the primary asset for most households, its value directly dictates wealth distribution and income inequality (Causa and Pichelmann, 2020; Dustmann *et al.*, 2021), possibly constituting a barrier to long-term aggregate growth.

In the economics literature, recent studies that have examined how the housing sector influences economic growth include Aizenman *et al.* (2019), Asadov *et al.* (2023) and Anthony (2023).

Exploring the house prices channel, Aizenman *et al.* (2019) investigate how economic growth is influenced by directional changes in house prices, i.e. appreciations vs. depreciations, while Asadov *et al.* (2023) add to the former the analysis of the consequences of house prices volatility for economic stability. The results from Aizenman *et al.* (2019) indicate that excessive increases in house prices lead to overinvestment in the property market, diverting capital away from more productive sectors, while sharp declines can correct this misallocation and stimulate economic growth. The study reached these conclusions based on a sample of 19 countries, including both advanced and emerging economies: some are OECD members, while others are not. The quarterly data covers the period from 1975 to 2013. The authors consider three alternative dependent variables: the real GDP growth rate, the real GDP per capita growth rate, and the growth rate of total factor productivity. Among the explanatory variables, the logarithm of house prices stands out, used to measure the direct impact of fluctuations in the housing market. The model also includes variables related to production factors and controls for macroeconomic factors such as interest rates, inflation, and fiscal policies, ensuring robustness in the estimates. The panel data models are estimated using the Generalised Method of Moments (GMM), which addresses endogeneity and country-specific effects. Asadov *et al.* (2023) focus on the link between house price instability and output, specifically the effect of house price volatility on economic stability, testing also the impact on economic growth, using quarterly data for 17 OECD countries from 1970 to 2019 and

dynamic panel data models estimated using Pooled Mean Group (PMG), Dynamic Fixed Effects (DFE) and Dynamic OLS (DOLS), ensuring robustness and correcting for endogeneity problems. The control variables include private credit (linear and quadratic), private investment growth, public spending, the inflation rate, trade openness and investment volatility. Their findings point to a significant asymmetric impact of house price returns on economic growth, with negative returns exerting twice the effect of positive ones. Additionally, the findings suggest that house price volatility plays a substantial role in contributing to economic instability.

Although Aizenman *et al.* (2019) and Asadov *et al.* (2023) focus on house prices, there is a direct connection with the impact of housing affordability on economic growth. High house prices can raise housing cost burdens and weaken affordability by increasing the financial pressure on households. In this context, another recent study by Anthony (2023) analyses 100 U.S. metropolitan statistical areas (MSAs) for the years 2000, 2010, and 2015 to assess the impact of housing affordability on regional economic growth. Using multiple panel data regressions, the author estimates the relationship between the proportion of cost-burdened households and the change in real GDP per capita. Control variables include unemployment rates, population density, and each region's initial real GDP per capita. The results show that an increase in the proportion of cost-burdened households has a negative and significant effect on economic growth in metropolitan areas, with renters being the most affected.

While the link between the housing sector and macroeconomic performance is well-established in the previous studies, our work occupies a distinct niche. Rather than focusing on house price dynamics, as in Aizenman *et al.* (2019) and Asadov *et al.* (2023), we shift attention to household budget constraints within the European Union. This EU-specific focus contrasts with the OECD and emerging-economy samples used in those studies, which may obscure institutional and structural particularities of the EU, and it moves beyond the regional U.S. perspective of Anthony (2023) by offering a cross-country analysis. By employing the 'Housing Expenditure Share of Final Consumption' we bridge the gap between the broad, price-based approaches of Aizenman *et al.* (2016) and Asadov *et al.* (2023), which, while informative, do not fully capture the financial burden on households' consumption and quality of life, and the localized, burden-focused analysis of Anthony (2023).

The focus on EU member states is a timely one as, regardless of the country, prices for housing and energy have been rising relative to household consumption, with roughly 22% of household consumption dedicated to housing and over 20% of renters living in overcrowded units, 2022 numbers, while other market segments experienced "under-occupation" (large homes with few inhabitants), as discussed in Egner and Krapp (2025). According to the European Commission European Commission (2025), between 2013 and 2024 house prices across the EU increased 60%, faster than household income, rents grew on average 20%, with new rents growing significantly more, while residential building permits decreased 20% since 2021 and unoccupied dwellings increased by 20%. A housing crisis has thus been unfolding across the EU, but housing provision is not an EU-level task; it is managed at the national level. However, a common European approach to solving these issues is being attempted. Recent EU-specific housing policy initiatives include the European Affordable Housing Plan, launched late 2025 and announced by the European Commission as 'Europe's response to the housing crisis'. The plan is structured around four primary objectives: boosting housing supply; mobilizing investment; enabling immediate support while driving reforms; and protecting the most affected. To achieve these goals, the EU has introduced several specific

mechanisms, including reprogramming Cohesion funds for investments in social, affordable and sustainable housing, with additional support from the Social Climate Fund. Other examples include a new housing simplification package to reduce administrative burden, accelerate permitting and renovation and improve cost efficiency; revising State aid rules to enable faster and simpler public support for social and affordable housing; encourage reforms in areas such as spatial planning, social housing, and taxation, reducing complexity and enhancing housing supply. In any case, as discussed by Egner and Krapp (2025) based on the experience of twelve EU member states plus Norway and the UK, and by Hochstenbach (2025) for the case of Netherlands, national differences regarding the housing sector remain a fundamental issue that should not be forgotten when analyzing the policy implications of our findings for the average EU member state, which should additionally be framed through the lens of national specificities. For instance, countries differ in how their populations are distributed across tenures (owner-occupation vs. private rental vs. social rental). This distribution dictates who suffers most, with cost overburden and overcrowding more prevalent among renters than owners.

3. EMPIRICAL STRATEGY AND DATA

To investigate the link between housing affordability pressures and economic growth in the EU we use data for 21 member states: Austria, Belgium, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden. Regarding the period under consideration, since economic growth is shaped by a broad set of determinants beyond housing affordability pressures, including physical and human capital, labor, trade, or institutions (more details below), the limited availability of consistent and comparable data across all relevant indicators has constrained the feasible period of investigation. In particular, the human capital indicator is available only up to 2019, while financial development measures extend only to 2021. As a result, the empirical analysis focuses on the period 2000–2019, which maximizes the overlap of relevant variables, and additionally avoids the noise and volatility due to the COVID-19 pandemic that hit the world economy in 2020. This choice is also consistent with the studies more closely related to our work, Aizenman *et al.* (2019), Asadov *et al.* (2023) and Anthony (2023). The panel is balanced.

The baseline empirical model is given by equation (1), which serves as a conceptual reference point:

$$d\_logGDP_{it} = \alpha + \lambda logGDP_{it-1} + \beta\, logHousing_{it} + \theta X_{it} + \vartheta_i + \tau_t + \varepsilon_{it} \quad (1)$$

where d_logGDP_{it} is our measure of economic growth, $logGDP_{it-1}$ is the log of initial output, $logHousing_{it}$ is the log of our indicator of housing affordability pressures (higher values indicating a larger housing expenditure share and hence stronger cost pressures), X_{it} is a vector of control variables, ϑ_i represents the individual country effects, τ_t represents time effects, ε_{it} is the error term, i represents the country and t represents the year. The coefficient β captures the association between housing affordability pressures and growth, conditional on controls and fixed effects.

Following Aizenman *et al.* (2019) and Asadov *et al.* (2023), we measure economic growth, our dependent variable, as the log difference of real GDP (or real GDP per capita in the

sensitivity analysis). Our explanatory variable of interest is housing expenditure as a share of final consumption expenditure of households from the OECD Affordable Housing Database. This indicator was chosen for its broader temporal coverage. Other possible indicators, such as households' housing cost burden (mortgage and rent cost) as a share of disposable income, were not used due to limited data availability. The proportion of housing expenditure in household final consumption offers valuable insight into the significance of housing-related costs within overall household spending. It facilitates comparisons across different consumption categories, countries, and time periods. According to OECD (2024), this indicator encompasses expenses related to actual and imputed rentals for housing and the maintenance and repair of housing (including materials and services), as well as essential utilities and services such as water supply, waste collection, sanitation, and communal services like elevator maintenance, cleaning, and security. This comprehensive measure captures both direct and indirect housing costs, providing a fuller understanding of housing's financial burden on households. We interpret this measure primarily as a proxy for housing affordability pressures (a higher share indicates that housing costs take a larger slice of the consumption basket). The variable *logHousing* is therefore expected to present a negative association with economic growth, because stronger cost pressures may restrict geographical mobility and the efficient allocation of labor and human capital, redirect investment toward the real estate sector and away from more productive activities, and increase inequality, as discussed above.

As for the vector of control variables (X), again following Aizenman *et al.* (2019) and Asadov *et al.* (2023), we control for the initial level of output, proxied by $logGDP_{it-1}$, as initially poorer countries are expected to grow faster and converge to the output levels of initially richer countries (Solow, 1956) and so λ should be negative. We also control for the availability of capital and labor, captured, respectively, by gross fixed capital formation as a percentage of GDP (*inv*), a human capital index that reflects both average years of education and returns to education (*logHC*) and the log of the unemployment rate (*logUnemp*). These variables control for the availability (or lack of) of inputs, physical and human capital and labour, with the influence of the first two expected to be positive and of the third to be negative. Similar to Aizenman *et al.* (2019) we also control for inflation (*infl*), measured by the annual growth rate of the consumer price index (CPI); trade openness (*logOpen*), defined as the ratio of the exports plus imports to GDP; government consumption as a percentage of GDP (*logGovc*); and financial development (*logFD*) measured using the financial development index of the International Monetary Fund (IMF), an index that captures the depth, access, and efficiency of the financial institutions and financial markets in different countries. Other control variables from the literature that we include are the quality of institutions, measured using the World Bank index of government effectiveness (*gef*), and social expenditure on housing as a percentage of GDP (*logSEHous*). Table no. 1 contains details on the variables used and respective sources. Table no. 2 contains summary statistics.

Table no. 1 – Variables and sources

Variable	Description	Source
d_logGDP	Difference of the log of real GDP, PPP (constant 2021 international $).	World Bank
d_logGDPpc	Difference of the log of real GDP per capita, PPP (constant 2021 international $).	World Bank
Housing	Share of housing expenditure in household final consumption.	OECD Affordable Housing Database

Variable	Description	Source
inv	Gross fixed capital formation as a percentage of GDP.	World Bank
Open	Sum of exports and imports as a percentage of GDP.	World Bank
SEHous	Public social expenditure on housing as a percentage of GDP.	OECD Social Expenditure Database (SOCX)
gef	Government effectiveness index that captures perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. Ranges from approximately -2.5 to 2.5	World Bank
HC	Human capital index, based on years of schooling and returns to education. Ranges from approximately 1 (no formal education) to 4.5, although it has no strict upper or lower bound in theory.	Penn World Table 10.1
infl	Growth rate of the consumer price index (%).	World Bank
Unemp	Unemployment as a percentage of total labour force.	World Bank
Govc	General government final consumption expenditure as a percentage of GDP.	World Bank
FD	Financial development index that captures the depth, access, and efficiency of the financial institutions and financial markets. Ranges from approximately 0 to 1.	International Monetary Fund (IMF)

Table no. 2 – Summary statistics

Variable	Mean	Std. Dev.	Min.	Max.
d_logGDP	0.021	0.034	-0.175	0.121
d_logGDPpc	0.019	0.035	-0.158	0.130
logGDP	26.706	1.345	24.108	29.293
logGDPpc	10.684	0.411	9.550	11.853
logHousing	3.082	0.183	2.494	3.497
inv	22.240	3.848	10.687	36.800
logUnemp	2.062	0.471	0.591	3.321
infl	2.277	2.068	-1.736	15.402
logOpen	4.615	0.442	3.816	5.946
logGovc	3.006	0.130	2.669	3.330
logFD	-0.635	0.424	-1.889	-0.104
logSEHous	2.262	1.650	-2.303	4.494
logHC	1.160	0.104	0.802	1.348
gef	1.205	0.551	0.099	2.347

4. FINDINGS

We start by applying cross-sectional dependence tests to the series used, after which we proceed to testing for stationarity. We next carry out the estimation of the selected model.

4.1. Cross sectional dependence and stationarity analysis

Before estimating the baseline empirical model given by equation (1), a diagnostic test was carried out to see if the series show cross-sectional dependence (CSD). CSD occurs when shocks or events that affect one country tend to influence the other countries. As our sample contains only EU member states, this dependence is particularly likely due to the economic,

financial and institutional integration between these countries. The presence of CSD can bias estimates and influence the validity of statistical tests, making it necessary to use robust methodologies to correct this problem.

Table no. 3 contains the results of the Pesaran (2021) test, which assesses the average correlation between the residuals of different countries to test for the existence of CSD. The variable *logHC* was excluded from the test due to its near-linear behavior. The null hypothesis assumes cross-sectional independence; when this hypothesis is rejected, it indicates the presence of cross-sectional dependence (CSD). In such cases, it becomes necessary to either include variables in the model that capture the impact of common shocks across countries – such as time effects – or to apply estimation methods that account for this dependence. As shown in Table no. 3, the variables *logGDP, logGDPpc, infl, logOpen, inv, logUnemp, logGovc, logFD*, and *logHousing* all reject the null hypothesis at a p-value of 0, indicating significant cross-sectional dependence.

Table no. 3 – Pesaran (2004) **Test Results for Cross-Sectional Dependence (CSD)**

Variable	Statistic	p-value
logGDP	48.18	0.000
logGDPpc	43.84	0.000
logHousing	23.52	0.000
inv	22.53	0.000
logUnemp	17.91	0.000
infl	40.19	0.000
logOpen	51.67	0.000
logGovc	15.71	0.000
logFD	25.36	0.000
logSEHous	-0.83	0.404
gef	1.48	0.139

Notes: the null hypothesis is that of cross-sectional independence.

After confirming cross-sectional dependence (CSD) in most variables, we assess whether the series are stationary using the Pesaran (2007) Cross-sectionally Augmented IPS (CIPS) test, reported in Table no. 4 (with and without a deterministic trend). The results suggest that several macro series are I(1) in this sample – notably *logGDP*, *logOpen*, *logGovc*, *logSEHous*, and *gef* – so we work with first differences for these variables in the baseline specification. The results for *logHousing* are mixed across trend and lag choices, which motivates the robustness specifications that use both *logHousing* and *d_logHousing* as the housing affordability pressure regressor. Finally, the *logFD* series yields mixed outcomes across trend specifications, so we difference it for robustness.

Table no. 4 – Pesaran (2007) **Second-Generation Unit Root Test - CIPS**

		Test without trend		Test with trend	
Variable	**Lags**	**Zt-bar (No Trend)**	**P-Value**	**Zt-bar (Trend)**	**P-Value**
logGDP	0	1.419	0.922	2.084	0.981
logGDP	1	-1.985	0.024	-0.615	0.269
logGDPpc	0	1.538	0.938	4.075	1.000
logGDPpc	1	-0.937	0.175	1.066	0.857
logHousing	0	-1.154	0.124	1.715	0.957
logHousing	1	-2.758	0.003	-0.487	0.313
inv	0	-1.687	0.046	-0.222	0.412

		Test without trend		Test with trend	
inv	1	-2.301	0.011	-1.685	0.046
logUnemp	0	3.034	0.999	1.107	0.866
logUnemp	1	-2.419	0.008	-0.219	0.413
infl	0	-5.238	0.000	-3.380	0.000
infl	1	-3.883	0.000	-2.111	0.017
logOpen	0	0.290	0.614	2.597	0.995
logOpen	1	0.233	0.592	2.284	0.989
logGovc	0	0.263	0.604	2.544	0.995
logGovc	1	-0.228	0.410	2.274	0.989
logFD	0	-1.775	0.038	-2.809	0.002
logFD	1	-0.953	0.170	-2.727	0.003
logSEHous	0	2.102	0.982	3.230	0.999
logSEHous	1	1.277	0.899	3.378	1.000
gef	0	-5.898	0.000	-6.856	0.000
gef	1	0.733	0.768	-0.307	0.379

Notes: the null hypothesis assumes that the variable has a unit root (non-stationary).

In light of these results, the variables *logOpen*, *logGovc*, *logSEHous*, *logGDP*, and *gef* were differenced, as the CIPS test indicated that they are non-stationary in most cases. Table no. 5 presents the results of Pesaran (2007) Cross-sectionally Augmented IPS (CIPS) second-generation unit root test for these differenced variables, as well as for *logHousing* and *logFD*. When differenced and tested without a trend, all variables reject the null hypothesis, indicating stationarity. This transformation ensures that the estimated coefficients are not affected by spurious relationships and supports the statistical validity of the model. Furthermore, due to the divergence in unit root test results for the *logFD* variable – with the null hypothesis accepted without a trend and rejected with a trend – we opted to difference the variable to enhance the robustness of the results and avoid potential issues related to higher-order integration. The stationarity of the *logHousing* variable also yielded ambiguous outcomes. Given this uncertainty, alternative model specifications will be tested, including versions both with and without differencing *logHousing*, to evaluate the robustness of our findings.

Table no. 5 – CIPS Unit Root Test - First Differences

Variable	Lags	Test without trend Zt-bar (No Trend)	P-Value	Test with trend Zt-bar (Trend)	P-Value
d_logGDP	0	-4.45	0.000	-2.308	0.010
d_logGDP	1	-3.063	0.001	-0.746	0.228
d_logGDPpc	0	-3.755	0.000	-2.227	0.013
d_logGDPpc	1	-2.452	0.007	-0.931	0.176
d_logOpen	0	-5.076	0.000	-3.470	0.000
d_logOpen	1	-2.434	0.007	-1.198	0.115
d_logGovc	0	-6.662	0.000	-6.068	0.000
d_logGovc	1	-2.373	0.009	-1.723	0.042
d_logFD	0	-12.567	0.000	-10.489	0.000
d_logFD	1	-7.856	0.000	-6.011	0.000
d_logHousing	0	-7.43	0.000	-6.425	0.000
d_logHousing	1	-2.539	0.006	-1.395	0.081
d_logSEHous	0	-7.451	0.000	-5.889	0.000
d_logSEHous	1	-1.551	0.060	-0.086	0.466
d_gef	0	-15.673	0.000	-13.617	0.000
d_gef	1	-6.098	0.000	-3.492	0.000

Notes: the null hypothesis assumes that the variable has a unit root (non-stationary).

Finally, equation (1) is operationalized as a dynamic panel model with fixed effects, incorporating differenced non-stationary variables, lagged variables, and time controls through annual dummy variables. The inclusion of the lagged dependent variable (d_logGDP_{it-1}) captures the persistence of economic growth, reflecting the notion that past growth influences current performance. This dynamic specification is standard in empirical growth regressions and helps capture adjustment processes in growth rates over time see, e.g., Caselli *et al.* (1996); Bond *et al.* (2001). The required transformations are applied to equation (1), resulting in the regression presented in equation (2):

$$d\_logGDP_{it} = \alpha + \lambda logGDP_{it-1} + \gamma d\_logGDP_{it-1} + \beta\, logHousing_{it-1} + \theta X_{it-1} + \vartheta_i + \tau_t + \varepsilon_{it} \qquad (2)$$

Equation (2) is the final estimated specification used for the main results reported below. The vector X_{it-1} contains the following variables lagged one period: the investment rate (*inv_1*), the logarithm of the unemployment rate (*logUnemp_1*), the inflation rate (*infl_1*), the first difference of the logarithm of the openness variable (*d_logOpen_1*), the first difference of the logarithm of public consumption (*d_logGovc_1*), the first difference of the logarithm of the financial development index (*d_logFD_1*), the logarithm of the human capital index (*logHC_1*), the first difference of government effectiveness (*d_gef_1*), and the first difference of the logarithm of public social housing expenditure (*d_logSEHous_1*).

Including both the initial output level ($logGDP_{it-1}$) and lagged growth (d_logGDP_{it-1}) serves distinct purposes. The former captures conditional convergence—initially poorer countries are expected to grow faster conditional on fundamentals—while the latter captures short-run persistence in growth rates that may arise from propagation mechanisms and gradual adjustment (e.g., Caselli *et al.*, 1996; Bond *et al.*, 2001).

This specification can also be interpreted in error-correction terms. Starting from a simple dynamic level equation in which output depends on its own lag and lagged covariates, differencing yields a growth equation that includes the lagged level of output (capturing adjustment toward a conditional steady state) alongside lagged growth (capturing short-run dynamics), as in panel ARDL/error-correction models (e.g., Pesaran *et al.*, 1999). To reduce concerns about simultaneity, all regressors are lagged one period; nevertheless, reverse causality between growth and housing affordability pressures remains a potential limitation, and the results should be interpreted as associations rather than causal effects. In the Annex, Table no. A1 therefore reports a dynamic-panel GMM *transparency* exercise (not an identification strategy) using restricted and collapsed internal instruments to limit instrument proliferation following standard practice (Arellano and Bond, 1991; Blundell and Bond, 1998). Given the well-known fragility of dynamic GMM in small-N macro panels with persistent regressors, we do not rely on GMM for inference and treat it only as a robustness check alongside the main FE+DK results.

An additional measurement-related channel is worth noting: because the housing variable is an expenditure *share* of household consumption, it can increase mechanically if non-housing consumption falls (e.g., during downturns) even with unchanged housing costs. This feature reinforces the interpretation of the baseline results as associations.

We first estimated equation (2) using fixed effects to consider the possibility of omitted variable bias due to unobserved events and to control for time-invariant unobserved heterogeneity at the country level, which is particularly important in our context given persistent structural differences across countries. After estimating equation (2) with fixed effects, the Pesaran (2021)

CSD test was applied again to check whether the model adequately captures potential interdependencies among countries in the sample. Contrary to the findings for the individual variables, the results shown in Table no. 6 indicate a p-value of 0.2834, suggesting no statistically significant evidence of cross-sectional dependence between countries. Having addressed stationarity and CSD, the next step was to examine autocorrelation. Table no. 7 presents the Wooldridge test for panel data, described in Wooldridge (2002), which tests for the presence of first-order autocorrelation in the model's residuals. The null hypothesis assumes no autocorrelation. However, with a p-value of 0.000, the test strongly rejects the null hypothesis at conventional significance levels, indicating the presence of autocorrelation. To account for this issue, robust estimation methods are required. One appropriate approach is the Driscoll and Kraay (1998) estimator, which adjusts the error variance-covariance matrix and is robust to heteroscedasticity and serial correlation, and can also accommodate general forms of cross-sectional dependence. While the residual cross-sectional dependence test for the baseline FE model does not reject at conventional levels (Table no. 6), cross-sectional dependence is a pervasive concern in macro panels and such tests may have limited power in small panels. With T = 20 and N = 21, neither Driscoll-Kraay nor country clustering has perfect small-sample justification, as they rely on different asymptotic arguments. We therefore report Driscoll-Kraay inference as a robustness benchmark, alongside country-clustered inference in the Annex (Table no. A2).

Table no. 6 – Cross-Sectional Dependence Test (Pesaran, 2021) applied to equation (2) estimated with FE

	Value
Pesaran test for cross-sectional independence	-1.073
p-value	0.2834
Average absolute off-diagonal values	0.272

Notes: the null hypothesis corresponds to cross-sectional independence.

Table no. 7 – First-Order Autocorrelation Test (Wooldridge) applied to equation (2) estimated with FE

	Value
F-Test (1, 20)	41.789
p-value	0.0000

Notes: the null hypothesis corresponds to no autocorrelation.

4.2. Estimation results

Table no. 8 presents the results of the estimation of equation (2) with fixed effects (FE) and with Driscoll-Kraay (DK) corrected standard errors. Because the Driscoll-Kraay correction affects the estimated variance-covariance matrix, the FE point estimates in columns (1) and (2) are identical; what changes is inference via the standard errors (and associated p-values).

The results in Table no. 8 show that the variable *logHousing_1* is negative but not statistically significant at conventional levels under one-way country-clustered inference; under Driscoll-Kraay inference it is statistically significant at the 5% level (Table no. A2). Among the other explanatory variables, all except human capital (*logHC_1*), have the expected signs. The estimated coefficients for inflation and unemployment are negative as expected and positive for the other explanatory variables, but statistical significance is low

and varies across regressions for the same explanatory variable. Notably, the coefficient for *logGDP_1*, which tests the convergence hypothesis, confirms that countries with lower initial GDP tend to experience faster growth. Additionally, the positive and statistically significant coefficient of *d_logGDP_1* confirms persistence in economic growth, meaning that past growth positively influences current growth. Inference is sensitive to the standard-error estimator in this macro panel; we therefore report both Driscoll-Kraay and country-clustered inference and focus on the sign, magnitude, and robustness of the estimated association. In terms of magnitude, the DK point estimate implies that a 10% relative increase (e.g., 20% to 22%) in the housing expenditure share is associated with roughly 0.3 percentage points lower annual real GDP growth, suggesting a modest economic magnitude. Table no. A2 also reports wild cluster bootstrap p-values for the clustered specification as a conservative small-sample benchmark. Even modest annual growth differentials can cumulate over time; we note this only to aid interpretation and not as a prediction. The signs of the remaining explanatory variables remain basically unchanged.

Table no. 8 – Response of the growth rate of real GDP to housing affordability pressures

Variable	(1) FE (clustered)	(2) FE (DK/SCC)	(3) FE (clustered)	(4) FE (DK/SCC)
logHousing_1	-0.029	-0.029**		
	(0.018)	(0.013)		
d_logHousing_1			-0.014	-0.014
			(0.043)	(0.039)
inv_1	0.000	0.000	0.000	0.000
	(0.001)	(0.001)	(0.001)	(0.001)
logUnemp_1	-0.008	-0.008	-0.006	-0.006
	(0.007)	(0.005)	(0.008)	(0.005)
infl_1	-0.005***	-0.005	-0.004***	-0.004
	(0.001)	(0.003)	(0.001)	(0.003)
d_logOpen_1	0.042	0.042	0.039	0.039
	(0.044)	(0.040)	(0.045)	(0.041)
d_logGovc_1	-0.106*	-0.106	-0.100*	-0.100
	(0.051)	(0.097)	(0.051)	(0.099)
d_logFD_1	0.028*	0.028	0.031*	0.031
	(0.016)	(0.032)	(0.016)	(0.033)
d_gef_1	0.004	0.004	0.004	0.004
	(0.004)	(0.003)	(0.004)	(0.003)
d_logSEHous_1	0.008	0.008	0.008	0.008
	(0.006)	(0.006)	(0.005)	(0.006)
logHC_1	-0.046	-0.046	-0.053	-0.053
	(0.107)	(0.052)	(0.108)	(0.054)
logGDP_1	-0.077**	-0.077**	-0.079**	-0.079**
	(0.033)	(0.029)	(0.033)	(0.030)
d_logGDP_1	0.411***	0.411***	0.423***	0.423***
	(0.071)	(0.091)	(0.072)	(0.092)
Constant	2.215**	2.215**	2.183**	2.183**
	(0.827)	(0.775)	(0.845)	(0.786)
R2	0.737	0.7292	0.735	0.7348
Observations	378	378	378	378

Notes: country and time fixed effects. Standard errors in parentheses. Columns (1) and (3) report one-way country-clustered (Arellano-style) standard errors; columns (2) and (4) report Driscoll–Kraay (SCC) standard errors. ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

As an additional sensitivity check, Table no. A3 reports leave-one-country-out re-estimations of the DK specification. The coefficient on *logHousing_1* remains negative in all 21 runs for both real GDP growth and real GDP per capita growth, indicating that the result is not driven by any single country.

Since the results of the stationarity test for *logHousing* were ambiguous, Table no. 8 also contains an alternative specification considering the first difference of housing affordability pressures, *d_logHousing*, instead of the variable in levels. The coefficient on *d_logHousing_1* remains negative but is not statistically significant, which is consistent with the interpretation that short-run changes in housing expenditure shares are noisy and may not map cleanly into short-run growth fluctuations in this setting.

To check the robustness of our results, we use as alternative measure of economic growth the difference of the log of real GDP per capita and replicate the estimations carried out before. Table no. 9 contains these results obtained with the FE and the DK estimators and considering the explanatory variables of interest, housing affordability pressures, either in levels or first differences. Using this alternative measure of economic growth, our core findings remain consistent: an increase in the housing expenditure share is negatively associated with economic growth. As before, statistical significance depends on the inference method: the coefficient is significant under Driscoll-Kraay but not under country-clustered inference when housing affordability pressures are measured in log-levels (see Table no. A2). For the remaining control variables, the results remain basically unchanged, maintaining the sign of the respective estimated coefficient, while statistical significance improves in some cases such as for government effectiveness.

Table no. 9 – Response of the growth rate of real GDP per capita to housing affordability pressures

Variable	(1) FE (clustered)	(2) FE (DK/SCC)	(3) FE (clustered)	(4) FE (DK/SCC)
logHousing_1	-0.028	-0.028*		
	(0.020)	(0.013)		
d_logHousing_1			-0.010	-0.010
			(0.046)	(0.035)
inv_1	0.000	0.000	0.000	0.000
	(0.001)	(0.000)	(0.001)	(0.000)
logUnemp_1	-0.009	-0.009	-0.007	-0.007
	(0.008)	(0.005)	(0.008)	(0.006)
infl_1	-0.005***	-0.005	-0.004***	-0.004
	(0.001)	(0.003)	(0.001)	(0.003)
d_logOpen_1	0.040	0.040	0.038	0.038
	(0.043)	(0.041)	(0.044)	(0.043)
d_logGovc_1	-0.111*	-0.111	-0.105*	-0.105
	(0.054)	(0.099)	(0.054)	(0.101)
d_logFD_1	0.019	0.019	0.022	0.022
	(0.018)	(0.034)	(0.019)	(0.034)
d_gef_1	0.007*	0.007	0.007*	0.007*
	(0.004)	(0.003)	(0.004)	(0.003)
d_logSEHous_1	0.008	0.008	0.008	0.008
	(0.006)	(0.007)	(0.005)	(0.007)
logHC_1	-0.106	-0.106*	-0.114*	-0.114*
	(0.062)	(0.056)	(0.061)	(0.059)
logGDP_1	-0.070**	-0.070***	-0.071**	-0.071***
	(0.027)	(0.020)	(0.028)	(0.021)
d_logGDP_1	0.393***	0.393***	0.403***	0.403***

Variable	(1) FE (clustered)	(2) FE (DK/SCC)	(3) FE (clustered)	(4) FE (DK/SCC)
	(0.066)	(0.090)	(0.065)	(0.092)
Constant	0.998***	0.998***	0.927***	0.927***
	(0.246)	(0.252)	(0.281)	(0.249)
R^2	0.740	0.7402	0.738	0.7383
Observations	378	378	378	378

Notes: country and time fixed effects. Standard errors in parentheses. Columns (1) and (3) report one-way country-clustered (Arellano-style) standard errors; columns (2) and (4) report Driscoll–Kraay (SCC) standard errors. ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

5. CONCLUSION

Building on the literature concerning the relationship between housing and economic growth, we study how housing affordability pressures relate to economic growth in the European Union. We use a panel dataset that includes 21 member states spanning from 2000 to 2019. Applying fixed effects and Driscoll-Kraay corrected standard errors, we account for lagged economic growth, initial output and the housing expenditure share of final consumption expenditure of households, our proxy for housing affordability pressures, along with a comprehensive set of control variables. We find that stronger housing affordability pressures are associated with lower real GDP growth. Using the growth rate of real GDP per capita as our dependent variable yields a consistent pattern. Taken together, these findings improve our understanding of the potential macroeconomic correlates of housing cost burdens. While affordability pressures may affect growth through labor allocation and mobility, capital allocation, and inequality channels, the evidence in this paper is observational and consistent with these mechanisms but does not establish them causally.

While the analysis does not deal directly with policy issues, the results are consistent with the view that policies that alleviate housing cost burdens may be supportive of growth in the EU context. Even though our measure shows only a moderately negative association with growth and should not be interpreted as identifying causal effects, such policies could, if effective, matter for living standards over time. Different types of policies could mitigate elevated housing cost burdens and reduced affordability and, consistent with the negative association we estimate, could coincide with more favorable growth outcomes in the EU context, as discussed by Monroy *et al.* (2020). One such housing policy instrument to stimulate supply in the owner-occupied housing market could be the introduction or increase of a tax on vacant urban land providing incentives for more efficient use of well-located urban land. Redesigning property taxes could also incentivize more efficient land use towards higher-density housing development. Reducing the administrative burden, accelerating permitting and renovation, and improving cost efficiency could also stimulate supply. The European Strategy for Housing Construction will promote advanced construction materials and methods, such as offsite and modular construction, and digitalization to increase resource efficiency and reduce building costs (European Commission, 2025). As an alternative to expanding the owner-occupied market segment, which can result in over-consumption of housing space, governments may boost the rental market by defining clear, balanced and stable tenant–landlord regulations. Housing allowances and rent-subsidy vouchers can improve housing affordability for low-income groups, as well as developing affordable housing programs. Because housing sectors vary significantly by country, national policies

must be customized to address local specificities, as argued by Egner and Krapp (2025) and Hochstenbach (2025).

While the estimated negative association is stable across specifications within our EU sample, the sign and implied magnitude of the housing coefficient are robust, the statistical significance is sensitive to the inference method (Table no. A2). We recognize that the unique institutional and economic characteristics of the European Union, sharing a common market and harmonized regulations across multiple policy domains, suggest that generalizations to non-member countries should be made with caution. Future studies could broaden the scope and examine the relationship between housing affordability pressures and economic growth in a wider sample of countries, offering a more comprehensive understanding of the consequences of the housing sector for long run aggregate economic dynamics. Additionally, future research should explore the channels of transmission from housing affordability pressures to economic growth, i.e. whether it affects the availability of physical and human capital, productivity and inequality.

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ANNEX

This Annex provides dataset-preserving robustness exercises that address endogeneity and sensitivity concerns raised by the referees, without changing the sample or the operational concept (housing affordability pressures proxied by the housing expenditure share).

First, in response to referee requests for an IV/GMM-type exercise, Table no. A1 reports a parsimonious dynamic-panel GMM *transparency* check in levels using the GMM-DIF (Arellano-Bond) and GMM-SYS (Blundell-Bond) estimators, with collapsed instruments and restricted lag ranges to limit instrument proliferation. Because dynamic-panel GMM in small-N macro panels with persistent regressors is known to be delicate, we report this exercise to document fragility and to reinforce a cautious, associational interpretation; it is not treated as an identification strategy or a pillar of our conclusions.

Table no. A1 – Dynamic-panel GMM robustness (endogeneity check)

Estimator	Coef. on logHousing	p-value	# instr.	AR(2) p-value	Sargan p-value	N
GMM-DIF	-0.099	0.200	26	0.018	0.701	378
GMM-SYS	-0.146	0.251	29	0.013	0.381	399

Notes: the dependent variable is logGDP. Regressors are logHousing, inv, logUnemp, infl, and logHC, plus time dummies. For GMM-style instruments we use lags 3–4 of logGDP and logHousing (collapsed); for the system specification we additionally use GMMlevel instruments with lag 1.

The diagnostics reported in Table no. A1 underscore that standard internal-instrument approaches are fragile in this setting, so we do not rely on GMM for inference. We also do not search over instrument choices to obtain more favorable diagnostics; instead we present Table no. A1 for transparency and focus on FE-based associations, with robust inference benchmarked under alternative standard-error estimators.

Second, to provide low-cost sensitivity evidence focused on inference and influence, Table no. A2 reports alternative inference benchmarks for the baseline *logHousing_1* coefficient (country-clustered vs. Driscoll–Kraay), and Table no. A3 reports leave-one-country-out sensitivity summaries for the DK specification.

Table no. A2 – Alternative inference benchmarks for the logHousing coefficient (baseline specification)

Dependent variable	DK (SCC) coef.	DK SE	DK p-value	Cluster (country) coef.	Cluster (country) SE	Cluster (country) p-value	Wild cluster bootstrap p-value
d_logGDP	-0.029	0.013	0.034	-0.029	0.018	0.122	0.140
d_logGDPpc	-0.028	0.013	0.050	-0.028	0.020	0.184	0.253

Notes: DK uses Driscoll–Kraay (SCC) standard errors and Cluster(country) uses one-way country-clustered standard errors. The wild-cluster column reports a wild cluster bootstrap-t p-value (Rademacher weights, 9999 replications) as a small-sample robustness check for the clustered specification.

Table no. A3 – Leave-one-country-out sensitivity (DK specification)

Dependent variable	# runs	# negative	Min coef.	Median coef.	Max coef.
d_logGDP	21	21	-0.039	-0.030	-0.018
d_logGDPpc	21	21	-0.039	-0.028	-0.017

Notes: each run re-estimates the baseline DK model excluding one country at a time and records the coefficient on logHousing_1.

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Branchless Banking and Inclusive Growth: Comparative Evidence from European Emerging Economies

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Abstract: The paper investigates digital and traditional finance-related inclusive growth relationships in 17 emerging European economies during the period 2005-2022. The research employs the Panels-corrected standard errors (PCSE) model and the instrumental-variable generalized method of moments (IV-GMM) approach. The study finds that a CEE region with a relatively higher number of ATMs, coupled with individuals using the internet for internet banking experiences higher levels of human development than the SEE region, which has a lower level of development of branchless banking channels. The study concludes that, while branchless banking generally benefits human development, its impact is limited. In fact, the effect branchless banking on inclusive growth is more significant in the CEE region due to the higher institutional capacity and developed digital infrastructure. Conversely, in the SEE region, underdeveloped institutions and initial stages of digital finance can only have negligible or even negative consequences. This implies the need to adopt complementary policies, with the hope that campaigning for the adoption of branchless banking will go hand in hand with the quest to reinforce institutions and digital literacy, so that any digital financial innovation is converted into sustainable and inclusive economic growth.

Keywords: branchless banking; inclusive growth; emerging European countries; PCSEs model; IV-GMM approach.

JEL classification: C23; G20; G21.

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1. INTRODUCTION

The recent technological development has also helped to solve the sustainability issues to a very great extent. An example of sustainable practices and technology is the field of financial technology (FinTech), which has become a disruptive element in the financial sector (Cruz Rambaud and López Pascual, 2023; Atayah *et al.*, 2024). Many issues exist when financial technology (FinTech) and sustainability are integrated. Information technology (IT) can play an essential role in facilitating this integration in this context. According to Anshari *et al.* (2019), the combination of FinTech and digital markets has the potential to substantially enhance sustainability.

As liquidity providers, banks enable investment in more productive assets, thereby boosting capital accumulation and economic growth. However, a 2014 World Bank survey revealed that only about 50% of adults globally have access to formal financial institutions, partly due to the limited presence of these institutions in remote rural areas (World Bank, 2015). Willis *et al.* (2001) note that ITC have enabled banks to reorganize their networks to better serve various client needs. McKay and Pickens (2010) suggest that branchless banking is a potential way to reach the "unbanked" population, primarily in rural areas.

Although governments are committed to inclusive growth, market discrimination and poverty continue to prevent millions in developing countries from accessing financial services. This is what makes inclusive finance one of the priorities of the world as mentioned by the United Nations (2015). While some earlier research has focused on the technological basis, primarily mobile phones, and their integration into banking services (Luarn and Lin, 2005) some more recent research (Gupta *et al.*, 2015; Ganić, 2025) advocates policies that support both growth and inclusion. In some other studies, for example, Asongu and Le Roux (2017) find that the expansion of digital infrastructure (broadband internet, mobile telephony) in sub-Saharan African countries can negatively affect inclusive growth, suggesting that technology alone is not a universal solution.

However, there is a lack of research addressing the effects of branchless banking on inclusive growth. As a result, a more complex understanding of its dynamics has become an important component of the agenda. Often, decades of data are needed to examine the elements that shape inclusive growth and branchless banking. The ability to evaluate its impact was limited until recently because comparable global data on branchless banking were not available. In the current literature, there is very little concrete empirical evidence regarding the effects of branchless banking; additionally, a cross-sectional approach is frequently ignored, which results in measurement errors and cross-country heterogeneity. Additionally, there is a selection bias because research on the benefits of financial inclusion primarily concentrates on countries with favourable economic conditions. This indicates the necessity of addressing the issue of selection bias and examining the potential differences in effects across countries.

The precise impact that branchless banking has on inclusive growth is still unclear. By examining how branchless banking impacts inclusive growth, this study aims to fill that gap.

Although some research has been done on the connection between traditional finance and growth in the world the connection between digital and traditional finance and inclusive growth in the European emerging economies remains under researched. Accordingly, the purpose of this paper is to compare European emerging economies with other regions and to explore how the unique European institutional, regulatory and infrastructural framework shapes the impact of digitalization finance on inclusive growth. Our work provides the major contribution in terms of

developing a comparative analytical framework, which demonstrates that the efficiency of branchless banking does not have universal features, but varies depending on the degree of regional development. By doing so, the study extends beyond the limits of single case studies and shows that policies that concentrate on digital payments alone can be ineffective or even counterproductive in the SEE countries. It is particularly suggestive in the countries where the mere access to physical and digital infrastructure remains a pivotal assumption. This very possibility to carefully determine regional policy paths is what makes our research the value addition.

As a result, the empirical evidence in the existing literature is very limited that ignore heterogeneity across countries and institutional structures, with focus on countries with better economic conditions, which creates selection bias.

Therefore, it remains unclear what the real impact of digital payments on inclusive growth is with including institutional structures. This study seeks to fill this gap and empirically examine this relationship.

In fact, it brings several novelties to the existing empirical literature. First, with the help of the UNDP Human Development Index (HDI) (2024), we examine the contribution of digital and traditional finance-related inclusive growth relationships, which does not necessarily mean only growth in the economy. Economic growth is no longer an adequate measure of societal well-being. The goal is to ensure that the benefits of growth are distributed to include the more vulnerable and poor segments of the population, which is the essence of inclusive growth (Asian Development Bank, 2011).

Second, this research contributes to the body of literature on financial development and inclusive growth as it presents a new outlook which brings these two fields of study together in one analytical framework. Although past research mostly thinks of financial development and technology as independent growth factors, this area of research presents new findings that digital infrastructure can enhance the effectiveness of financial systems in ensuring inclusive economic performance. This wide evidence in the various emerging European economies lends a regionalization to a research territory that has largely been restricted to country-based research.

Third, this research is the first to empirically examine whether branchless banking matter for sustainable inclusive growth in 17 European emerging countries divided in two subregions: Southeastern Europe – SEE region (Albania, Bosnia and Herzegovina, North Macedonia, Montenegro, Serbia, Bulgaria, Romania, Türkiye) and the Central and Eastern Europe -CEE region (Czech Republic, Croatia, Poland, Hungary, Latvia, Lithuania, Estonia, Slovakia and Slovenia) indicating that the forces of inclusive growth in the more digitally advanced CEE region differ fundamentally with those in the SEE region.

2. LITERATURE REVIEW

There is a wide consensus among economists that financial development promotes economic growth. Several empirical studies examined the role of financial systems in economic growth of developing economies (Levine and Zervos, 1998; Rajan and Zingales, 2003). Through the demand or supply channel, financial development creates favourable conditions for growth, according to numerous theories. The expansion of the financial system aids economic expansion, according to Rajan and Zingales (2003). The main factor in economic growth was the accumulation of physical capital, according to early studies of economic growth. For example, according to early macroeconomic studies conducted in the

late 1980s and early 1990s, ICT did not contribute much to economic growth and productivity (Jorgenson and Stiroh, 1999; Oliner and Sichel, 2000).

However, in recent research, the idea of capital has been broadened to include technology and knowledge, which have become essential growth factors. Many endogenous growth models have tried to explain how technology and new knowledge the primary drivers of growth in recent years can be (Romer, 1990; Grossman and Helpman, 1991; Aghion and Howitt, 1992). Presenting ICT as an endogenous growth factor, the distinction between human capital and technology as embodied or codified knowledge is one of the essential features of these models. In endogenous growth models, where long-term growth is seen because of information technology (IT) development, ICT is a critical component of R&D.

Investment in telecommunications infrastructure has a significant effect on economic growth, according to most of the early empirical literature on the effects of telecommunications technology (Röller and Waverman, 2001; Toader *et al.*, 2018; Aghaei and Rezagholizadeh, 2020). In many cases, investment in telecommunications infrastructure can boost economic growth. According to Deng *et al.* (2019), patterns of economic growth significantly shape the relationship between FinTech and sustainable development. The competitive environment in the FinTech and banking sectors has been altered by the COVID-19 pandemic, according to Yan and Jia (2022).

The relationship between growth and financial inclusion has recently become more important in research (Demirgüç-Kunt *et al.*, 2017), but little is known about the impact of branchless banking on inclusive growth. Morison and Frazer (1982) published the first article on this subject. They examined banking services and the future of American banking, including the rise of non-branch banking. According to Richardson and Marshall (1996), this term refers to the delivery of banking services by means of ICT to provide retail services outside of physical bank branches. Suhrab *et al.* (2024) studied the connection between digital finance, financial inclusion and income inequality and found that technological innovation is essential in the Sustainable Development Goals. The authors propose that digital financial infrastructure has the potential to help close financial gaps and inclusive economic growth. Also, Pushp *et al.* (2023) investigated the moderating role of digital finance with economic development in India, and the researcher discovered that internet-based financial services enhance financial inclusion and support sustainable economic growth. Several studies indicate that technological integration – such as the spread of the internet, mobile networks and digital payments – increases market efficiency, reduces transaction costs and expands the reach of financial services (Odeleye and Olusoji, 2016; Ofori *et al.*, 2024; Saeed and Klugah, 2025). For example, the benefits of mobile banking and digital payments have greatly helped the unbanked population, enabling them to join the formal economy.

Through equal access to economic markets and resources, inclusive growth promotes equal opportunities in the economy, as the World Bank (2009) noted. Inclusive growth requires equity and growth, according to Zhang and Wan (2017). Allowing all economic actors to realize their economic potential, it includes economic equality and fair chances for all (Asian Development Bank, 2011). In other words, growth must be inclusive for a sustainable development plan to reduce poverty. In fact, through inclusive growth, the poor can obtain economic opportunities and basic services.

Governments, policymakers, and international development institutions put a high priority on inclusive growth, which presupposes achieving a more balanced distribution of the fruits of economic growth (Nizam *et al.*, 2020). Its success must be supported by the policies

that would not only be focused on the overall growth but also include the marginalized groups such as women, rural populations, and low-income families (Beşe and Friday, 2022). Inclusive growth is not confined to classical indicators of economic growth (e.g. GDP per capita). It does not only explain the dynamic but also the distribution of the benefits of growth (Anand *et al.*, 2013). As much as economic growth may be a critical condition, it does not suffice when the benefits thereof are not extended to extended parts of society. To illustrate this, the Asian Development Bank (2011) defines inclusive growth as growth that allows all categories of the population to share equally in the process and reap the gains of the same. In this paper, inclusive growth is measured by the Human Development Index (HDI). Sen (1999) perceived development in terms of opportunities and freedoms where people were able to lead lives, they find worthwhile while not just in terms of level of income. The HDI encompasses three important dimensions, namely, healthy life, education, and living standards. This way, when we examine the effect of branchless banking on the HDI, we are in effect evaluating how it will positively influence these fundamental dimensions of human development. This renders the HDI as a sound and covering indicator to measure inclusive growth.

It is a known theoretical relationship that exists between financial services and economic development. Indicatively, Schumpeter (1911) is among the original thinkers who emphasized the significance of financial intermediaries in promoting growth and innovation by enhancing the efficient allocation of capital. This knowledge has also been used to entrench the current concept of financial inclusion, which states that increasing access to financial services can alleviate inequality and poverty (Demirgüç-Kunt *et al.*, 2017).

Branchless banking as a more technologically advanced form of financial services delivery can operate through several channels:

First, digital channels (ATMs, online payments, mobile banking) allow a larger group of the population, including rural and previously unreachable ones, to enter the formal financial system because they simplify the process and do not need physical barriers (Auer *et al.*, 2023; Tombini, 2024). Second, efficiency and empowerment channel where digital banking saves time and costs on transactions, making more resources available to households to invest further in health and education, which are major areas of the HDI (Mushtaq and Bruneau, 2019; Mburamatare *et al.*, 2025). And third, human capital investment channel where availability of better finance can help overcome credit restrictions and greater investment in health and education, which directly enhances long-term inclusive growth (Sarwar *et al.*, 2021; Opoku *et al.*, 2024).

Nevertheless, theory also leaves the possibility of heterogeneous effects—technology is not sufficient. It affects it based on the conditions of institutions, rules, and digital infrastructure (Asongu and Le Roux, 2017). The strength of these channels will, however, differ among countries.

Different European countries have different access to credit markets. Sinclair (2013) examines financial inclusion in the United Kingdom in a broader European context. He points out that, for low-income clients, there were issues with accessing basic banking services and that there was a shortage of credit that was appropriate and affordable. Additionally, there is a controversy over whether British banks have taken away services from communities in need or taken away services from people with lower incomes. According to Collard (2007), the effects of being excluded from the formal financial sector are becoming more serious as the United Kingdom moves towards cashless businesses. Fonté (2012) argues that, in the United States, mobile payments can increase access to financial services at a lower price point; however, he cautions that advertising is more focused on the wealthy than on financial inclusion.

Ganić (2025) studies the relationship between digital and traditional finance-related poverty reduction relationships, including the mediating role of European Union membership in 18 countries (2004–2021) by using panel data regression models. The findings indicate that the dominant method of poverty reduction through banking institutions remain the traditional financial inclusion instruments, such as bank accounts and bank branches, while digital financial channels have not yet fully realized their poverty-fighting potential.

Alekhina and Ganelli (2023) explored the elements that might help make growth more even in ASEAN countries. Investigating the determinants of inclusive growth in 14 Latin American countries (1995–2019), Angulo-Bustinza *et al.* (2023) found that it was driven by fiscal redistribution, women's labor force participation, productivity, digitalization, savings, and foreign direct investment. While inflation, unemployment and the occurrence of crises have a negative effect on inclusive economic growth, public spending and international trade have a positive effect on it. Using a particular measure that combines income distribution and growth, Hussein *et al.* (2017) examined the current state of inclusive growth in Africa between 2000 and 2015. To achieve inclusive growth in Africa, they emphasize the importance of macroeconomic policies (fiscal and monetary), high-quality governance and institutions, and information and communication technologies (ICT). Existent research recognizes that increase in financial inclusion in developing countries are increasingly dependent on technology, such as electronic payments, mobile banking, and advances in financial technology (De Koker and Jentzsch, 2013). The significant role of ICT in the social and economic advancement of the last decade is emphasized by the increasing literature on ICT and economic development, as stated by Mushtaq and Bruneau (2019).

The complicated connection between sustainability and IT adoption has been studied in several studies. A critical assessment of the impact of information technology on sustainability and significant research findings are the centre of this discussion. Several studies stress that sustainability must be incorporated with technologies like FinTech (Callsen *et al.*, 2021; Battisti *et al.*, 2023), blockchain technology (Mercuri *et al.*, 2021) and ICT (Ahmed *et al.*, 2021; Sahoo *et al.*, 2024).

The potential of mobile banking and digital payment platforms has already been demonstrated in terms of accessing groups of the population that cannot access traditional banking facilities and making them participants in the formal economy. Although technology is not enough to eliminate all barriers, a combination with financial systems contributes considerably to the ability to reach economic inclusion and increase efficiency, particularly in the underserved areas (Saeed *et al.*, 2024; Sahoo *et al.*, 2024; Saeed and Klugah, 2025).

When it comes to the connection between inclusive growth and branchless banking, most of the evidence is found at the micro-level, at the individual level. In fact, very little research has been done on this subject at cross-regional context, despite the possibility that branchless banking can positively affect these aspects. Mohamed and Elgammal (2024) found out that the greater the use of branchless banking in 2,996 MFIs in 123 countries, the better the productivity and social reach. Equally, Bruhn and Love (2014) discover that more financial services can boost incomes of low-income earners and enhance the expansion of informal businesses in Mexico while Burgess and Pande (2005) find that the proliferation of bank branches can alleviate rural poverty in India. These results are however doubted by Panagariya (2006) and Kochar (2011).

Financial integration, income inequality, economic growth, and institutional quality are the main subjects of most of the available literature on inclusive growth and finance. In addition, so far, research has mainly concentrated on individual countries, specific economies in panel

studies, or developing countries from Asia and Africa. Nevertheless, no empirical research has examined the connection between branchless banking and inclusive growth, particularly in the context of Eastern European economies; this issue has also not been examined in any study. A noticeable gap in the literature regarding the effects of branchless banking on inclusive growth is the focus of this study because the role of branchless banking in inclusive growth remains scarce. In less developed countries, especially when it comes to the Sustainable Development Goals (SDGs), increasing economic growth is not a primary concern, according to development literature. Researchers and policymakers are more interested in growth that lowers unemployment, poverty, and income inequality Ajide *et al.* (2021).

The hypothesis development

Despite the high-profile coverage concerning the micro advantages of digital finance, macro empirical evidence regarding the role of digital finance in the inclusive growth of the emerging European economies is mixed (Ganić, 2024; Mohamed and Elgammal, 2024). However, the theoretical effects may be heterogeneous. This research, in accordance with the defined theoretical mechanisms (access, efficiency, and human capital), assumes that digital finance positively affects inclusive growth. This expectation is supported by empirical findings that digital payments can enhance productivity and social outreach (Mohamed and Elgammal, 2024), serve as a tool for financial inclusion to decrease inequality and poverty (Hussein *et al.*, 2017; Wong *et al.*, 2023; Azmeh, 2025; Ganić, 2025; Memon *et al.*, 2025), and ultimately lead to high inclusive growth (Rahman *et al.*, 2020; Ganić, 2024). As Asongu and Le Roux (2017) state, the institutional and regulatory environment mediates the effect of the presence of digital technology, and it does not necessarily lead to positive consequences. We hypothesize these channels will be stronger depending on the current institutional quality and level of digital infrastructure of a region, a factor that can be seen in the work of other researchers who discover diverging impacts between old and new EU member countries (Ganić, 2024, 2025).

Based on this, we test the following hypotheses:

H1*: Penetration of branchless banking services (ATMs, digital payments, internet banking) has a positive effect on inclusive growth (HDI) in emerging European economies.*

H2*: The positive effects are more pronounced in Central and Eastern European countries as compared to Southeastern European countries because of superior institutional frameworks and elevated digital readiness.*

3. METHODOLOGY AND DATA

3.1. Data and Variables

Inclusive growth (IG) is the dependent variable in our econometric models proxied by the UNDP's HDI index to measure three facets of human development: education, life expectancy, and standard of living. In this research, we considered two different kinds of explanatory variables. Three distinct measures of branchless banking constitute the first category: the number of ATMs per 100,000 adults, the proportion of people over the age of 15 who have made or received a digital payment, and the proportion of people who use the Internet for online banking. Set of control economic variables constitutes the second type of

variables including: inflation, unemployment rate, population growth rate, financial development and institutional quality.

Using the Panels corrected standard errors (PCSEs) model and the generalized method of moments (IV-GMM), we empirically analyse how different indicators of branchless banking affect inclusive growth, as measured by the Human Development Index (HDI). We also include selected economic control variables in our analysis to assess their impact on inclusive growth. To examine the dynamic relationships and determinants of branchless banking and inclusive growth in the CEE countries and the SEE countries panel data techniques are employed. To fulfil the research objectives, the study considers the following variables (as shown in Table no. 1). These variables are derived from the existing empirical literature.

Table no. 1 – Summary of variables used in regression model

Variable	Description	Data Source
HDI (inclusive growth proxy)	The Human Development Index (HDI) is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and having a decent standard of living.	UNDP (2024)
ATM	Automated teller machines (ATMs) (per 100,000 adults)	World Bank (2024)
DIGPAY	Made or received a digital payment (% age 15+)	World Bank (2024)
IIBAN	Individuals using the internet for internet banking	European Comission Eurostat (2024)
UNEMPL	Unemployment, total (% of total labor force) (modeled ILO estimate)	World Bank (2024)
INFL	Inflation, consumer prices (annual %)	World Bank (2024)
POPGR	Annual population growth rate for year t is the exponential rate of growth of midyear population from year t-1 to t, expressed as a percentage.	World Bank (2024)
FINDEV	Domestic credit to private sector (% of GDP)	World Bank (2024)
INSTQ	Institutional Quality index based on World Governance indicators	Author's calculation

Source: author's elaboration

The HDI is employed in the study as an indicator of inclusive growth because it includes living standards, life expectancy, and education Adeleye *et al.* (2023); Parvez *et al.* (2023). The world is not only worried about the growth but also the reduction of inequality and poverty among policymakers (Osinubi and Olomola, 2020; Ajide *et al.*, 2021; Adeleye *et al.*, 2023). Klasen (2010) stresses the role of measures that are not limited to income. Three independent variables of ATM, DIGPAY and IIBAN are employed as proxy variables for measuring the level of the branchless banking. The idea of branchless banking combines significant advances in the delivery of banking services outside of conventional branches. As a tool for financial inclusion, ICT has the potential to speed up inclusive growth, decrease inequality and poverty. The concept means the delivery of banking services in different forms, namely, ATMs, e-banking, and mobile banking. As Stegman *et al.* (2005); Hussein *et al.*

(2017); Rahman *et al.* (2020); Mohamed and Elgammal (2024); Ganić (2025) all argue, branchless banking can have high inclusive growth. A variable of inflation rate is used to control macroeconomic stability. High inflation exacerbates inequality by forcing the poor to cut spending. Studies by Dollar and Kraay (2003); Anand *et al.* (2013); Hussein *et al.* (2017) and Barro and Lee (2001) show that moderate inflation can promote more inclusive growth.

The link between inclusive growth and institutional quality is often overlooked. From an institutional-economic perspective, inclusive growth depends on whether institutions are inclusive and if all members of society can contribute effectively to economic life and income generation. The rule of law, political stability, and other governance indicators are linked to greater economic growth, according to some studies (Dollar and Kraay, 2002; Resnick and Regina, 2006). According to a study conducted by Doumbia (2019), only the rule of law and government efficiency contribute to inclusive growth in a sample of 112 countries from 1975 to 2012. Similarly, Parvez *et al.* (2023) find in 25 developing Asia countries that institutional quality can improve human development. Following the studies above it is expected that institutional quality has a positive effect on inclusive growth. Therefore, we expect that an increase in institutional quality leads to the growth.

We assume that unemployment rates have a negative sign in relation to inclusive growth. This can be explained by the fact that high unemployment rates contribute to poverty by limiting people's access to earning opportunities, which negatively affects inclusive growth (Cysne, 2009; Castells-Quintana and Royuela, 2012; Angulo-Bustinza *et al.*, 2023). It anticipates a direct statistically significant relationship between inclusive growth and the unemployment rate a priori while rise of employment lead to higher inclusive growth and vice versa.

We are inconclusive on the impact of population growth on inclusive growth. One strand of the literature suggests mixed results where population growth deteriorates the level of inclusive growth in Africa (Tella and Alimi, 2016; Ajayi and Oburota, 2020). On the other hand, Parvez *et al.* (2023) documented a negative association between population growth and inclusive growth. Therefore, the relationship between population growth on inclusive growth can be positive or negative, depending on whether population growth is anticipated or not.

At the modern stage of the rapid shift to the digital world and the inability to eliminate inequality across the globe, the understanding of the connection between technology and financial systems in the context of their collaboration in ensuring inclusive growth gains an even greater relevance (Kouladoum, 2023; Huang, 2024; Ofori *et al.*, 2024). Although financial development has traditionally been known to propel economic growth, the role of financial growth in making growth more equitable and sustainable is increasingly reliant on the degree of digital maturity and technology adoption at the country level. To consider financial development, we include domestic credit to the private sector (a percentage of GDP) in our analysis. It is assumed that financial development can create conditions for social mobility and reduction of unemployment. We anticipate that it will positively promote inclusive growth. According to the literature on economic growth, the effort to examine the connection between financial sector development and economic growth is represented by the selection of this measure.

The expansion of the financial system aids economic expansion, according to Rajan and Zingales (2003); Hussein *et al.* (2017) although Ganić *et al.* (2016) found mixed results in the case of Bosnia and Herzegovina. However, in some other studies (Ibrahim *et al.*, 2024; Nassani *et al.*, 2025), a U-shaped relationship has been observed between financial development and inclusive growth and is effectively based on the quality of regulation and the capacity of financial institutions to cater to vulnerable groups.

3.2. Model Specification

The literature review reveals a gap in research on the impact of branchless banking on inclusive growth in Eastern European countries (2005–2022), where inclusive growth requires certain preconditions in addition to economic growth. The macroeconomic environment, consistent inflation rates, population growth, improved quality of institutions, financial development and stable inflation levels, especially for vulnerable and excluded groups, are important determinants for improving living standards. Higher employment is a key objective of inclusive growth.

In our econometric model, these factors, including branchless banking variables, were selected to assess their effects on inclusive growth. In this research, principal component analysis (PCA) is employed to determine INSTQ index. The representation of the factors is justified by the fact that there is a significant correlation between six Worldwide governance original variables (Control of corruption, Rule of Law, Government effectiveness, Voice and Accountability, Regulatory quality, and Political Stability and Absence of Violence/ Terrorism). The quality of institutions is measured by the variable INSTQ (Table no. A1 and no. A2 from Annex). The KMO index (0.8203) shows the suitability of the sample for principal component analysis (PCA), which is justified in this case. Table no. A1 and no. A2 contain details on the calculation of INSTQ.

The study hypothesis that there is a positive association between inclusive growth and branchless banking. For panel data, the following general linear regression model is taken into consideration:

$$HDI_{i,t} = \alpha + \beta_1 BB_{i,j,t} + \beta_2 CV_{i,k,t} + \mu_i + \epsilon_{i,t} \quad (1)$$

where HDI is proxy for inclusive growth, BB refers to vector of branchless banking variables which measure the $BB_{i,j,t}$, development in country i at time t for $j = 1,2,3$ are : ATM, IIBAN and DIGPAY, $CV_{i,k,t}$ is vector of control variables in the model of country i, at time t, for $k = 1,2..,5$ (UNEMPL, INFL, POPGR, INSTQ, and FINDEV), $\epsilon_{i,t}$ represents general error terms and μ_i refers to the individual- specific component.

The country in the panel data and time (year) in the model is represented by (i, t), while intercept is presented with α. Vectors that contain the coefficients from the equations related to our three main variables in branchless banking are represented by the estimated coefficients, β_1 and β_2.

To condense the six selected Worldwide governance indicators into one index of Institutional quality, the study used the PCA technique. This method can be used to express the index of the jth factor as:

$$Index_j = W_{j1}X_1 + W_{j2}X_2 + W_{j3}X_3 + \cdots . W_{jP}X_P \quad (2)$$

where $Index_j$ is the Institutional quality index; Wp is the factor weighting coefficient; X is the corresponding original value of the components; and P is the number of variables in the equation.

According to Baum *et al.* (2007), in the event that economic growth is endogenous – that is, if it is associated with error, which can result in inaccurate conclusions and biased results – instrumental variable techniques are employed within the context of the generalized method of moments (IV- GMM).We examined several instrumental variables and performed

regressions with lagged endogenous variables, where the results could be impacted by reverse causality and endogeneity. A dynamic panel model is shown in this context. When estimating a dynamic model with the equation (3), the generalized method of moments (GMM) is primarily employed in panel data econometrics as follows:

$$HDI_{it} = \rho HDI_{i,t-1} + \beta_1 BB_{i,j,t} + \beta_2 CV_{i,k,t} + \mu_i + \epsilon_{it} \quad (3)$$

4. EMPIRICAL RESULTS

Table no. 2 illustrates the relationships between the variables, showing both positive and negative partial correlations. According to this data, inclusive growth is positively correlated with ATM, IIBAN, DIGPAY, POPGR, INSTQ and FINDEV highlighting the importance of these branchless banking proxies. Conversely, inflation and unemployment are negatively correlated with inclusive growth. Other explanatory variables also show varied positive and negative correlations. No multicollinearity is detected, as all correlation coefficients are below 0.80.

The lower section of Table no. 2 provides the summary statistics of the variables. The average HDI for 17 Eastern European countries from 2005 to 2022 is 0.818. The lowest value was recorded by Albania at 0.687 in 2005, while Slovenia had the highest at 0.921 in 2020. On the index of institutional quality, the average value is 0.0346, and the standard deviation of 1.8419 indicates that the subregions are distributed around the sample mean. The minimum value is −4.203, while the maximum is 3.398. The number of ATMs (per 100,000 adults) ranged from 4.23 to 156.8, with an average value of 60.946 and a standard deviation of 24.926. The share of individuals using the Internet for online banking varied from 0.63% (Romania, 2005) to 83.36% (Estonia, 2022), while the share of those who made or received a digital payment (% over 15 years old) varied from 0.204 (Albania, 2009) to 0.98 (Estonia, 2022).

Additionally, the mean VIF is 3.10, and the 1/VIF values range from 0.132691 to 0.75901. It indicates there is no serial multicollinearity.

Table no. 2 – Pairwise Correlation matrix and Summary statistics

	HDIindex	ATM	IIBAN	DIGPAY	POPGR	UNEMPL	INFL	INSTQ	FINDEV
HDIindex	1								
ATM	0.5165***	1							
IIBAN	0.7631***	0.2143**	1						
DIGPAY	0.7615***	0.3456***	0.8704***	1					
POPGR	.1847 *	0.0151	0.0132	0.0351	1				
UNEMPL	-0.689***	-0.318***	-0.420***	-0.536***	-0.176*	1			
INFL	-0.1730 *	-0.1501	-0.1631	-0.1047	0.1115	-0.0318	1		
INSTQ	0.6928***	0.2720***	0.630***	0.7008***	0.1837*	-0.5961	-0.093***	1	
FINDEV	0.1207	0.4561***	0.1518	0.0889	0.1394	0.0772	-0.0234	0.1369	1
Summary statistics - Multicolinearity issue									
Mean	0.8180	60.946	29.864	0.6698986	-0.34621	11.82394	4.024227	0.03463	50.13778
Max	0.921	156.8	83.36	0.9865141	1.570973	37.32	72.30884	3.39849	101.388
Min	0.6872	4.23	0.63	0.2046092	-6.18725	2.015	-1.5448	-4.2033	17.95247
Standard dev.	0.0520	24.92	23.26	0.2048235	0.81766	7.152937	5.589804	1.84193	14.29938
1/VIF	-	0.616	0.132	0.18051	0.75901	0.557948	0.593894	0.27749	0.597719

Note: *, **, ***means significance of the tested variables at 10%, 5%, 1% levels.

Source: author's calculation

The cross-country dependence test (CSD) identifies the suitable analysis methods. Due to close associations and shared attributes, panel units face a high risk of cross-dependence. Pesaran (2004) notes that this can lead to biased estimates and conclusions. Moreover, the study conducts a preliminary check of cross-sectional dependence, stationarity, and cointegration to assess the impact of branchless banking on inclusive growth. To prevent biased estimates due to high correlations between countries, the CSD statistics test is applied (Pesaran, 2004, 2015). This test is appropriate for different panel models, robust against structural breaks, parameter heterogeneity, and non-stationarity, and relies on the correlation coefficients between unit pairs.

Furthermore, following Pesaran's methodology (2004), the study applies the unit root test for heterogeneous panels with cross-dependence once it has found that there is cross-dependence. Each series is non-stationary according to the null hypothesis. To eliminate dependence across regressions and panels, the test is performed by means of the augmented Dickey-Fuller approach (CADF), which raises the cross-sectional averages of the residual levels and the first differences of the series.

Table no. 3 – Preliminary check estimates

Variables	CSD statistics	PESCADF		Kao cointegration test	
		I(0)	I(1)		
HDIindex	47.721***	-1.985	-2.385***	Modified Dickey-Fuller t	-1.6112**
ATM	30.282***	-1.991	-2.385***	Dickey-Fuller t	-2.3867***
IIBAN	37.624***	-1.143	-1.656*	Augmented Dickey-Fuller t	-1.647**
DIGPAY	35.607***	N/A	N/A	Unadjusted modified Dickey-Fuller t	-1.6566**
POPGR	3.552***	-1.164	-2.204**	Unadjusted Dickey-Fuller t	-2.4096***
UNEMPL	26.041***	-2.518***	-2.670***		
INFL	24.433***	-1.670	-2.654***		
INSTQ	1.983**	-0.861	-2.959***		
FINDEV	9.342***	-1.867	-2.233**		

Note: *, **, ***means significance of the tested variables at 10%, 5%, 1% levels.

Source: author's calculation

The results in Table no. 3 indicate cross-sectional dependence among countries, as the null hypothesis of cross-sectional independence is rejected for all variables at the 1% significance level and for the INSTQ variable at the 5% level. Additionally, panel unit root tests (PESCADF) show that after applying the first difference, the variables became stationary at significance levels of 1% (HDIndex, ATM, UNEMPL, INSTQ), 5% (POPGR, FINDEV), or 10% (IIBAN). The variables DIGPAY could not be computed due to insufficient data. The all five Kao tests for cointegration reject the null hypothesis of no cointegration, confirming that all panels in the data are cointegrated (Table no. 3).

Panel-corrected standard errors (PCSE) are used to address heteroscedasticity and autocorrelation in panel data, which improve the accuracy of estimates by correcting for spatial correlation and heteroscedasticity. Before applying PCSE, it is important to consider all types of serial correlation (Table no. 4).

Table no. 4 – Panels corrected standard errors (PCSEs) output

	Full Sample 1	CEE region 2	SEE region 3
ATM	.0003185*** (.0000356)	.0002351** (.0001158)	.0005757*** (.000112)
IIBAN	.0005854*** (.0000855)	-.000797*** (.0001658)	.0010348*** (.0001206)
DIGPAY	.0014502 (.0065166)	.01114318*** (.0197901)	-.0670715*** .0074527)
POPGR	.0068331*** (.0020797)	-.0003127 (.0013462)	.0016336 (.0014578)
UNEMPL	-.0017898*** (.0001434)	-.0039078*** (.0002874)	-.0014568*** .0001648)
INFL	-.0000386 (.0002883)	-.000196 0006005)	-.0003949 (.0003202)
INSTQ	.0093097*** (.0008283)	.022192*** (.0016171)	-.0011971*** .0021568
FINDEV	-.0002845*** (.0001021)	. -.0004227*** (.0000717)	-.0003301* (.0001936)
Constant	.826776*** (.003074)	.8158777*** (.0071658)	.6596276*** (.0230892)
Observations	188	92	101
Number of groups	17	8	9
Wald χ^2 (8)	20506.77	1673.40	2082.96
Prob > χ^2	0.0000	0.0000	0.0000

Note: *, **, ***means significance of the tested variables at 10%, 5%, 1% levels. Standard errors are in brackets.
Source: author's calculation

Table no. 4 of the PCSE estimation model reveals that the connection between branchless banking and inclusive growth is not exclusive. Indeed, it varies within geographical clusters. The divergent experiences in the CEE region and the SEE region confirm the fact that the new European economies cannot be perceived as a homogeneous group. These variations are mainly due to the various levels of development. For example, CEE countries possess more advanced digital infrastructure, better institutions, and higher GDP per capita, which makes the adoption of digital financial services much broader and more effective. By comparison, SEE countries have weaker institutions, weak financial intermediation and greater dependence on cash and physical banking infrastructure.

The ATM coefficient (0.0003185) in the full sample is positive at the 1% significance level, which supports the view that ATM infrastructure as a central aspect of branchless banking has a positive effect on inclusive growth in emerging European nations. The effect size is regionally different. To illustrate, the coefficient of ATM is higher in the SEE region (0.0005757) at the 1% significance level, implying that a positive effect of increasing the density of ATMs on inclusive growth is greater in that area. Conversely, the coefficient of ATMs in the CEE is positive at the 5% significance level but lower (0.0002351). This implies that the ATM is an important channel of access to finance, particularly in the SEE region where it is a more significant aspect of inclusion in the formal financial system than in the more digitally advanced CEE economies. Our findings agree with previous studies for emerging markets (Stegman *et al.*, 2005; Hussein *et al.*, 2017; Rahman *et al.*, 2020; Mohamed and Elgammal, 2024; Ganić, 2025).

Moreover, for the full sample, the variable internet banking (IIBAN) is positive at the 1% significance level; thus, an increase of 1 percentage point in internet banking usage increases the

HDI by 0.0005854 on average. The effect may appear minor, but in the narrow (0–1) range of HDI, its time-based sum is not insignificant. A coefficient of IIBAN (-0.000797) is negative at the 1% significance level in the CEE region. Internet banking is already very commonplace in the digital and banking societies that are highly developed, and no additional inclusion is brought by further growth. The negative correlation can also reflect unobserved variables, such as population aging or market saturation, in which mere internet banking no longer reflects actual growth in inclusiveness. Conversely, the coefficient of IIBAN in the SEE region is positive at the 1% significance level, and in line with Suhrab *et al.* (2024) and Pushp *et al.* (2023). The growth of internet banking is a notable development of the accessibility of the financial sector, particularly to the urban population and the middle classes, whereby cash and ATM transactions are substituted with the online platform. This transition not only saves time and costs but also increases HDI dimensions directly and is a strong determinant of inclusive growth.

At the 1% significance level, the coefficient of DIGPAY for the CEE region is positive. The high use of digital payments in developed digital economies leads to the efficiency and formalization of transactions and e-commerce. These findings align with previous research conducted in developing and emerging economies (Hussein *et al.*, 2017; Rahman *et al.*, 2020; Mohamed and Elgammal, 2024).

Conversely, the coefficient of the DIGPAY in the SEE region is negative at the 1% significance level (-0.0670715), and this could be a sign of a digital divide. Any initial development of digital payments in less developed countries tends to have a temporary effect of increasing inequality on certain more technologically and financially endowed groups. Provided that the returns to digitization remain concentrated in a small elite, there is a risk of adverse impacts on inclusive growth (HDI). Moreover, such forced formalization in these areas can be detrimental to such sectors that rely on cash, more so without safety nets and without digital literacy.

In the case of the institutional quality variable (INSTQ), the essential role of institutions is supported by the positive and statistically significant value of the coefficient at the 1% significance level in the full sample and the CEE region (0.0093097 and 0.022192, respectfully). Good governance, rule of law, and corruption control provide an enabling environment for the diffusion of benefits of both financial and technological innovations. The coefficient of the INSTQ in the CEE region is higher, which means that institutional changes in more developed and stable situations have higher returns. Comparatively, in the SEE region, the coefficient of INSTQ is negative/influential. This finding implies that institutional quality in the SEE region does not efficiently translate into inclusive growth, perhaps because weaker institutions, narrow interest structures, or the influence of other crucial determinants (e.g., underlying macro stability or post-conflict dynamics) are stronger than the governance dimensions represented by the INSTQ index. According to the findings, countries with high-quality institutional systems can promote inclusive growth, decrease increasing inequalities in income distribution, and lower poverty (Adeleye *et al.,* 2023; Parvez *et al.,* 2023).

The unemployment findings acknowledge a theoretically valid, traditional negative relationship at the 1% significance level, with a greater influence in more formalized the CEE economies (-0.0039) compared to the SEE economies (-0.00145). It is in line with some previous research done by Cysne (2009), Castells-Quintana and Royuela (2012), Angulo-Bustinza *et al.* (2023). This implies that even in more formalized and productive CEE economies, job losses are far more damaging to inclusive growth, as social protection is more directly linked to formal employment. In SEE countries, the relative degree of dominance of

the informal economy partially mitigates the effects of unemployment, and thus the official unemployment rate does not reflect the real loss of living standards as effectively.

The results of financial development (FINDEV) on inclusive growth are very indicative. The negative value of the coefficient of all groups indicates that a current level of financial development in the countries under studied is not inclusive. This is more pronounced in the CEE region at the 1% significance level (−0.0004227), and this could be a sign of saturation of the financial system and more intense unproductive lending. The same trend can be observed in the SEE region at the 10% significance level (-0.0003301. This is an indicator of an organizational flaw in the distribution of financial resources. In other words, credit is not likely to go to the productive real sphere and poor households, but rather to concentrated groups that fail to bring about inclusive growth. It is in line with Ibrahim *et al.* (2024) and Nassani *et al.* (2025) and might be explained that financial development is useful, its effectiveness depends on the quality of regulation and the ability of financial institutions to serve vulnerable groups.

Even though the sample is quite limited (N=188), the methodologies applied are very robust to this data structure. The PCSE model is a model of large T, small N, as it removes heteroscedasticity and inter-panel correlation that typically exists in macro panels. Furthermore, endogeneity can be considered by the IV-GMM estimation (Table no. 5), and high Hansen p-values (0.4840; 0.2637; and 0.7939) justify the soundness of the instruments. The fact that the results from the PCSE and GMM specifications are consistent, despite the limited sample size, goes a long way towards making this paper's results credible.

Table no. 5 – IV-GMM output

	Full Sample 1	CEE region 2	SEE region 3
ATM	.0002965*** (.0000676)	.0002185** (.0001032)	.0005011*** (.0001717)
IIBAN	.0006595*** (.000188)	-.0007999*** (.0001222)	.0011369*** (.0002662)
DIGPAY	.0019633 (.017769)	.110691*** (.0206221)	-.0647086*** (.0170804)
POPGR	.008399*** (.0020245)	.0000514 .0014916)	.0029439 (.0019225)
UNEMPL	-.0019139*** .0002728	-.0040224*** (.00029)	-.0016095*** (.000353)
INFL	-.0010435 (.000919)	-.0006951 (.0009477)	-.0012098 (.0008215)
INSTQ	.0077127*** (.0017768)	.0219904*** (.0014521)	-.0014639 (.0028626)
FINDEV	-.0002421** (.0001294)	-.0004077 *** (.0000963)	-.0002566 (.0002528)
Constant	.8309856*** (.0088482)	.8190179*** (.0109138)	.8252542** (.0122288)
Observations	188	92	100
Number of groups	17	8	9
R-squared	0.8132	0.8585	0.6498
F-statistics	133.60 Prob > F = 0.0000	78.46 Prob > F = 0.0000	29.41 Prob > F = 0.0000
Hansen p-value	1.451 (0.4840)	2.666 (0.2637)	0.461 (0.7939)

Note*:* *, **, ***means significance of the tested variables at 10%, 5%, 1% levels. Standard errors are in brackets

Source: author's calculation

The system IV GMM findings used to check robustness for the full sample, SEE countries, and CEE countries are presented in Table no. 5. For most of the selected variables, the findings demonstrate strong consistency, as most of the regression coefficients support the robustness of the results.

5. CONCLUSION

The study examines whether new financial technologies and branchless banking can support inclusive growth across 17 emerging European economies. The main determinants of this trend are, specifically, the accessibility of ATMs and internet banking. Although these technologies have a favourable impact on human development across the board, in CEE region, the use of digital payments has a particularly large impact. The efficiency of branchless banking differs depending on the location. For example, in SEE region, digital payment usage is not as prevalent. However, the selection of proxy variables affects the growth or development of branchless banking. One of the branchless banking indicators had a negative correlation with human development, while the other had a positive correlation; three indicators together did not demonstrate a meaningful impact. These findings show the many impacts that, depending on how they are applied within the financial system, various branchless banking variables may have.

The findings support H_1, confirming that branchless banking has a positive impact on inclusive growth in emerging European economies, although the magnitude of the effect varies by service type and region. The results also support H_2, showing that institutional quality and digital readiness enhance the benefits of branchless banking. As a result, inclusive growth is more pronounced in the CEE region compared to the SEE region. More specifically, in regions with stronger institutions and developed digital infrastructure (CEE), the benefits of branchless banking are particularly pronounced. However, some digital finance measures (e.g. early-stage digital payments) may have negative or negligible effects in weaker institutional environments, such as the SEE region. The importance of these complementary policy findings is that the expansion of branchless banking should be accompanied by initiatives to strengthen the institutional framework and digital literacy, in order to maximize inclusive growth.

According to the results, increases in the number of ATMs and in internet banking use are significant predictors of the institution's development, even after controlling for regional and macroeconomic factors. Conversely, the impact of internet banking implies that the quality of digital access in more complex financial processes is more developmental than the presence of the internet itself. It means that the digital financial literacy policies may be more efficient than the just infrastructure expansion.

Moreover, the empirical findings show that the processes of inclusive growth vary greatly across regions. Although both regions enjoy the advantages of branchless banking, in the CEE region, the most important aspect is the development of the digital ecosystem on the premise of the digital payment (DIGPAY) whereas basic internet banking (IIBAN) has been decreasing returns lately. Conversely, in the SEE region inclusive growth is still mostly associated with the growth of physical access points (ATMs) and simple internet banking (IIBAN). This implies a circuit of financial development, in which the technological efficiency of the industrial sector evolves with the institutional and digital maturity of the area.

Furthermore, efforts to improve institutional quality must be considered to promote inclusive growth, maintain macroeconomic stability, and boost employment. The results

underscore the significance of broadening the scope of branchless banking services and enhancing institutional frameworks to promote inclusive growth within these economies. Using mobile banking, payment cards, and electronic payments more frequently can offer several benefits, including reducing cash use, which will save costs for banks and individuals alike. First, it has been shown that despite its positive effects on human development, the impact of branchless banking remains limited. Second, although the current level of financial development in emerging European economies is not conducive to improving human development, improved institutional quality can contribute significantly to human development.

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ANNEX

Table no. A1 – Corelation matrix including INSTQ and Institutional variables

	INSTQ	CCOR	GOVE	PSAV	REQ	VAAC	ROLAW
INSTQ	1.000						
CCOR	0.9128	1.000					
GOVE	0.9268	0.8554	1.000				
PSAV	0.8542	0.6442	0.7305	1.000			
REQ	0.9146	0.7932	0.8122	0.7218	1.000		
VAAC	0.9368	0.8309	0.7905	0.8483	0.8171	1.000	
ROLAW	0.4531	0.5196	0.4117	0.2889	0.3979	0.4325	1.000

Source: author's calculation

Table no. A2 – PCA and Eigenvectors

Variables	Sample
Kaiser-Meyer-Olkin measure of sampling adequacy (overall)	0.8203
The highest value of PCA eigen vectors	4.39064
Proportion explained	0.7318

Source: author's calculation

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Do CEOs Characteristics Affect Banks' Risk-Taking? International Evidence

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Abstract: We examined the effect of CEO characteristics on bank risk-taking. The study collected data from of 540 international banks from 2011 to 2023, resulting in a panel that had 6,825 observations. A fixed-effects panel regression model was used to analyze the relationship between CEO attributes and risk-taking in banks. Bank risk-taking is measured by using a Z-score, non-performing loans, and standard deviation of volatility. The analysis indicates that CEOs with younger age, greater experience, and postgraduate degrees are more inclined to take on risky decisions. Furthermore, we find a significant positive relationship between CEO experience and risk-taking behavior in banks. The findings indicate that female CEOs tend to be more risk-averse than their male peers. The findings from this study have played a role in shaping regulatory policies aimed at decreasing bank risk, such as requirements for transparency in CEO decision-making and improved oversight of corporate governance practices. By analyzing a large sample of banks across different countries, the study provides empirical evidence on this relationship, contributing to the literature on corporate governance and risk management in the banking sector. The results may have important implications for regulators, shareholders and boards of directors in their assessment and selection of bank executives.

Keywords: CEO characteristics; CEO age; CEO gender; CEO education; bank risk-taking.

JEL classification: G30; G32.

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1. INTRODUCTION

The performance of a bank is indicative of how effective its management team has utilized its assets to enhance shareholder value (Gupta and Mahakud, 2020; Ur Rehman *et al.*, 2022; Menicucci and Paolucci, 2023). This responsibility primarily falls on the Chief Executive Officers (CEOs), who lead the company and whose decisions are crucial for assessing their performance (Brahma and Economou, 2024). These decisions are ultimately mirrored in the company's reported profits and stock price.

Many factors can influence the decision-making process and bank performance (Hai and Diem, 2024). Human capital theory posits that an individual's education, experience, and skills influence their perception and productivity, thereby enhancing firm performance (Dom and Ahmad, 2020). Additionally, upper echelon theory suggests that CEOs' decisions are influenced by their personal values and psychological traits. In competitive markets, CEOs might opt for riskier decisions to achieve superior performance, which can impact their bank's growth (Jilani *et al.*, 2023). Risk-taking is a crucial determinant of a bank's performance and long-term sustainability (Hiebl, 2022).

The risk-taking is largely influenced by its CEOs' decisions, and their personal traits have an impact on these choices (Tang and Chang, 2024). The individual personality of the CEO can greatly influence the bank's risk profile and strategy. However, agency theory highlights a conflict in risk preferences between shareholders and managers due to the separation of ownership and control in public companies (Ramli, 2019). The skills and reputation a CEO build over their career are closely linked to their bank's performance.

A risky decision that fails can tarnish their professional standing (Kim *et al.*, 2016). In contrast, shareholders are more inclined toward riskier investments to boost future returns, as they can mitigate risks through portfolio diversification (Anjum *et al.*, 2020). CEOs often prioritize their personal interests when making strategic decisions, which can lead them to avoid risky strategies, while shareholders might advocate for riskier investments that could yield higher returns (Mustapha and Che Ahmad, 2011).

Therefore, the existing literature on the influence of CEOs' characteristics on corporate risk-taking is relatively scarce (Faccio *et al.*, 2016; Farag and Mallin, 2018). They argue that CEOs' demographic traits are significant factors in shaping their levels of overconfidence and hubris, which in turn affect the company's approach to risk-taking. Therefore, this research aims to examine the relationship between the CEOs characteristics and banks' risk-taking. Considering these factors, this paper aims to offer plausible answers to the following question:

How do CEO characteristics influence banks' risk-taking behavior?

This study examines the impact of CEO characteristics on bank risk-taking behavior. Analyzing data from 540 international banks between 2011 and 2023, we find a negative association between CEO age and bank risk. Conversely, a positive relationship exists between CEO higher education and prior board experience and bank risk. Additionally, our results suggest that female CEOs exhibit risk-averse tendencies.

Studies on the impact of CEO characteristics on bank risk-taking have several gaps. Many studies focus on a limited number of banks or countries, which limits the generalizability of results. Some studies focus on relatively short periods, which may not fully capture the long-term impact of CEO characteristics on bank risk-taking. While other studies focus on a restricted number of banks or regions, this research uses a larger, more diversified

sample, allowing for more generalizable findings. This research considers economic factors, which influence risk-taking, thus providing a more comprehensive perspective.

This study makes several key contributions. The study enriches the leadership literature by integrating CEO characteristics as an influential factor on risk-taking, adding a dimension to existing theories. It offers valuable insights for shareholders who are focused on hiring highly skilled CEOs to meet their objectives and enhance competitiveness in the global market. Based on international datasets, the study provides new insights into how CEO characteristics can influence risk. The findings provide practical recommendations for boards of directors on the selection and evaluation of CEOs, considering the traits that favor prudent risk management.

Additionally, these insights have informed the development of more effective regulatory policies, improved corporate governance, and stronger risk management strategies in banks. Furthermore, the research enhances our understanding of bank operations and provides guidance on better management practices to mitigate risks and support financial stability. The study suggests that banks could benefit from training programs targeting the development of risk-taking skills. The findings could influence the design of remuneration policies to align CEO incentives with prudent risk management.

The structure of the paper is organized as follows: Section 2 covers the literature review and the formulation of hypotheses. Section 3 details the research methodology. The results are presented in Section 4, followed by robustness checks in Section 5. Finally, Section 6 offers the conclusion.

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

Corporate governance is typically dominated by the CEO, as they have the most decision-making authority within the company (Chen, 2013; Peni, 2014; Jilani and Chouaibi, 2021). According to agency theory, CEOs may prioritize their own risk preferences, potentially leading them to avoid taking the level of risk necessary for maximizing firm value (Jensen and Meckling, 2004). In line with the theory, Pathan *et al.* (2023) found a negative association between bank risk-taking and CEO power, particularly when the CEO had the role of Chairperson. Yim and Kang (2024) affirmed that young people are more inclined to take risks, while older CEOs may prefer a more settled environment.

Hassanein *et al.* (2024) showed that overconfident CEOs tend to adopt risk reporting practices. These practices can lead to increased stock returns, due to positive investor perceptions. More transparent voluntary risk disclosure might be particularly valued by investors as it provides insights into how the company is managing and mitigating these heightened risks, potentially reducing uncertainty and increasing firm value (Hassanein and Elsayed, 2021). Hassanein and Albitar (2024) indicated that excessive reporting can affect investor perception, leading to a reduction in firm value.

Older CEOs or those who have been in their positions for a long time may feel more secure and confident in their decision-making abilities. These CEOs may take on more dangerous financial strategies (Ho *et al.*, 2022). The Upper Echelons Theory (UET) proposed by Hambrick and Mason (1984) suggests that the characteristics of top managers influence their decision-making, which in turn affects organizational outcomes. According to this theory, while individuals aim to make rational decisions, their ability to do so is *limited* by cognitive constraints and the information available to them (Lee and Moon, 2016).

Several gaps remain in the literature. The majority of studies focus on specific characteristics, such as academic background or professional experience, without exploring other relevant traits such as executive personality. Most studies focus on firms, neglecting the impact of managerial characteristics in the banking sector.

2.1. CEO age and bank risk taking

The relationship between CEO age and risk-taking has been a prominent focus in early studies (Barker and Mueller, 2002; Ting *et al.*, 2015). CEO age as a crucial element that affects how executives approach risk, influencing their strategic decisions. There is research showing that younger CEOs may be more inclined to take risks, while other studies indicate that older CEOs, with more experience, make riskier decisions because of their confidence (Agha and Pramathevan, 2023; Yim and Kang, 2024; Yin *et al.*, 2025). According to Upper Echelons Theory, older CEOs who have successfully navigated past financial crises might possess a heightened sense of confidence in their ability to manage risk (Ali *et al.*, 2022). Barker and Mueller (2002) found that Older CEOs, who may be nearing retirement, might be less willing to commit to such long-term investments, leading to a reduction in RandD spending. They suggest that this is because RandD investments are inherently risky and require significant capital, with potential benefits often realized only after a lengthy period.

According to agency theory, As CEOs approach the end of their careers, their concern for future employment and reputation may decrease (Li *et al.*, 2016). Serfling (2014) showed that younger CEOs tend to adopt riskier corporate policies compared to their older counterparts. This is attributed to younger CEOs' greater willingness to pursue ambitious strategies. Ting *et al.* (2015) suggested that younger CEOs tend to maintain higher levels of financial leverage. Gupta (2022) suggest that younger CEOs often seek to establish a strong reputation and may therefore be more prone to overstate their confidence in decision-making. This drive to project a competent managerial image can result in greater risk-taking behavior among younger CEOs.

Additionally, Agha and Pramathevan (2023) propose that as CEOs age, their financial responsibilities to their families increase, leading to a more cautious approach compared to younger CEOs. This implies that younger CEOs, with fewer obligations beyond themselves, are more inclined to take risks. Yin *et al.* (2025) argued that the way managers are compensated can influence the level of risk their firms are willing to take. Similarly, Chowdhury and Fink (2017) pointed out that CEOs approaching retirement tend to allocate less to RandD, a tendency they termed the "horizon problem." they indicated that younger CEOs are more inclined to invest in RandD compared to their older peers. The younger CEOs are more inclined to take risks compared to older CEOs, suggesting a potential deviation in risk behavior among younger CEOs (Peltomäki *et al.*, 2021). Hence, we hypothesise the following:

H1*: CEO age has a positive effect on the bank risk-taking.*

2.2. CEO gender and bank risk taking

It has been found by many studies that men are more inclined to take risks in their decision-making than women (Hoang *et al.*, 2019; Expósito *et al.*, 2023). It's possible that the low percentage of women on bank boards is due to the perception that women are less risk-

averse than men (Skała and Weill, 2018). Peni (2014) stated that there is a low proportion of women on boards because male CEOs are more risk-averse. According to resource dependency theory, Female CEOs may seek to mitigate risks to maintain relationships with stakeholders (Akram and Abrar Ul Haq, 2022). This reliance on external resources can lead to more cautious decision-making to ensure stability.

On the other hand, Firms with more gender diverse boards had lower sub-prime lending involvement (Lewellyn and Muller-Kahle, 2022). Similarly, Huang and Kisgen (2013) also report that female CEOs are less inclined to use long-term debt and are less likely to engage in acquisitions. They find that female CEOs tend to exercise stock options earlier than male CEOs, indicating that male CEOs may exhibit greater overconfidence in their corporate decision-making.

According to stakeholder theory, Female CEOs may focus more on stakeholder interests rather than solely on shareholder value (Cooper, 2017). This broader perspective can lead to more conservative risk-taking as they aim to ensure long-term sustainability and stakeholder welfare. Alm El-Din *et al.* (2022) affirmed that firms would aim to achieve a more positive financial performance, which can lead to less transparent information for stakeholders. Firms that engage in proactive risk disclosure can benefit from improved investor perception, which translates into higher returns (Hassanein, 2022).

However, a higher percentage of female board members is linked to a greater propensity for taking risks(Berger *et al.*, 2014). This diversity may encourage more innovative and bold strategies, leading to a greater propensity for risk-taking. Adams and Funk (2012) affirmed that Female directors are less power-oriented than their male counterparts. They proved that female directors like taking more risks than their male counterparts.

In addition, Faccio *et al.* (2016) show female CEOs are more risk averse. They claim that firms run by female CEOs have lower advantage, less volatile earnings, and a higher chance of survival than firms run by male CEOs. Expósito *et al.* (2023) argue that implementing process innovations is more common among male CEOs than their female counterparts. In contrast, Palvia *et al.* (2015) found that banks led by women tend to be more conservative, maintaining approximately 5-6% more equity capital compared to those led by men. They indicate that female CEOs face lower default risks during financial crises, suggesting that this conservative approach plays a crucial role in the stability of banks. We formulate the second hypothesis based on the previous discussion:

H2*: The presence of female CEOs has a negative effect on the bank risk-taking.*

2.3. CEO experience and bank risk taking

According to agency theory, a more experienced CEO might have a possess greater power to influence the board towards a higher risk appetite (Bonazzi and Islam, 2007). Experience equips CEOs with a more comprehensive understanding of the firm's external environment, including insights into customers, suppliers, and regulatory frameworks (Anderson *et al.*, 2018). This expertise allows CEOs to assess investment opportunities more effectively by balancing the associated risks and returns (Orens and Reheul, 2013). Studies show that CEOs with long experience are more likely to take risks, while others find that this experience can also lead to risk aversion (Barker and Mueller, 2002; Zhang and Rajagopalan, 2010; Anderson *et al.*, 2018). Moreover, CEOs with professional expertise are also more likely to perceive business issues more clearly, which could improve coordination and

communication within the organization and lead to better decision-making (Ali *et al.*, 2022). Their experience also serves as a strong indicator of their knowledge, values, and skills, reflecting their strategic decision-making. Longer tenure might lead to greater embeddedness in the community and a stronger commitment to social goals, potentially encouraging more social value risk-taking (Lee, 2025). Conversely, it could also lead to more risk aversion.

Upper echelons theory suggests that a leader's experiences and personalities significantly influence strategic choices (Ting *et al.*, 2015). A CEO's experiences could shape the bank's risk-taking. Furthermore, Barker and Mueller (2002) suggests that experienced CEOs contribute valuable expertise to the board, which can enhance their confidence. As a result, these CEOs tend to be less risk-averse compared to their less experienced counterparts. Le *et al.* (2023) suggests that CEOs who have previous experience are more likely to make bold decisions because they are open to innovation, enthusiastic about challenges, and can handle risky ventures.

Consequently, more experienced CEOs are better equipped to make decisions from a broader perspective Zhang and Rajagopalan (2010). In this context, Loukil and Yousfi (2022) found that firms with lower leverage ratios are more likely to have CEOs with prior professional experience, which indicates a less inclined to risk. On the other hand, Farag and Mallin (2018) affirmed that CEOs with external experience are more likely to seize new opportunities and embrace innovation, thereby showing a greater willingness to take risks. Given this explanation, the third hypothesis for this study is formulated as follows.

H3*: CEO experience has a positive effect on the bank risk-taking.*

2.4. CEO education and bank risk taking

Anderson *et al.* (2018) suggest that the educational background of CEOs influences their perspectives, and the decision-making process. CEOs with higher levels of education prefer innovative projects and investment opportunities with an open mind to new changes (Gao *et al.*, 2017). Martino *et al.* (2020) found that CEOs with higher levels of education and strong skills are more inclined to adopt audacious strategies, fostering innovation and growth. Upper echelons theory posits that education increases an individual's skills and knowledge, making them more productive and capable decision-makers (Ali *et al.*, 2022). As a CEO, higher education could lead to better strategic decision-making, which includes risk management.

Barker and Mueller (2002) asserted that CEOs with higher education levels are more likely to lead innovative firms and are more inclined to pursue novel projects and investment opportunities. Beber and Fabbri (2012) claimed that overconfident directors with MBA degrees might be more willing to take risks. From an agency perspective, the level of a CEO's education could influence their alignment with shareholders' interests regarding risk. Highly educated CEOs might have a better understanding of shareholder value maximization (Yahaya, 2025). Wei *et al.* (2025) showed that CEOs with a financial background tend to make risky decisions, which can lead to improved financial performance. This type of CEO shows a preference for investment strategies that balance risk and return, drawing on their expertise.

Some research shows that CEOs with an MBA degree make more conservative decisions, while others suggest that they are more inclined to take risks to maximize performance (Orens and Reheul, 2013; Gao *et al.*, 2017; Farag and Mallin, 2018). Additionally, Orens and Reheul (2013) suggest that CEOs' decisions are influenced not only by their psychological and social traits but also by their educational background. They suggested that CEOs who are educated more tend to be more risk-averse and more open to

innovative business ideas. Farag and Mallin (2018) found a strong positive association between education for CEOs and increased risk-taking in firms in China. Higher education levels may enhance a CEO's confidence in their ability to navigate the uncertainties. Therefore, we hypothesise the following:

H4*: CEO's education level has a positive effect on the bank risk-taking.*

3. RESEARCH DESIGN

3.1. Dataset and source

To conduct a thorough empirical analysis of the impact of CEO characteristics on bank risk-taking, we began by examining a preliminary sample of 800 commercial banks from 34 countries, spanning from 2011 to 2023. The banks were selected based on their efficiency rankings within their respective countries. Banks were chosen according to their efficiency rankings within their own countries. This implies that the study aimed to analyze the most effective banks. Banks that had incomplete or missing data were not included in the analysis. This step ensures that the dataset used for the study is reliable. The final dataset included 540 banks, along with 7020 bank-year observations. This indicates a comprehensive analysis over long period, which can help in understanding bank performance.

Panel A of Table no. 1 outlines the selection process used for the study. Panel B provides a regional breakdown of the sample banks. The majority of the banks are based in Europe (43.35%), indicating a strong presence of the banking sector in the region. Banks located in the Americas make up 20% of the sample, while the remaining 6.65% are distributed across other regions. Additionally, a macroeconomic variable sourced from the World Development Indicators database was included in the analysis. Bank financial data were obtained from Thomson Reuters (Datastream), while CEO-related information was manually gathered from annual reports, Bloomberg, and the banks' websites. Table no. 1 summarizes the sample selection and data collection procedures.

Table no. 1 – Sample selection and distribution

Panel A: Sample selection		
	Banks	Observations
Initial sample	800	10400
Less banks with missing data	260	3380
Final sample	540	7020
Panel B: Sample distribution by country		
Region	Banks	%
Africa	51	9.44
Asia	69	12.78
America	108	20
Europe	234	43.33
Middle east	78	14.45
Total	540	100

Source: authors' own work.

3.2. Measurement of variables

3.2.1. Dependent variable: bank risk-taking

Banks' risk-taking is the dependent variable in this study. In previous research, several measures have been employed to quantify this variable, including the Z-score, the non-performing loan ratio, and the standard deviation of the stock return (Faccio *et al.*, 2016; Mathew *et al.*, 2018; Martino *et al.*, 2020; Loukil and Yousfi, 2022). Laeven and Levine (2009); Mathew *et al.* (2018); Adu (2022) have referred to the Z-score as a measure of risk-taking.

This measure is determined by summing the equity-asset ratio (or capital-asset ratio (CAR) and the return on assets (ROA), then dividing this total by an estimate of the standard deviation of ROA. A higher Z-score signifies lower risk and greater solvency, representing how many standard deviations ROA can drop before equity capital is exhausted and the bank becomes insolvent. The Z- score is calculated as follows:

$$Z_{it} = \frac{ROA_{it} + CAR_{it}}{\sigma ROA_{it}}$$

where ROA represents the return on assets and CAR denotes the equity-asset ratio for bank i at time t, measured at the end of the year. The return on assets (ROA) is computed as the ratio of pre-tax profit to total assets.

We use a ratio to measure banks' risk-taking, which is known as the non-performing loan (NPL) ratio. This ratio is calculated as the proportion of non-performing loans to gross loans at the end of the fiscal year. This ratio provides insight into the quality of a bank's loan portfolio. However, this measurement is not directly comparable to the Z-score because it focuses on banks' traditional lending activities.

Lastly, we also examine our hypotheses using the standard deviation of return on assets (σ(ROA)i,t) (Delis *et al.*, 2009). The volatility of the bank's earnings can be determined through the standard deviation of return on assets, as riskier operations lead to more volatile (Zhang and Rajagopalan, 2010). The risky investment decisions made by firms can be captured by earnings volatility (Faccio *et al.*, 2016).

3.2.2. Independent variables

The independent variables in this study were CEO characteristics, with firm characteristics accounted for as control variables. Four attributes of CEOs were examined: age, gender, education level, and experience. CEO age was quantified using the natural logarithm of the CEO's age up to year t. CEO age is measured by the number of years from the CEO's year of birth in the year of the study. Gender was represented by a binary variable, where a value of one indicated a female CEO and zero denoted a male CEO.

The education level of the CEO was measured using a binary variable, which simplifies the assessment into two categories. If the CEO has a Master of Business Administration (MBA), they receive a value of one; if they do not have an MBA, they are assigned a value of zero. Rather than considering different levels of education or types of degree obtained, we have simplified the measure by focusing specifically on whether or not they have an MBA. This approach allows us to classify CEOs in two distinct groups based on this specific educational criterion. CEO experience was measured by the total number of years the individual had served as a CEO.

3.2.3. Control variables

To examine how CEO characteristic effects bank risk-taking behavior, this study includes many control variables that could affect this relationship. These variables include board independence, CEO duality, CEO ownership, bank size, bank age, real GDP growth, and inflation rate. Table no. 2 below provides information on the measurement of these control variables and related variables.

Table no. 2 – Definitions and measurements of study variables

Variables	Symbols	Measures	Sources
Dependent variable: Bank risk-taking			
Insolvency risk	Z-score	The sum of the return on assets and equity/assets, normalized by the standard deviation of the return on assets (ROA).	Thomson Reuter (DataStream)
Credit risk	NPL	Ratio of nonperforming loans to gross loans	Thomson Reuter (DataStream)
Market risk	SDVL	Annualized standard deviation of daily stock returns for each bank year.	Thomson Reuter (DataStream)
Independent variables			
CEO age	CEO_AGE	Number of years of CEO age	Annual reports
CEO gender	CEO_GEN	A binary variable that is set to 1 if the CEO is female and 0 if the CEO is male.	Annual reports
CEO experience	CEO_EXP	The total number of years an individual has held the position of CEO.	Annual reports
CEO education	CEO_EDU	A dummy variable, taking the value 1 if the CEO has an MBA degree and 0 otherwise.	Annual reports
Control variables			
Board independence	B_IND	The proportion of independent non-executive directors sitting on the board of directors	Thomson Reuters (Datastream)
CEO duality	CEO_DUAL	A dummy variable equal to 1 if the CEO also holds the chairman of the board position and "0" if not.	Thomson Reuters (Datastream)
CEO ownership	CEO_OWN	The percentage of share of capital owned by the CEO to total assets of the firm.	Thomson Reuters (Datastream)
Bank size	SIZE	Natural Logarithm of total assets for bank i in year t	Thomson Reuters (Datastream)
Gross loan growth	LOAN	The change in the loan portfolio from the previous year to the current year, expressed as a ratio of the previous year's loan portfolio.	Thomson Reuters (Datastream)
GDP growth rate	GDP	Annual real GDP growth in the economy where the bank is located.	World Development Indicators (WDI)
Inflation rate	INF	Percentage variation in the consumer price index.	World Development Indicators (WDI)

Notes: The variables utilized in the study are defined in this table.

3.3. Model

Panel regression analysis was conducted using STATA 17 as the statistical software. The panel regression model is described below:

$$\begin{aligned}RISK_{i,t}=&\beta_0+\beta_1 CEO\_AGE_{i,t}+\beta_2 CEO\_GEN_{i,t}+\beta_3 CEO\_EXP_{i,t}+\beta_4 CEO\_EDU_{i,t}+\beta_5 B\_IND_{i,t}\\&+\beta_6 CEO\_DUAL_{i,t}+\beta_7 CEO\_OWN_{i,t}+\beta_8 SIZE_{i,t}+\beta_9 LOAN_{i,t}+\beta_{10} GDP_{i,t}+\beta_{11} INF_{i,t}+\\&\sum_{i=12}^{24}\beta_i year_{i,t}+\sum_{j=25}^{58}\beta_j country_{j,t}+\varepsilon_{i,t}\end{aligned}$$

Table no. 2 defines the variables used in this study. YEAR and COUNTRY denote the fixed effects for year and country, respectively. The term ε represents the error term, while the indices i and t refer to the bank and the year, respectively.

4. EMPIRICAL RESULTS

4.1. Descriptive statistics

Table no. 3 provides a summary of the statistics for the main variables utilized in the empirical analysis. For Z-score variable, the average value and standard deviation were 4.854 and 2.392 respectively. The mean indicates a relatively high level of risk-taking. Some banks have much higher Z-scores (10.386), indicating very high risk, while others have lower scores (-1.818), suggesting lower risk. The mean of the variable "NPL" indicates that, on average, banks in the sample have 4% of their loans that are non-performing.

The low ratio of nonperforming loans indicates that banks are diligent in monitoring and managing these loans effectively. The variable "SDVL" reflects the variability of potential losses for the bank. The oldest CEO is 65 years old, and the youngest is 34. Qawasmeh and Azzam (2020) found that the average age of a CEO is about 47.135 years, which is consistent with this. Female CEOs are significantly underrepresented in the sample, comprising just 4.56% of the total. This finding is consistent with the study by Adams and Funk (2012), which highlights the low representation of women in executive roles within the banking sector.

Table no. 3 shows that, on average, the CEOs in the sample have held their positions for about 4 years, with a range from 6 to 27 years. These findings are consistent with Qawasmeh and Azzam (2020), who found that CEOs have significant prior experience. Table no. 3 shows the education level of the CEOs, with 32% having an MBA degree and 67% having lower degrees.

For the control variables, the average bank size is 14.745 with a 3.108 standard deviation. Board independence ranges from 0.038 to 0.805 with a mean value of 0.324 directors with the percentage of CEO duality being 61%. The mean values are 8.9% for inflation and 9.4% of GDP. The standard deviations for these variables are below their mean values, suggesting that the data exhibit relatively low dispersion.

Table no. 3 – Descriptive statistics of the sample

Variable	Obs.	Mean	SD	Minimum	Maximum
Panel A: The dependent variables: Bank risk-taking					
Z-score	7.020	4.854	2.392	-1.818	10.386
NPL	7.020	0.040	0.051	0.002	0.736
SDVL	7.020	0.058	0.036	0.003	0.409
Panel B: The continuous variables					
CEO_ AGE	7.020	47.135	6.750	34	65
CEO_ EXP	7.020	7.148	4.191	6.080	27.000
B_IND	7.020	0.324	0.104	0.038	0.805
CEO_OWN	7.020	0.023	0.078	0.097	0.701
SIZE	7.020	14.745	3.108	10. 091	21.976
LOAN	7.020	9.768	4.205	-11.709	62.362
GDPG	7.020	0.089	0.057	-0.036	0.194
INF	7.020	0.094	0.037	-0.026	0.182
Panel C: The dichotomous variables					
		Modality		Percentage	
CEO_ GEN		0		95.44	
		1		4.56	
CEO_EDU		0		67.06	
		1		32.94	
CEO_DUAL		0		37.90	
		1		61.01	

Note: Variables definitions are provided in Table no. 3.

4.2. Correlation matrix

Table no. 4 presents the Pearson correlation coefficients for all variables. It reveals a positive association between CEO age and both CEO experience and education. Additionally, there is a positive correlation between CEO experience and education. In contrast, CEO education is negatively correlated with CEO gender. The correlation coefficients among the independent variables are all below 0.70. To address potential concerns about multicollinearity, we computed the variance inflation factor (VIF), as presented in the last column of Table no. 4. The VIF values are all under 10, confirming that multicollinearity is not an issue in this analysis (Gujarati, 2003).

Table no. 4 – Pearson Correlation Matrix and VIF value

	CEO_ AGE	CEO_ GEN	CEO_ EXP	CEO_ EDU	B_IND	CEO_ DUAL	CEO_ OWN	SIZE	LOAN	GDP	INF
CEO_AGE	1.000										
CEO_GEN	-0.032	1.000									
CEO_EXP	0.408	-0.111	1.000								
CEO_EDU	0.034	-0.046	0.102	1.000							
B_IND	0.046	-0.088	0.037	0.169	1.000						
CEO_DUAL	0.056	0.069	0.032	0.106	0.144	1.000					
CEO_OWN	0.014	0.023	0.079	0.049	0.182	0.272	1.000				
SIZE	0.187	-0.100	0.225	0.085	0.169	0.162	-0.028	1.000			
LOAN	0.027	0.038	0.011	-0.016	0.120	0.219	0.372	-0.007	1.000		
GDP	0.055	0.099	-0.201	-0.022	0.060	0.187	0.102	-0.235	-0.058	1.000	
INF	0.221	-0.319	0.443	0.157	0.078	-0.106	0.123	-0.337	0.052	0. 253	1.000
VIF	1.47	1.69	1.72	5.38	1.56	1.26	2.48	1.03	4.81	1.92	1.58

Notes: Variables definitions are provided in Table no. 2.

4.3. Selection of fixed or random effect

The empirical analysis demonstrates a statistically significant model fit at the 1% level, as evidenced by the p-values of the F-statistics. Moreover, the adjusted R-squared metric indicates that a substantial portion of the variance in the dependent variable is explained by the included explanatory variables. These findings collectively support the model's overall significance and explanatory power. To select the most appropriate panel data estimation method, a Hausman test was conducted. The results of this test favored the fixed effects model over the random effects model (p-value < 0.05). This suggests that individual-specific effects are present and should be accounted for in the estimation process. Consequently, the fixed effects regression model emerges as the most suitable approach for analyzing the relationship between the dependent and independent variables in this context.

4.4. Regression analysis

To investigate the relationship between banks' risk-taking and CEO characteristics, we apply multiple regression analysis to the data. The findings are summarized in Table no. 5. It is evident from the columns 1, 2 and 3 in Table no. 2 that CEO age is negatively related to Z-score, NPL and SDVL with coefficients of -0.049, -0.853 and -0.474, respectively. An increase in CEO age by a unit will lead to a decline in banking and risks. The result affirmed that CEO age has a negative effect on risk-taking. The hypothesis 1 is rejected. This suggests that an older manager is associated with a lower Z-score, indicating reduced financial stability and a higher risk of bankruptcy. In addition, the result showed that an older manager is associated with a lower non-performing loan ratio, indicating better asset quality and lower credit risk.

This could suggest that older CEOs are more conservative or more risk averse. This result aligns with previous studies, which has found a negative relationship between CEO age and risk-taking behavior (Andreou *et al.*, 2017; Kaur and Singh, 2021; Yeoh and Hooy, 2022). When it comes to taking risks, older CEOs usually take more care. This finding is in line with previous literature that suggests that older CEOs are less flexible and more focused on maintaining their career stability and financial security. Older CEOs can influence their decision-making, pushing them to prioritize stability and capital preservation over aggressive growth, which could entail higher risks.

The primary objective may be to leave the bank in a strong and stable position, without introducing short-term uncertainty. When CEOs engage in risky investments, they are more likely to see immediate negative impacts on their profits. Risky investments often have the potential for substantial long-term rewards. However, those with shorter career horizons may not have enough time to benefit from these potential gains, making the risks seem less worthwhile.

Consequently, older CEOs often avoid risky decisions to protect their financial status and preserve their legacies during the final years of their careers. In contrast, younger CEOs, who are generally associated with traits like creativity, openness to new ideas, and intuition, have longer career horizons. They are more inclined to demonstrate their capabilities to the market and enhance their status through entrepreneurial ventures, as supported by the managerial signalling model.

According to Table no. 5, the coefficients obtained for the Z-score, NPL, and SDVL are -1.295, -1.882, and -1.198, respectively. The level of risk taken by the bank is significantly negative due to the presence of female CEOs. A coefficient of -1.295 indicates that banks headed by female CEOs have a Z-score on average 1.295 units lower than those headed by male CEOs do. Banks led by female CEOs have a significantly lower non-performing loan ratio than those led by male CEOs. Female CEOs may be more prudent in lending or more effective in managing credit. These findings corroborate Hypothesis 2. In line with upper echelons theory, these results are consistent with previous research such as Martín-Ugedo and Minguez-Vera (2014); Faccio *et al.* (2016); Expósito *et al.* (2023).

In line with top management theory, these results are consistent with previous research such as Martín-Ugedo and Minguez-Vera (2014); Faccio *et al.* (2016); Expósito *et al.* (2023). We find that gender is an important factor in risk-taking, with male CEOs showing a higher propensity to engage in risky activities. Female CEOs show a lower inclination toward taking risks, which may be attributed to lower self-confidence in bank decisions.

In contrast, male CEOs tend to overrate their skills and display heightened optimism regarding potential profits from risky investments, which results in greater willingness to invest. Male CEOs also tend to prioritise profitability through higher risk-taking, while female CEOs often consider family and personal factors in their business relationships, placing a greater emphasis on harmony. Consistent with resource dependency theory, we suggest that male CEOs are likely to bring a wide range of viewpoints, perspectives and professional skills to the board.

This wealth of contributions could explain their preference for riskier decisions. Female CEOs possess insightful vision and confident judgment in the decision-making process, making a positive contribution to the company's financial performance. They exhibit greater risk aversion than their male counterparts, preferring stability to the high-risk strategies that men may pursue for profits. Additionally, female CEOs are often perceived as less inclined towards innovation and technological transformation.

Table no. 5 shows that there is a positive and significant relationship (p value <1%) between CEO experience and bank risk- taking measures. For each additional year of CEO experience, the Z-score increases by an average of 0.068 units, for each additional year of CEO experience. More experienced CEOs may have developed a better understanding of risks and prefer more cautious strategies. Thus, the third hypothesis is supported by the results mentioned above. The findings are consistent with Chen (2013); Hsu *et al.* (2020); Loukil and Yousfi (2022). CEOs are more likely to take chances when making decisions because of their experience, which broadens their viewpoints and makes them more willing to support creative and risky ideas. This indicates that CEOs with longer tenure tend to be more externally focused and receptive to new business ideas than their shorter-tenured counterparts, potentially making them more inclined to explore riskier decisions.

We contend that CEOs with longer tenures may be more concerned with the effectiveness of their banks and, as a result, may take on more risk. Long-tenured CEOs may be more willing to take risks. This could be explained by the claim that CEOs with longer tenure become more dependent on obtaining and analysing information, which makes them more receptive to different viewpoints. A longer tenure also gives CEOs more authority, which boosts their independence and lessens stakeholder pressure. As a result, they become more inclined to make riskier decisions, as their tenure increases.

Being more experienced, CEOs may tend to adopt a progressive approach and become more flexible in their decisions, which in turn would raise the bank volatility. CEOs with more

experience are inclined to make bolder choices because they are pushed to be more creative and embrace decisions that are more daring.

The Table no. 5 indicates a significant positive relationship between CEOs with MBA degrees and increased risk-taking in banks. These results support our fourth hypothesis. This aligns with previous studies by Beber and Fabbri (2012); Orens and Reheul (2013); Anderson *et al.* (2018). Studies in different areas can develop different ways of thinking, solving problems and processing information. Managers with different educational backgrounds may have different risk tolerance thresholds and distinct ways of assessing the probabilities and implications of risks. This can lead to a more thorough and less conservative consideration of risky options.

CEOs with an MBA may be overconfident and more inclined to take risks. The CEOs who have a high level of education tend to be less risk-averse and are more open to innovative ideas, which helps them stay better informed about their external environment. Furthermore, CEOs who have a higher level of education are less likely to be hesitant to take risks and more inclined to accept new and inventive company concepts. Compared to their counterpart with less education, they are therefore more knowledgeable about their external environment.

Upper echelons theory supports hypothesis H4, which states that CEO education has a positive effect on bank risk-taking. This theory posits that individuals with higher levels of education possess greater skills and knowledge, making them more confident in their ability to assess and manage risks. Therefore, an educated CEO may be more inclined to adopt risky strategies, believing that they can maximize returns while controlling associated risks.

CEOs with MBAs who possess a stronger comprehension of risk management, financial markets, and strategic decision-making. Their ability to make more educated and deliberate risk-taking decisions can result from this skill. CEOs with more education may have greater faith in their abilities to recognize and successfully manage risks. This self-assurance may result in a higher willingness to take on hazardous endeavors. A CEO's ability to strategically think can be improved with advanced education, making it possible for them to assess and seize opportunities more effectively even when they come with greater risk.

The statistical results indicate that the control variables have an impact on the bank risk-taking. Bank risk-taking is negatively and significantly affected by the bank size. This finding proposes that larger banks might be less risky due to their ability to diversify investments across various assets. Such diversification can mitigate the effects of any single investment failing. Furthermore, these banks often have more advanced risk management systems and a more experienced team to handle potential risks. The results show that there is a significant association between loan growth and bank risk-taking.

When banks rapidly increase their loan, they often extend credit to borrowers with lower credit. This can lead to a higher proportion of non-performing loans, which can negatively influence a bank's financial performance. Inflation and gross domestic product (GDP) significantly influence bank risk-taking behavior. When GDP grows, liquidity and credit risks tend to decrease, but the total risk may increase. Conversely, rising inflation rates generally contribute to higher overall banking risks.

Moreover, CEO duality and managerial ownership positively influence risk-taking in banks. When the CEO doubles as chairman of the board, it can lead to faster decision-making and greater consistency in strategic direction, thus enabling bolder risk-taking. Managerial ownership encourages executives to be more invested, making them more likely to champion risky projects they believe will benefit long-term growth. On the other hand, board independence has a negative effect on risk-taking. Independent members may be motivated

by concerns about their reputation and legal liability, which leads them to avoid risky decisions that could result in losses.

Table no. 5 – Multiple regression results

	Z-score		NPL		SDVL	
Variable	**Coefficient**	**T-statistic**	**Coefficient**	**T-statistic**	**Coefficient**	**T-statistic**
CEO_AGE	-0.049**	-2.29	-0.853***	-2.35	-0.474**	-2.42
CEO_GEN	-1.295**	-2.55	-1.882***	-3.05	-1.198**	-2.28
CEO_EXP	0.068***	3.35	0.290**	2.54**	0.289***	2.81
CEO_EDU	1.874***	3.64	1.265***	3.13	0.052 **	2.15
B_IND	-0.671**	-2.17	-0.385	-1.80	-0.375*	-2.01
CEO_DUAL	0.067***	4.07	1.512***	3.37	0.057**	2.37
CEO_OWN	0.064**	2.43	1.003**	2.28	1.106	3.27
SIZE	-0.067**	-2.41	−0.168***	-3.16	-0.289***	-3.29
LOAN	-0.208**	-2.39	-0.636**	-2.03	-0.551**	-2.48
GDP	1.038***	-4.19	-0.227***	-2.74	-0.491***	-3.65
Inflation	0.176***	5.07	1.036***	4.14	1.328***	4.09
Constant	0.589***	10.16	0.549***	9.94	0.683***	12.03
Year FE	Yes		Yes		Yes	
Country FE	Yes		Yes		Yes	
Hausman Test	66.85 (0.000)		67.53 (0.000)		66.39 (0.000)	
R^2	0. 480		0.396		0.489	
F-statistic	8.52***		8.97***		9.13***	
Observations	7.020		7.020		7.020	

Notes: This table presents results from linear regressions in our model. Year and country indicators are included in the model. The asterisks *** and ** indicate significance at the 5% and 1% levels, respectively.

5. ROBUSTNESS CHECKS

The findings might be subject to different endogeneity problems, as pointed out in the research on corporate governance. Dynamic endogeneity could have an impact on them (Wintoki *et al.*, 2012). This phenomenon arises when past values of the dependent variable influence current values of one or more explanatory variables. Hermalin and Weisbach (2003) suggest that governance mechanisms are determined endogenously, implying that the direct relationship between any CEO characteristic and firm outcomes could be misleading. To address this endogeneity in our analysis, we include bank fixed effects in our regressions, which help control for bank-specific characteristics that might be omitted from the model.

To mitigate the potential impact of dynamic endogeneity and omitted variable bias in our results, we additionally employ a two-step system Generalized Method of Moments (GMM) estimation (Arellano and Bond, 1991). The system GMM method helps correct for endogeneity issues (Blundell and Bond, 1998). The results from these GMM regressions are shown in Table no. 6. For clarity, we only include the findings related to the model, as previously presented in Table no. 6.

We opted for the GMM system method, as it enables robust estimation thanks to the internal instruments available in the panel data structure. This method uses lagged dependent variables as explanatory variables, thus controlling for potential endogeneity bias. In addition, it allows us to consider the presence of lagged independent variables, a crucial element in capturing the temporal dynamics and potential time lags of the relationship. The GMM

method strengthens the validity of the analysis and provides a robust framework for examining the relationship between the variables in the study. Consequently, the estimated dynamic model consists of establishing a relationship between the level of risk-taking over period t, denoted Y, and its value lagged one year, with CEO characteristics and control variables. The model is therefore as follows:

$$\begin{aligned}RISK_{i,t}=&\beta_0+\beta_1 RISK_{i,t-1}+\beta_2 CEO\_AGE_{i,t}+\beta_3 CEO\_GEN_{i,t}+\beta_4 CEO\_EXP_{i,t}+\beta_5 CEO\_EDU_{i,t}\\&+\beta_6 \boldsymbol{B}\_IND_{i,t}+\beta_7 CEO\_DUAL_{i,t}+\beta_8 CEO\_OWN_{i,t}+\beta_9 SIZE_{i,t}+\beta_{10} LOAN_{i,t}+\beta_{11} GDP_{i,t}+\beta_{12} INF_{i,t}\\&+\sum_{i=13}^{25}\boldsymbol{\beta_i year_{i,t}}+\sum_{j=26}^{59}\boldsymbol{\beta_j country_{j,t}}+\varepsilon_{i,t}\end{aligned}$$

The dynamic panel model was estimated in Stata 17 using Roodman's (2009) Xtabond2 procedure. Across all model specifications, the tests performed indicated their overall significance. Furthermore, the Hansen test for over-identification provided evidence that the lagged and differenced instruments are valid. Serial correlation tests for the residuals (AR1 and AR2) supported the absence of second-order autocorrelation and the presence of first-order autocorrelation, suggesting that the error terms are not serially correlated in a way that would invalidate the model.

These results indicate that the moment conditions are appropriately specified and the residuals are irrelevant. The significance level and the coefficient of lagged risk-taking compellingly justify the dynamic specification of our model and the inclusion of these temporal dependencies. The risk-taking levels are largely predicted by past risk-taking, and our results confirm the importance of considering their evolving effects. This dynamic perspective enables a more integrated and clearer understanding of previously results.

Table no. 6 – Robustness checks

	Z-score		**NPL**		**SDVL**	
Variable	**Coefficient**	**T-statistic**	**Coefficient**	**T-statistic**	**Coefficient**	**T-statistic**
CEO_AGE	-0.049**	-2.29	-0.853***	-2.35	-0.474**	-2.42
CEO_GEN	-1.295**	-2.55	-1.882***	-3.05	-1.198**	-2.28
CEO_EXP	0.068***	3.35	0.290**	2.54**	0.289***	2.81
CEO_EDU	1.874***	3.64	1.265***	3.13	0.052 **	2.15
B_IND	-0.671**	-2.17	-0.385	-1.80	-0.375*	-2.01
CEO_DUAL	0.067***	4.07	1.512***	3.37	0.057**	2.37
CEO_OWN	0.064**	2.43	1.003**	2.28	1.106	3.27
SIZE	-0.067**	-2.41	−0.168***	-3.16	-0.289***	-3.29
LOAN	-0.208**	-2.39	-0.636**	-2.03	-0.551**	-2.48
GDP	1.038***	-4.19	-0.227***	-2.74	-0.491***	-3.65
Inflation	0.176***	5.07	1.036***	4.14	1.328***	4.09
Constant	0.589***	10.16	0.549***	9.94	0.683***	12.03
Year FE	Yes		Yes		Yes	
Country FE	Yes		Yes		Yes	
Hausman Test	66.85 (0.000)		67.53 (0.000)		66.39 (0.000)	
R^2	0.480		0.396		0.489	
F-statistic	8.52***		8.97***		9.13***	
Observations	7.020		7.020		7.020	

Notes: This table presents results from linear regressions in our model. Year and country indicators are included in the model. The asterisks *** and ** indicate significance at the 5% and 1% levels, respectively.

6. CONCLUSION

This study analysed the relationship between CEO characteristics and bank risk-taking using a sample of 540 international banks from 2011 to 2023. The results confirm expectations regarding the effect of CEO characteristics (CEO age, CEO gender, CEO experience and CEO education) on risk-taking at banks. The CEO is considered to be the decision-making body of a company, responsible for defining strategic priorities and objectives in various areas, including financial results, which can have an impact on risk-taking.

Indeed, older CEOs generally tend to be more risk-averse, perhaps due to concerns about their reputation and retirement. Higher levels of education among CEOs are associated with increased risk-taking. This suggests that education equips CEOs with better analytical skills to assess and mitigate risk, especially in volatile environments. CEOs with high levels of experience may overestimate potential returns and underestimate risks, leading to increased risk-taking.

The findings also show CEOs with longer experience might be less willing to take risks because they are more invested in the long-term viability of the bank. CEOs who are older are frequently seen as less risk-averse. But younger CEOs might also be more willing to take risks, especially if they have a strong drive for success. Although taking more risks can be linked to higher education levels, risk-taking behaviour can also be influenced by the particular type of education. Given these findings, the board of directors should consider these attributes when selecting a CEO, as they can impact the company's long-term performance.

This study contributes to the financial literature in several areas. In addition, CEO performance could be assessed not only on the basis of financial results, but also on how they manage risk. Banks could be encouraged to revise their risk policies according to the characteristics identified as influential, incorporating training for CEOs and management teams on risk management. If certain characteristics are linked to higher or lower risk-taking, recruitment committees could give preference to candidates with specific traits that match the bank's desired risk culture. The results could encourage the search for CEOs with diversified backgrounds to balance risk-taking and avoid overly conservative behaviour.

Therefore, boards should consider the personality traits and experience of CEOs when recruiting, as these elements influence the risk culture within the institution. It is essential to provide CEOs with ongoing training in risk management, to promote a balanced approach to opportunities and challenges. Investors should analyse CEO characteristics as an indicator of risk-taking propensity, incorporating this analysis into their investment decisions. Regulators should monitor governance practices related to CEO characteristics and their impact on risk-taking, establishing guidelines. Banks should carefully consider the potential impact of CEO characteristics on risk-taking when selecting and evaluating candidates for leadership positions. This includes assessing factors such as tenure, age, education, compensation, personality, and alignment with the bank's risk appetite. However, this work has some limitations. Firstly, the analysis relies in part on manually collected data on CEO characteristics. This manual collection process, while meticulous, introduces an inherent risk of data bias. Also, the study is limited to banking industry. Finally, future studies could subdivide the total sample according to the country’s region or the size of the bank.

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Public Debt and Tax Revenues in the West African Economic and Monetary Union (WAEMU) Countries: The Role of Human Development

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Abstract: This study aims to examine the role of human development in the relationship between public debt and tax revenues in the West African Economic and Monetary Union. Using econometric models with the panel-corrected standard error (PCSE) method and the robust standard error method of Driscoll and Kraay to account for heteroskedasticity, autocorrelation, potential serial correlations and cross-sectional dependence on panel data covering the period 1995-2022, we analyze these complex links. Our results indicate that human development has a positive effect on government revenues. In addition, we find that rising public debt is a brake on tax revenue mobilization. Finally, our analysis suggests that the negative effect of public debt on revenues could be moderated in the context of human development. Our results suggest that human development policies have a positive effect on the public finances. To reinforce this dynamic, we recommend increasing investment in education and health, which are essential pillars of human development. These investments should be accompanied by reforms aimed at optimizing the allocation of public resources in these sectors. The use of public debt can be an effective tool for stimulating economic growth and increasing public revenues in the context of well-developed human development.

Keywords: public debt; tax revenues; human development; PCSE method; WAEMU.

JEL classification: C5; F45; H2; H6; O15.

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1. INTRODUCTION

The International Monetary Fund (IMF) defines debt as all financial obligations contracted by one economic agent toward another, involving the payment of interest and/or repayment of the principal at one or more future dates (IMF, 2001). Public debt, on the other hand, represents all the loans contracted by the State and public administrations to finance their budget deficits. This amount fluctuates according to the repayments made and the new loans contracted to cover the state's financing needs. Developing countries, faced with the ambitious goal of achieving sustainable development goals (SDGs), need massive investments in infrastructure, human capital and climate resilience. However, their ability to mobilize sufficient public revenues or attract private investment is limited (Adeve and Karabou, 2022). This is why many states have turned to public debt as one of the main sources of financing for their economies. However, excessive public indebtedness can hamper public investment in sectors crucial to human development, such as education, health, sanitation and infrastructure. Therefore, resolving the problems faced by developing countries in achieving the SDGs requires a renewed global commitment, strengthened cooperation, and effective partnerships at all levels, as highlighted by SDG 17 "Partnerships for the Goals." The latter recognizes that achieving the 17 SDGs requires global collaboration and multi-stakeholder partnerships among governments, civil society, the private sector, international institutions, and other stakeholders.

West African Economic and Monetary Union (WAEMU) countries saw their indebtedness rise steadily, from 57.6% in 2022 to 59.5% in 2023, an increase of 1.9 percentage points linked to an increase in domestic debt (UEMOA., 2023). Total revenues and grants rose by 13.5% in 2022 to represent 18.0% of GDP in 2023, driven mainly by a 14.5% increase in tax revenues. The result is a tax burden rate of 14.5% in 2023, compared with 13.8% in 2022, which is well below the 20% target set by the Convergence, Stability, Growth and Solidarity Pact (CSGS). Despite an increase in tax revenues due in part to the implementation of tax reforms, none of the member countries has reached the 20% target. The average human development index for the WAEMU zone remains below that of sub-Saharan Africa, at 0.470 versus 0.5 in 2022.

In the literature, the relationship between public debt and tax revenues is complex and depends on many factors. While some, following the footsteps of Wagner (1893) or Ashinze and Onwioduokit (1996), see debt as a lever for stimulating growth and improving living conditions, others, such as Ricciuti (2003) and Huang *et al.* (2018), highlight the risks of excessive debt, which could compromise the sustainability of public finances and the well-being of populations. In the same vein, Amoh and Adom (2017) noted that public debt is a key determinant of tax revenues. Al-Qudair (2005) highlighted a long-term equilibrium between public debt and public revenues, suggesting a bidirectional causal relationship between these two variables in the short and long term, whereas Zaghdoudi (2018) noted that beyond a certain debt threshold, developing countries risk seeing their development compromised. These studies highlight the dynamic and often contradictory relationship between public debt and tax revenues. Human development could play a crucial role in this complex relationship between public debt and tax revenues. Indeed, human development acts as a lever for improving the public debt situation by stimulating economic growth, reducing public spending and strengthening the resilience of the economy. High human development leads to higher tax revenues and lower debt-related expenditures, thus contributing to greater sustainability of public finances. Empirically, Paweł (2023) reported that an increase in the share of spending on

education, health and social protection positively stimulates debt levels. In the same vein, Noga *et al.* (2018) reported a positive relationship between human development and public debt.

Understanding the role of human development in the relationship between public debt and tax revenues is therefore essential for designing effective public policies in the WAEMU zone. The aim of this study is therefore to analyze the role of human development as a mediating variable between public debt and tax revenues in WAEMU countries. This research is distinguished by several major contributions. The first is the analysis of the direct effects of public debt and human development on tax revenues. The second is the interaction variable between human development and public debt. The final element concerns the use of several econometric techniques, which guarantees the stability and robustness of the results.

The rest of the study is organized as follows: Section 2 presents the literature review, and Section 3 presents the methodology and data. The results and discussion are analyzed in Section 4. Section 5 presents conclusions and policy implications.

2. LITERATURE REVIEW

This section presents the theoretical and empirical literature on the relationship between public debt, tax revenues and human development.

2.1. Theoretical literature

The economic literature abounds with theoretical analyses of the role of public debt in development.

Among the proponents of moderate public debt is the famous Wagner (1893) law. According to this German economist, government spending tends to increase as the economy develops. This growth in public spending would be financed in part by borrowing, thus meeting society's growing needs in terms of infrastructure, public services and social protection. Industrialization and urbanization lead to a growing demand for complex and costly infrastructure, as well as an increased need for public services. As societies modernize, expectations of education, health and social services increase. These public goods and services, whose demand is income-elastic (Lybeck, 1988), require substantial investment. As a result, public debt can be seen as a necessary tool to finance these expenditures and stimulate economic growth.

In addition to Wagner's analysis, the Keynesian approach provides a theoretical benchmark for diagnosing consequences and legitimizing the budgetary courses of action adopted. The Keynesian view of the positive effects of public debt is that indebtedness in general is necessary because of the new investment opportunities it generates for economies. In the Keynesian debt model, aggregate demand and multiplier and gas pedal effects are fundamental characteristics. According to this school, an increase in public sector spending (public debt) can stimulate economic activity by increasing aggregate demand. Indeed, in a situation of underactivity, an increase in government spending financed by the capital market, thus increasing public debt, can have a stronger positive effect on economic growth even in the presence of tax burdens since it does not dampen aggregate demand. This is because the gas pedal effect of higher aggregate demand leads to increased private investment, which in turn increases output. A budget deficit can therefore be a factor in boosting economic activity and thus job creation for economies. In conclusion, the interventionist approach to budget deficits considers that state intervention, even though public borrowing, is necessary because

of the inability of liberal market norms to overcome cyclical crises, which can be disastrous for the future of economic activity. Financing economic activities by means of a budget deficit will have a positive effect on the level of development of states via improved consumer demand (Belmkaddem, 2019). These analytical frameworks demonstrate the positive correlation between public debt and economic development.

While some economists believe that public debt can stimulate investment and consumption, others warn of its perverse effects on economic activity. The theory of debt overhang, notably developed by Myers (1977), is a good illustration of this perspective. According to this theory, excessive public debt can crowd out private investment by increasing interest rates and reducing investor confidence. In other words, by borrowing heavily, the public sector can deprive the private sector of the financial resources it needs to develop.

This theory is supported by certain traditional growth models, which are inspired by classical and neoclassical methods. Unlike Keynesians, classics see no benefit to the economy from indebtedness (Ricardo, 1817; Barro, 1974). In some cases, indebtedness can have undesirable effects on future generations. Indeed, the various classical models assume that public borrowing can reduce the financial discipline of the budgetary process, thereby increasing the future tax burden. In other words, they equate indebtedness with a future tax that consumers must repay. For classics, a demand-driven fiscal policy is inefficient and only has inflationary effects on the economy. Economic agents see public borrowing as a form of tax deferred in time, which they will pay at a later date to repay these loans. Public debt constitutes a form of burden for future generations, as there is a transfer of the tax burden from the current generation to future generations (Ricciuti, 2003). According to classical theory, since the budget deficit based on public borrowing is equivalent to a tax burden, it has no effect on the level of production. Financing public spending through public debt will have no impact on economic activity, and even if it does, it could only be destabilizing (Belmkaddem, 2019).

In conclusion, while public debt can be a valuable tool for financing human development, high and unsustainable debt levels can severely undermine progress in health, education, and overall well-being. The interaction between human development and public debt depends on various factors, including the level of debt, how it is used, the quality of governance, and the overall economic context. Achieving a sustainable balance is crucial for developing countries to pursue both economic growth and improved human development outcomes.

2.2. Empirical literature

2.1.1. Public debt and tax revenues

The empirical literature devoted to the links between public debt and public revenues is vast. The following section summarizes some of the key works on this subject. Cassimon and Van Campenhout (2007) studied the fiscal response to public debt relief in 28 Heavily Indebted Poor Countries (HIPCs) over the period 1991-2004. Using a panel VAR model, they found that debt relief increased government revenues and encouraged growth in recurrent and development spending. On the basis of this finding, the authors conclude that the increase in public spending is due mainly to the increase in revenues resulting from public debt relief. Although taxation is generally accepted as a powerful strategic tool for assessing the macroeconomic impact of a country's fiscal policies, the measurement of tax revenues is often limited by methodological constraints. With this in mind, Andrejovská and Glova (2023)

studied the influence of public debt on total tax revenues by considering the tax competitiveness of the 28 EU member states. Their results suggest that public debt is a major determinant of tax revenues. Boukbech *et al.* (2018) explored the determinants of tax revenues in developing countries. After reviewing the main determinants discussed in the economic literature, two models are estimated in a panel including 29 lower-middle-income countries over the period 2001-2014. The results showed that public debt negatively affects tax revenues. Alawneh (2017) examined the impact of capital expenditures, current expenditures and internal and external public debt on taxes in Jordan from 2001-2014. The econometric analysis revealed a statistically significant and positive effect of both current and capital expenditures on taxes. The study also revealed a statistically significant and positive relationship between external and internal public debt on taxes in Jordan. Kiminyei (2019) also empirically investigated the relationships among Kenyan public debt, tax revenue and public expenditure. The study aimed to investigate the links between public debt, tax revenue and public expenditure from 1960-2011 via data obtained from economic surveys of the Kenya National Bureau of Statistics. A vector error correction model, forecast error variance decomposition and dynamic forecasting are employed. The results of the vector error correction model indicate that for the public debt and public expenditure equations, approximately 36% of deviations from long-term equilibrium are corrected in the following period, compared with approximately 8% for the tax revenue equation. The short-term model shows that the size of the public sector (public spending) has a debt-increasing effect, whereas the size of tax revenues has a debt-reducing effect. Furthermore, the results showed that public debt reacted positively to innovations in both tax revenues and public spending in the long term. Anastasiou *et al.* (2024) examined the existence and nature of causal relationships between tax revenue levels and a range of determinants using data from 26 European countries over the period 2015-2018. Specifically, by applying the panel cointegration method and estimating panel-based error-correction models, we explore the long-term and causal relationships between variables. The results of the analysis confirm the existence of cointegrating relationships between public debt and tax revenues.

2.2.2. Human development and tax revenues

Numerous empirical studies have examined the link between tax revenues and human development. The following section summarizes some of the key work on this subject. Taxation is an essential cog in the wheel of a modern economy. Governments are constantly striving to maximize their tax revenues to meet their financial obligations. Chettri *et al.* (2023) reported on South Asian countries between 2008 and 2017, showing that social factors play a decisive role in tax revenue levels. The authors show that life expectancy has a positive effect on tax revenues, whereas the infant mortality rate has a negative effect. These results underline the importance of investing in human capital to promote economic growth and strengthen the tax base. India's tax revenues are not sufficient to cover all public spending needs. To remedy this situation, it is essential to identify the levers for increasing these revenues. Garg *et al.* (2024) addressed this issue by analyzing the impact of various factors, both economic and institutional, on Indian tax revenues between 1991 and 2022. Their results revealed a positive link between the health status of the population and the government's fiscal effort. This correlation suggests that increased investment in the healthcare sector could help strengthen public finances. In Kenya, tax revenues have remained low for some time in relation to the

fiscal effort and policies in place, and the Kenyan government has always been on the lookout for an appropriate strategy to increase tax revenues and improve citizens' wellbeing. This has prompted researchers such as Singoro (2021) to examine the effect of the Human Development Index (HDI) on tax revenue performance in the country. The study employed secondary annual time series data for the period from 2003-2018 to estimate a linear model of tax revenue performance. Econometric estimates indicate that the human development index (HDI) is statistically significant and has a positive relationship with tax revenue performance. On the basis of these results, he concluded that Kenya's tax revenue performance is positively affected by the human development index.

2.2.3. Human development and public debt

Sustained growth in public debt has raised serious concerns about its potentially negative effects on the economy (Omrane *et al.*, 2015). Nevertheless, the economic literature also highlights the crucial role that moderate public debt can play in financing investment and stimulating growth. Indeed, several empirical studies suggest that an adequate level of debt can help attract capital, promote investment and improve the well-being of populations (Wang *et al.*, 2021). In local governments, debt is a key determinant of long-term solvency, financial stability and budgetary pressure. Debt in this sector can have repercussions on citizens' quality of life and business competitiveness. Paweł (2023) has thus studied the determinants of local government indebtedness in Europe while seeking to identify links between the debt burden and certain categories of expenditure. His analysis covers 27 European countries over the period 2007-2020. The results show that greater spending on education, health and social protection tends to increase debt levels. In their study, Mezni and Djebali (2022) analyzed the impact of IMF loans on the human development index (HDI) in Middle Eastern and North African (MENA) countries between 1990 and 2019. Using panel data, they showed that loans allocated to social sectors, such as health and education, had a significant positive effect on the HDI. In addition, their results revealed a positive correlation between the HDI and foreign direct investment, as well as trade openness. Conversely, loans to the domestic private sector appear to have a negative effect on the HDI. Zaghdoudi (2018) analyzed the nonlinear relationship between external debt and human development in a panel of 95 developing countries over the period 2002-2015. Using a smooth threshold regression model (PSTR), the author identified an optimal external debt threshold of 42%. Below this threshold, a one-percentage-point increase in external debt is associated with a 0.02% rise in the Human Development Index (HDI). Above this threshold, the effect is reversed, with a 0.01% decrease in the HDI for each additional percentage point of debt. These results suggest that external debt can stimulate human development when used judiciously but that excessive indebtedness can hinder economic growth and social well-being. The author therefore recommends prudent debt management, prioritizing investment in productive sectors and controlling population growth. More recently, Wang *et al.* (2021) examined the moderating role of public debt in the relationship between energy consumption and human development in BRICS countries (Brazil, Russia, India, China, and South Africa). Estimates reveal that public debt is detrimental to human development. Khan *et al.* (2025) examined the gap between public debt, globalization, and human development by considering the role of remittances and urbanization in the specific context of Pakistan. The study uses an advanced bounds testing approach of the autoregressive distributed lag (ARDL) model to assess the short-run and long-

run relationship between the selected variables, covering the period from 1990 to 2022. The results reveal a negative relationship between human development and public debt.

Empirical studies have extensively explored the bilateral links between public debt, tax revenues and human development. However, few studies have examined their complex interactions. Indeed, the relationships among debt, public revenues and human development are often complex. To draw robust conclusions and inform public policy, in-depth empirical analysis is needed. This study therefore sets out to explore these interactions empirically in the specific context of WAEMU countries.

3. METHODOLOGY AND DATA

3.1. Empirical specification

To study the impact of human development on the dynamics between public debt and tax revenues within the WAEMU, our analysis is based on the growth model proposed by (Lucas, 1988; Romer, 1989; Barro, 2001) and used by Afolabi and Raifu (2025) and Wirajing *et al.* (2023), as formalized in equation (1).

$$Y_{it} = A\,(K_{it})^{\alpha}(H_{it})^{1-\alpha} \tag{1}$$

The model indicates that improving technology (A), physical capital (K) and human capital stock (H) will improve a country's productivity (Y), which is important for increasing tax revenues. The linearized equation (1) gives:

$$logY_{it} = logA + \alpha logK_{it} + (1-\alpha)logH_{it} \tag{2}$$

Deriving the elements of equation (2) with respect to time, we obtain equation (3) as follows:

$$\frac{\dot{Y}_{it}}{Y_{it}} = \frac{\dot{A}_{it}}{A_{it}} + \alpha\frac{\dot{K}_{it}}{K_{it}} + (1-\alpha)\frac{\dot{H}_{it}}{H_{it}} \tag{3}$$

Equation (3) shows that the rate of productivity growth (which determines tax revenues) is influenced by growth in technology, human capital and physical capital.

We adjust this model to include public debt, human development and the interactive variable of the two variables, as well as control variables such as trade openness, private investment, urbanization, inflation, unemployment, institutional quality and foreign direct investment. By integrating these elements, the growth model becomes more complete and allows a more in-depth analysis of the determinants of economic growth, taking into account the complexity of the interactions between different factors. The resulting panel model is as follows:

$$\begin{aligned} TAXREV_t = {} & \alpha_0 + \alpha_1 HDI_t + \alpha_2 DEBT_t + \alpha_3 TRADE_t + \alpha_4 INV_t + \alpha_5 URBAN_t + \\ & \alpha_6 INF_t + \alpha_7 UN_t + \alpha_8 QINST_t + \alpha_9 FDI_t + u_{1t} \end{aligned} \tag{4}$$

The variable TAXREV represents tax revenues as a percentage of GDP, DEBT is external public debt as a percentage of GDP. The variable HDI indicates the human development index. TRADE represents trade openness, measured by the sum of imports and exports as a percentage of GDP. INV measures private investment as a percentage of GDP, UN refers to the unemployment rate, URBAN represents urbanization, measured by the evolution of the urban population growth rate, and INF is inflation. The variable QINST measures the overall index of institutional quality, which is calculated from the following indicators: (i) rule of law; (ii) citizen voice and accountability; (iii) regulatory quality; (iv) political stability and absence of violence; (v) control of corruption; and (vi) government effectiveness. FDI represents foreign direct investment, measured as capital inflows as a percentage of GDP, and u_t represents the error term.

To analyze whether simultaneous increases in human development and public debt are important for government revenues, this study incorporates an interactive human development and public debt term into equation (4), deriving empirical equation (5) with all model variables to be estimated as follows:

$$TAXREV_t = \alpha_0 + \alpha_1 HDI_t + \alpha_2 DEBT_t + \alpha_3 TRADE_t + \alpha_4 INV_t + \alpha_5 URBAN_t + \alpha_6 INF_t + \alpha_7 UN_t + \alpha_8 QINST_t + \alpha_9 FDI_t + \alpha_{10}(HDI * DEBT)_t + u_{1t} \quad (5)$$

Variables are presented in detail below.

3.2. Variables description

The variables of interest are presented first, followed by the model's various control variables.

– **Tax revenues:** This research uses tax revenues as a percentage of GDP. This refers to the share of a country's output that is collected by the state in the form of taxes. This variable is the dependent variable in our research. Tax revenues are used to finance public spending programs with the capacity to increase social welfare (Kiminyei, 2019).

– **Human development:** Human development is measured by the UNDP Human Development Index. Inspired by Amartya Sen's capability theory, the Human Development Index (HDI) was conceived by the United Nations Development Program (UNDP) in 1990 as an innovative tool for measuring human development. The HDI is a composite indicator that integrates three essential dimensions: (i) a long and healthy life, measured by life expectancy at birth; (ii) access to knowledge, assessed through indicators such as years of schooling and expected years of schooling; and (iii) a decent standard of living, reflected by gross national income per capita adjusted for purchasing power parity (PPP). By combining these dimensions, the HDI offers a more nuanced vision of human development, going beyond simple economic growth. Human development is a virtuous circle for public finances. By promoting economic growth, education, employment and formalization of the economy, it helps to broaden the tax base, improve tax compliance and increase the ability to pay taxes. A highly educated population has high-quality human resources, which increases production efficiency, enabling the government to increase tax revenues. Being well educated and well cared for makes people more aware of the benefits of paying taxes, as well as their responsibilities and obligations to the state. As a result, human development can have a

positive effect on tax revenues. When life expectancy increases, governments do indeed face pressure to adapt pension and social protection systems. However, it is not the increase in life expectancy itself that directly drives up tax revenues. In fact, this increase often puts a strain on public finances, sometimes necessitating reforms to pension systems and social transfers. The work of Castro and Camarillo (2014) and Svejnar (2002)deserves to be clarified with respect to the relationship they establish between human development measured by the under-fives mortality rate and tax revenues. The authors argued that developed countries tend to have a lower infant mortality rate, so we would expect a negative correlation between this variable and tax revenues. These results suggest a positive correlation between the level of human development and the level of government revenue.

– **Public debt:** Public debt is measured as the ratio of total gross public debt to gross domestic product (GDP) as a percentage. A country's debt level has a significant influence on its tax revenues. When a country is heavily indebted, particularly abroad, and its economic growth is insufficient to meet its commitments, governments are often forced to increase the tax burden to release the resources needed to repay the debt (Tanzi, 1977; Eltony, 2002). This tax increase can, however, have perverse effects. Excessive taxation can discourage investment, reduce economic activity and, ultimately, reduce tax revenues. Furthermore, high levels of public debt can lead to macroeconomic imbalance, resulting in increased trade deficits because import restrictions are often put in place to preserve foreign exchange reserves. These restrictions limit customs revenues and indirect taxes linked to imports, thus reducing overall tax revenues (Tanzi, 1992). Public debt is expected to have a negative effect on tax revenues.

– **Trade openness:** measured by the share of trade in gross domestic product (GDP). This is the sum of exports and imports of goods and services, measured as a percentage of GDP. Trade openness enables countries to specialize and benefit from large market shares. With this in mind, the relationships among trade openness, public debt and revenues will attract much more attention in both the theoretical and the empirical literature. Nagou *et al.* (2021) argue that trade openness is a driver of public debt accumulation. A positive sign is expected for the coefficient of the tax revenue variable.

– **Urbanization**: measured by the growth rate of the urban population. When well-managed, urbanization can be an important source of revenue for local and national governments. Indeed, the increase in urban land value, due to the growing demand for housing and commercial space, helps to increase property tax revenues. In addition, the concentration of economic activity in urban areas leads to an increase in individual and corporate income, which in turn broadens the income tax base. Chilima (2005) noted that the transition to urbanization is accompanied by a decline in the informal economy in favor of a more extensive formal sector. This structural transformation translates into higher tax revenues, as formal activities are generally more heavily taxed. A positive correlation is expected between urbanization and public revenues.

– **Foreign direct investment:** For the purposes of this research, foreign direct investment is defined as net investment inflows aimed at acquiring a lasting stake in the management of companies operating in WAEMU economies. Net investment inflows are measured as a percentage of GDP. The role of FDI as a composite stock of capital, knowledge and technology is to enable economic development (Popescu, 2014). Indeed, FDI reinforces the inadequacy of domestic funds in financing both changes in ownership and capital composition. FDI is also a major determinant of foreign capital inflows (Oche *et al.*, 2016). For these authors, foreign direct investment is vital for economic development, particularly

for developing countries that are known to have insufficient capital resources to meet the investment needs of the economy. Jenkins and Thomas (2002) saw FDI as a factor capable of providing foreign capital as well as attracting domestic investment. We anticipate a positive sign for the coefficient of the government revenue variable.

– **Inflation:** measured by the annual growth rate of the implicit GDP deflator, it indicates the rate of price change in the economy as a whole. The implicit GDP deflator is the ratio between GDP in the current local currency and GDP in a constant local currency. It is an indicator of macroeconomic stability, and when it is taken into account, we can see the effect of changes in the prices of all goods produced on economic performance. The relationship between inflation and economic performance has long been at the heart of decision-making. Accelerating inflation has been unanimously discouraged by all schools of economic thought because of its undesirable redistributive and welfare effects (Eggoh and Khan, 2014). Inflation is seen as part of a public finance problem, where high inflation rates are the result of an inefficient tax system (De Gregorio, 1993). A negative sign of the coefficient of the public revenue variable is expected.

– **Private investment:** Private investment is the main driver of long-term economic growth and strengthens market competitiveness (Sineviciene and Railiene, 2015). To this end, Abuselidze (2012) indicates that too high a tax burden can influence production technologies, the efficient use of resources and the productive capacity of economies. Vergara (2010) identifies two channels through which taxes affect private investment: on the one hand, higher taxes increase the cost of capital (cost of capital channel), and on the other hand, they reduce the internal funds available for investment (liquidity constraint channel). However, an increase in private investment can lead to an increase in government revenue. The expected sign is positive.

– **Institutional quality:** the global index of good governance indicates the complete index of governance quality. To avoid the problems of multicollinearity and bias associated with omitted variables, this research constructs a global composite index of the main indicators of institutional quality by employing principal component analysis (PCA), as was also done, on the one hand, by Bobbo (2018) and, on the other hand, by Langbein and Knack (2010) and Ouedraogo and Thiombiano (2025). PCA makes it possible to "summarize" a set of observed variables into a number of "components" that are linear combinations of these variables Ouédraogo (2020). Poor governance marked by rising levels of corruption can be detrimental to economic and social development. Corruption can have negative effects on the economy, notably on public debt through public spending. Indeed, corruption can lead to an increase in public spending. If a government finances its spending by increasing debt, in the case of corruption, a higher stock of debt is needed, leading to higher debt servicing costs. As such, corruption can not only increase the volume of public spending but also shift the composition of public spending away from vital sectors such as health and education (Mauro, 1998; Wei, 2001) toward more secretive and less transparent sectors such as defense (Cooray and Friedrich, 2013). A positive sign is therefore expected for the coefficient of the public revenue variable.

– **Unemployment:** In recent decades, most countries have suffered from high and persistent unemployment. As a result, the fight against unemployment is now at the top of the political agenda. It is now widely accepted in political debates that reducing unemployment rates requires less restrictive tax policies to stimulate employment (Koskela and Schob, 1999). Indeed, a reduction in taxes can increase employment (Bovenberg and Van der Ploeg, 1996), since a tax reform with a reduction in tax rates leads to a reduction in the burden on companies,

enabling them to recruit more and help combat unemployment. A negative relationship is expected between unemployment and government revenues.

3.3. Data

This research adopts a panel of seven WAEMU countries over the period 1995-2022 (Benin, Burkina Faso, Ivory Coast, Mali, Niger, Senegal and Togo). The empirical analysis is based on annual quantitative data and secondary sources from different databases, depending on the availability of variables. The data come mainly from the World Bank database (WDI., 2023) and the United Nations Development Program (UNDP, 2024). Figure no. 1 illustrates the joint evolution of public debt, tax revenues and human development in WAEMU countries between 1995 and 2022.

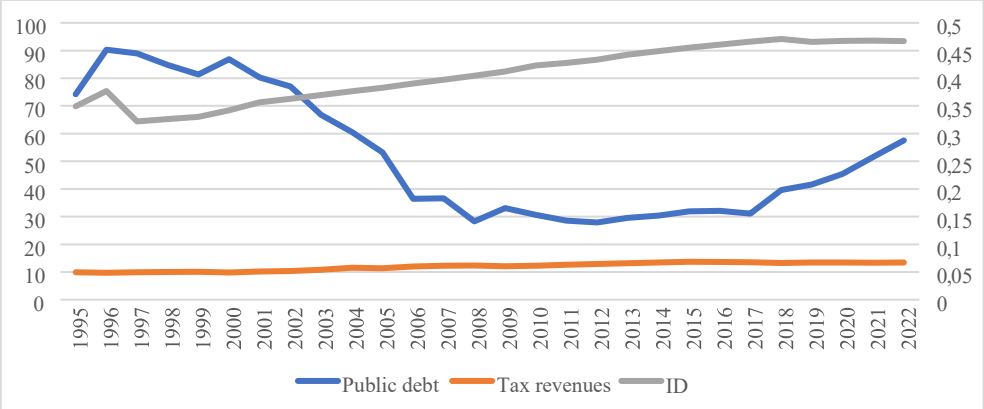

Figure no. 1 – Joint evolution of public debt, tax revenues and human development in the WAEMU from 1995-2022

4. RESULTS AND DISCUSSION

4.1. Results presentation

This section presents the results of the econometric tests and discusses the estimation method. The results of the multicollinearity tests are presented in Table no. 1. These tests are important for describing the degree of association between variables in the models. Multicollinearity analysis involves examining variance inflation factors (VIF). The VIF estimates the extent to which the variance of a coefficient is increased by its linear relationship with other predictors. It has been established in the literature that the deletion effect is a function of multicollinearity. Deletion of a variable should be allowed only if its variance inflation factor (VIF) is greater than 5 (Hair *et al.*, 2010; Akinwande *et al.*, 2015). However, the results presented in Table no. 1 indicate that the variance inflation factor (VIF) coefficients of the variables are all below 5, and the tolerance values (1/VIF) are all above 0.1, suggesting that our models would not suffer from multicollinearity problems.

With respect to the dependency tests, the results indicate that the variables are cross-sectionally dependent (Table no. 2). Stationarity tests are also performed. The results show that public revenue, trade openness, institutional quality, unemployment, urbanization and inflation are stationary at level. However, public debt, the human development index, foreign direct investment and private investment are stationary only in the first difference (Table no. 2).

In addition, the study uses Breusch and Pagan (1979) tests to check for heteroscedasticity. In addition, this research employs the Wooldridge (2010) test to examine possible error autocorrelation. The results of both tests reveal the existence of heteroscedasticity and autocorrelation in the models (see Annex for Tables no. A1 and no. A2). The null hypotheses that the error variances of our models are constant for all observations are therefore rejected. Given these results, estimating the models via the conventional ordinary least squares (OLS) strategy would provide inefficient results. Consequently, we estimate the tripartite relationship between public debt, tax revenues and human development using the panel-corrected standard error (PCSE) method. This technique effectively takes into account heteroscedasticity, autocorrelation and possible serial correlations Diendere and Yoda (2023). In addition, to increase the robustness of our results, we also estimate the models the robust standard error method of Driscoll and Kraay (1998). These two estimation techniques have been widely used in the literature (Ouedraogo *et al.*, 2025; Ouedraogo and Mano, 2025). The results of the two (02) estimators are presented in Tables no. 3 and no. 4.

Table no. 1 – Descriptive statistics

Variables	Obs	Mean	Std. dev	Min	Max	VIF	1/VIF
Tax revenues	196	11.955	2.634	4.954	20.30		
Public debt	196	49.019	29.616	11.176	160.830	2.07	0.483
Human development index	196	0.407	0.078	0.216	0.520	2.90	0.345
Trade openness	196	58.996	17.262	30.368	112.761	2.17	0.460
Foreign direct investment	196	1.616	2.583	-13.879	12.846	1.44	0.695
Private investments	196	13.847	5.155	2.612	33.066	1.77	0.564
Institutional quality	196	0.046	1.034	-2.726	2.290	1.16	0.861
Unemployment	196	4.087	2.926	0.273	11.710	1.57	0.638
Urbanization	196	4.216	0.893	2.721	6.725	1.64	0.608
Inflation	196	3.102	3.396	-7.594	16.286	1.09	0.914
Mean VIF						1.76	

Source: author

Table no. 2 – Tests for stationarity and variable dependence

Variables	CIPS	Hadri LM	LLC	Decision	CD-test	P-value
Public debt	-0.601	21.862***	-5.214**	I (1)	21.16	0.000
Human development index	-0.683	6.120***	-4.601***	I (1)	19.66	0.000
Tax revenues	0.059	14.690***	-3.619*	I (0)	18.95	0.000
Trade openness	-1.568	23.716***	-3.098	I (0)	12.11	0.000
Foreign direct investment	-2.914***	7.515***	-5.793***	I(I)	20.26	0.000
Private investments	-0.579	17.540***	-3.973*	I(I)	17.88	0.000
Institutional quality	-0.617	21.316***	-4.065	I (0)	16.21	0.000
Unemployment	0.215	23.769***	-3.770	I (0)	10.35	0.000
Urbanization	-4.642***	18.906***	-8.854***	I (0)	13.87	0.000
Inflation	-5.059***	0.840	-9.103***	I (0)	0.25	0.818

Note: ***, ** and * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

Source: author

Table no. 3 – Public debt and tax revenues: the role of human development (PSCE)

Variables	Tax revenues		
	1	2	3
Trade openness	0.4894*	0.4760*	0.5690*
	(0.2814)	(0.2483)	(0.2909)
Private investment	2.5686***	2.4283***	2.3643***
	(0.4403)	(0.2880)	(0.5822)
Urbanization	1.4102***	4.7511*	1.5566***
	(0.4124)	(1.8644)	(0.6617)
Institutional quality	4.5428**	5.4152**	4.6471***
	(2.4321)	(1.9467)	(1.6617)
Unemployment	-1.1036*	-0.3706	-0.7562
	(0.5936)	(0.3894)	(0.8636)
Inflation	-0.1125	-0.2900	-0.0158
	(0.4908)	(0.6097)	(0.4584)
Foreign direct investment	2.3515**	2.3801***	1.8627**
	(0.8655)	(0.6413)	(0.7129)
Human development index	0.0150***		0.0192**
	(0.0070)		(0.0081)
Public debt		-0.3861***	-0.5531*
		(0.1029)	(0.0577)
Human development index*Public debt			0.7469**
			(0.0050)
Constant	18.5996***	12.3547***	15.6394***
	(3.9539)	(2.9554)	(3.2910)
R-squared	0.5087	0.4092	0.5199
Number of observations	196	196	196

Note: Standard error in parenthesis, *** significant at 1% level, ** significant at 5% level, and * significant at 10% level.

Source: author

Table no. 4 – Public debt and tax revenues: the role of human development (Driscoll-Kraay)

Variables	Tax revenues		
	1	2	3
Trade openness	0.4894*	0.4760*	0.5690*
	(0.1448)	(0.1551)	(0.1647)
Private investment	2.5686***	2.4283***	2.3643***
	(0.3576)	(0.3773)	(0.4136)
Urbanization	1.4102***	4.7511*	1.5566***
	(0.5505)	(1.5666)	(0.8564)
Institutional quality	4.5428**	5.4152**	4.6471***
	(1.2533)	(1.3182)	(1.1778)
Unemployment	-1.1036*	-0.3706	-0.7562
	(0.4931)	(0.7011)	(0.9577)
Inflation	-0.1125	-0.2900	-0.0158
	(0.5519)	(0.6524)	(0.5406)
Foreign direct investment	2.3515**	2.3801***	1.8627**
	(0.7576)	(0.6894)	(0.7424)
Human development index	0.0150***		0.0192**
	(0.0028)		(0.0091))

Variables	Tax revenues		
	1	2	3
Public debt		-0.3861***	-0.5531*
		(0.0929)	(0.0177)
Human development index*Public debt			0.7469**
			(0.0080)
Constant	18.5996***	12.3547***	15.6394***
	(2.8561)	(2.0013)	(4.9332)
R-squared	0.5087	0.4092	0.5199
Number of observations	196	196	196

Note: Standard error in parenthesis, *** significant at 1% level, ** significant at 5% level, and * significant at 10% level.

Source: author

4.2. Discussion

This subsection presents and discusses the main results of the econometric model estimates analyzing the relationships among public debt, tax revenues and human development in the WAEMU. As a reminder, the models are estimated using the panel-corrected standard error (PCSE) and robust standard error methods of Driscoll and Kraay (1998) to account for heteroskedasticity, autocorrelation, possible serial correlations and cross-sectional dependence. The results of these estimates are presented in Tables no. 3 and no. 4.

With respect to the variables of interest, we observe the following:

The influence of human development on tax revenues is positive and statistically significant. This indicates that an increase in the level of human development would lead to an increase in public resources in WAEMU countries. Indeed, by improving health, education and living standards, human development stimulates economic growth. This growth in turn leads to an increase in income, thus broadening the tax base. Moreover, the transition to a formal economy, encouraged by human development, means that more corporate and income taxes can be collected. Finally, a higher standard of living creates greater demand for public services, which in turn reinforces the acceptance of higher levels of taxation. In short, human development is a long-term investment that generates positive returns for public finances. By promoting economic growth, improving tax compliance and increasing demand for public goods, human development helps strengthen a country's tax base. These results are in line with the work of Singoro (2021). The author examined the effect of the human development index (HDI) on tax revenue performance. Econometric estimates indicate that the human development index (HDI) is statistically significant and has a positive influence on tax revenue performance in Kenya. From the same perspective, Ofoegbu *et al.* (2016) argued that an increase in tax resources would improve the human development index, which is a better measure of Nigeria's economic performance. Although our findings are similar to those of previous authors, they differ in several ways. Unlike previous authors who focus on small areas of individual countries, our analysis covers a broader area, which provides more conclusive results.

The results of our investigation within the WAEMU indicate that public debt exerts a significant negative influence on tax revenues. This observation suggests that a trajectory of increasing debt tends to contract tax revenues. Several dynamics underlie this relationship. Rising debt translates into increased financial burdens, reducing budgetary capacity for

productive spending such as public investment. Furthermore, the growing share of debt service in total spending limits the resources available to finance essential public services. Furthermore, the crowding-out effect induced by high debt can hamper private investment, slowing economic expansion and, ultimately, tax revenue generation. In conclusion, the persistence of excessive public debt constitutes a brake on tax revenues, perpetuating a cycle of constrained spending, high interest rates, and anemic growth. These findings support the work of Boukbech *et al.* (2018).

With respect to the effect of the interaction between public debt and human development, the results reveal that there is a positive and significant link between the variables, with a larger coefficient than the two variables taken separately. Our results show that the interaction term between public debt and human development increases public revenues in the WAEMU. The positive sign of the "public debt*human development" coefficient shows that the effects of public debt on public revenues can be enhanced by human development. Indeed, human capital is a valuable asset for a country seeking to control its public debt. By stimulating growth, reducing expenditures and strengthening the resilience of the economy, it helps to improve long-term debt sustainability. The improvement effect of public debt and human development on public revenues obtained by our study is not surprising, as it means that carefully managed debt, when invested in critical sectors such as infrastructure, healthcare and education, can significantly improve human development indicators and stimulate economic growth, thereby increasing the opportunities and well-being of the population. A high level of human development is generally associated with increased tax revenues, owing to a broader tax base and better tax compliance. This finding is consistent with those of Igudia (2021) and Opara *et al.* (2021) but contrasts with those of Sadiq *et al.* (2022) and Wang *et al.* (2021). Unlike these authors, our analysis innovated by introducing the interaction variable "public debt * human development" in order to study the effects of the simultaneous increase of these two variables on tax revenues. The introduction of the interaction variable "public debt * human development" allows for a more sophisticated and realistic analysis of the relationship between public debt and tax revenues, taking into account the crucial role of the human development context. This can lead to more precise conclusions and more appropriate policy recommendations.

For the control variables, we note the following:

Trade openness is positively correlated with tax revenues in WAEMU countries. While greater integration into international trade exposes economies to competitive pressures, it also promotes economic growth, a broader tax base and the formalization of businesses, thus contributing to higher government revenues. These findings are consistent with those of Baunsgaard and Keen (2010) and Profeta and Scabrosetti (2010). Similarly, a study by Amoh and Adom (2017) examined the effect of trade openness on commercial tax revenues in Ghana. The results show that trade openness has a positive effect on tax revenues in the international trade sector in the short term.

The results also show that the institutional quality indicator is positively correlated with tax revenues in the WAEMU region. A rise in institutional quality increases tax revenues. An increase in the quality of institutions is an essential lever for increasing public revenues. By building trust, improving the efficiency of tax administration and combating corruption, strong institutions help create an environment conducive to economic growth and the mobilization of public resources. Empirical studies show a positive correlation between democracy and tax revenues; when democratic freedoms and political rights are fully and

strongly expressed, tax revenues are greater (Dioda, 2012). In countries with high levels of democracy and freedom, taxpayers are more aware of government and tax regulations and are more willing to address tax issues. In other words, people will voluntarily pay their taxes and appear less likely to engage in tax evasion. In addition, political stability and social security create a better environment for the economy to function. As a result, tax revenues are higher (Castro and Camarillo, 2014).

The results of our analysis reveal a positive and statistically significant correlation between private investment and tax revenues. This means that an increase in domestic investment is associated with an increase in tax revenues. This relationship is explained by the fact that private investment stimulates economic growth, broadens the tax base and generates additional revenues for public administrations. Our results are in line with those of Kotarba and Kolomvcew (2014) and suggest that allocating private spending to development projects can help create an economic environment conducive to growth and higher public revenues.

FDI has a positive and significant effect on tax revenues. In other words, in WAEMU member countries, the higher the level of foreign direct investment is, the higher the level of government revenue. This could be explained by the fact that FDI gives rise to new businesses, often in high value-added sectors. These companies generate new taxable income (corporate income tax, personal income tax). FDI also contributes to growth in gross domestic product (GDP). As GDP increases, so do the tax bases (income, profits, consumption). The increase in income linked to economic growth leads to an increase in consumption, which in turn increases revenues from VATs and other indirect taxes. Finally, FDI can increase the economy's overall productivity, resulting in higher revenues and tax receipts. These findings corroborate Pratomo (2020) research, which asserts that increased FDI has a positive relationship with total tax revenues, as well as with corporate, personal and value-added taxes in developing countries.

Unemployment has a negative and significant coefficient with respect to tax revenues. An increase in the unemployment rate reduces public revenues in WAEMU countries. This is because unemployment leads to a decrease in household incomes, reducing the income tax base. In addition, the drop in demand linked to unemployment affects corporate profits, thus reducing the corporate tax base. Finally, during periods of unemployment, some individuals may be tempted to work in the informal economy, thus escaping taxation. In short, unemployment represents a real challenge for public finances. To limit its negative impact, it is essential to implement active employment policies, strengthen social protection and promote economic growth. As Tahlova and Banociova (2019); Andrejovská and Glova (2023) have shown, there is a negative correlation between the unemployment rate and tax revenues. These studies suggest that the decline in corporate profitability resulting from higher unemployment leads to a reduction in tax revenues, particularly corporate income taxes.

Urbanization has a positive and significant effect on tax revenues. Urbanization, i.e., the process of population concentration in cities, has far-reaching implications for the economy, particularly for public revenues. Indeed, urban growth generally leads to an increase in tax revenues for several reasons: (i) cities concentrate a large number of businesses, which considerably broadens the corporate tax base; (ii) wages are generally higher in urban areas, which translates into increased income tax revenues; (iii) the concentration of the population in cities stimulates consumption, thus increasing revenues from VAT and other indirect taxes; and (iv) cities are generally service centers (finance, trade, transport, etc.), which are sectors that generate substantial tax revenues. These results are in line with those of Chilima (2005), whose argument was that urbanization transforms the economy from informal to more formal, increasing

the amount of revenue collected as people become employed in more formal work. The results are also similar to those produced by an empirical study carried out by Karagoz (2013).

5. CONCLUSION AND POLICY IMPLICATIONS

5.1. Conclusion and policy recommendations

Empirical studies of the interdependence between public debt and tax revenues have produced contrasting results. The literature has gradually been enriched by analyses incorporating human development as an additional explanatory variable. In line with this trend, our study aims to deepen our understanding of the relationships among public debt, tax revenues and human development at WAEMU. By estimating the models using Driscoll and Kraay (1998) robust standard error methods and the panel-corrected standard error (PCSE) to account for heteroskedasticity, autocorrelation, possible serial correlations and cross-sectional dependence on panel data covering the period 1995-2022, we analyze these complex relationships within WAEMU countries.

Our results indicate that human development has a positive effect on public revenues. In addition, we find that the increase in public debt acts as a brake on tax revenue mobilization. Finally, our analysis suggests that the negative effect of public debt on revenues could be moderated in the context of human development within the WAEMU. Our results suggest that human development policies have a positive effect on the public finances of WAEMU member states. To reinforce this dynamic, we recommend increasing investment in education and health, which are essential pillars of human development. These investments should be accompanied by reforms aimed at optimizing the allocation of public resources in these sectors. The use of public debt can be an effective tool for stimulating economic growth and increasing public revenues in the context of well-developed human development. An adequate level of human development can reinforce the effectiveness of public debt as a tool for stimulating economic growth by enabling better absorption of public investment and promoting more inclusive growth.

5.2. Limitations and Future Recommendations

5.2.1. Limitations

This study, although it provides valuable information on the relationship between public debt, tax revenues and human development in WAEMU countries, has certain limitations:

- The Human Development Index (HDI), although a widely used composite measure, does not capture all dimensions of human development (inequalities, environmental sustainability). The study may be limited by the aggregate nature of this index.
- WAEMU countries exhibit significant differences in terms of economic structure, level of development, institutional quality, and fiscal policies. Treating these countries as a homogeneous group could mask dynamics specific to each nation.
- Findings based on WAEMU countries may not be directly generalizable to other regions or groups of countries due to their specific economic, institutional and social contexts.

5.2.2. Recommendations for Future Studies

Future studies could focus on the relationship between public debt, tax revenues and human development in individual WAEMU countries. Future research could also analyze the relationship between public debt and revenue by considering the role of other recently developed human well-being indicators, such as the Multidimensional Poverty Index (MPI), the Gender Inequality Index (GII), and the World Happiness Index, depending on available data.

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ANNEX

Table no. A1 – Wooldridge autocorrelation test H0: no first-order autocorrelation

Equations	Statistics F	Wooldridge probability	Decision
1ere equation	F (7, 139) = 64.15	Prob > F = 0.000***	Presence of autocorrelation
2eme equation	F (7, 139) = 73,32	Prob > F = 0.000**	Presence of autocorrelation
3th equation	F (7, 139) = 55,93	Prob > F = 0.000***	Presence of autocorrelation

Source: author. ***p < .01; **p < .05; *p < .1.

Table no. A2 – Breusch-Pagan/Cook-Weisberg test of heteroskedasticity

Ho: constant variance

Equations	Statistics F	Breusch–Pagan probabilities	Decision
1ere equation	Chi2(1) = 19,25	Prob > chi2 = 0.000***	Presence of heteroskedasticity
2eme equation	Chi2(1) = 15.74	Prob > chi2 = 0.000***	Presence of heteroskedasticity
3th equation	Chi2(1) = 13.93	Prob > chi2 = 0.000***	Presence of heteroskedasticity

Source: author. ***p < .01; **p < .05; *p < .1.

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Spillover Dynamics of Sustainability Uncertainty: A Time-Varying Parameter Vector Autoregression Extended Joint Connectedness Analysis of BRIC Economies and the United States

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Abstract: Environmental, Social, and Governance (ESG) factors are increasingly shaping policies, investments, and risk assessments. The paper examines the cross-country spillovers and dynamic interlinkages of sustainability uncertainty between the BRIC economies (Brazil, Russia, India, and China) and the United States (U.S.) using the newly developed ESG-based Sustainability Uncertainty Index (ESGUI). To achieve this, we apply the Time-Varying Parameter Vector Autoregression (TVP-VAR) Extended Joint Connectedness Approach to a dataset spanning from November 2002 to September 2024.Our analysis reveals a moderate level of total connectedness (TCI) over the full sample period, indicating moderate cross-country spillovers. India emerges as the dominant transmitter of sustainability uncertainty, while Russia is the primary recipient of shocks. However, during the COVID and post-COVID period, the TCI increases significantly, reflecting heightened interconnectedness. Notably, India transitions from a major transmitter to a net receiver, while Brazil and Russia take on stronger roles in transmitting shocks. This study contributes novel insights into the time-varying and asymmetric nature of sustainability uncertainty transmission between the BRIC economies and the U.S. The results offer valuable implications for financial regulators, policymakers, and investors, highlighting the need for adaptive risk mitigation strategies and coordinated policy responses to manage systemic sustainability-related risks.

Keywords: ESG-Related Uncertainty Index; TVP-VAR; Extended Connectedness Analysis; BRIC Economies; Policy Uncertainty Spillovers; ESG Risk; Sustainability.

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1. INTRODUCTION

Environmental, Social, and Governance (ESG) factors have become central to the formulation of public policy, corporate strategy, and investment decision-making (Ellili, 2024). As global economies become increasingly interdependent (Kayani *et al.*, 2024), the transmission of sustainability-related shocks across countries (economies) has emerged as a critical concern for financial stability and policy coordination. Recent global disruptions ranging from the COVID-19 pandemic to ongoing geopolitical conflicts in Ukraine, Palestine, and the Middle East, coupled with intensifying climate risks have exposed the systemic, uncertain, and interconnected nature of sustainability challenges. These developments underscore the urgency of building adaptive economic systems that integrate ESG considerations to bolster resilience (Segovia-Vargas and Camacho-Miñano, 2024).

Ongan *et al.* (2025) introduced the ESG-based sustainability uncertainty index (ESGUI), a novel measure that quantifies sustainability-related risk dynamics across 25 developed and emerging economies. By leveraging textual analysis, the ESGUI captures the evolving landscape of ESG risks and regulatory developments, making it a valuable tool for policymakers, investors, and researchers. While the literature on economic policy uncertainty (EPU) and its cross-country spillovers is well-developed (Antonakakis *et al.*, 2018; Guo *et al.*, 2022; Guo *et al.*, 2025), empirical investigation into the interconnectedness of sustainability uncertainty invites attention. This study addresses this research gap by examining the interconnectedness and spillover dynamics of sustainability uncertainty (ESGUI) among the BRIC economies (Brazil, Russia, India, and China) and the United States (U.S.), the world's largest economy and a key player in ESG initiatives. Given their economic scale, resource endowments, and geopolitical significance, these economies play a crucial role in global financial markets, trade flows, and ESG policymaking (Balcilar *et al.*, 2018). Each of these economies presents distinct sustainability risks. Brazil faces sustainability concerns related to deforestation, political uncertainty in environmental governance, and resource overexploitation. Russia's sustainability risks stem from its fossil fuel dependency, exposure to climate change, and geopolitical instability. India confronts severe sustainability challenges, including extreme climate conditions, clean energy transition, and high pollution levels. China, despite being a global leader in renewable energy investments, remains heavily reliant on coal and faces significant environmental costs from industrialization and resource extraction. Meanwhile, the U.S. leads in clean energy innovation but grapples with policy inconsistencies, ongoing fossil fuel dependence, and increasing climate-related disasters. Sustainability uncertainty in these economies can generate spillover effects through trade linkages, capital markets, and policy coordination mechanisms (Huang and Li, 2024).

This study employs the Time-Varying Parameter Vector Autoregression (TVP-VAR) Extended Joint Connectedness Approach (Balcilar *et al.*, 2021) to quantify ESG uncertainty interdependencies among the BRIC economies and the U.S. using data from November 2002 to September 2024. Unlike static models, the TVP-VAR framework allows for time-varying coefficients, enabling the identification of evolving patterns in sustainability uncertainty spillovers over time. Leveraging the newly developed ESGUI, the paper provides a novel perspective by quantifying cross-country uncertainty spillovers from ESG dimensions. Focussing on the BRIC economies and the U.S. representing major emerging markets and a global financial leader, the paper underlines the importance of monitoring and managing sustainability risks in countries that have significant influence on the global economy and

environmental outcomes. By identifying the primary transmitters and receivers of sustainability uncertainty, the study offers actionable insights for investors, policymakers, and regulators seeking to mitigate systemic ESG risks. The findings also have broader implications for multilateral institutions such as the IMF, World Bank, and United Nations, which can leverage these insights to foster coordinated international efforts, promote global financial stability, and support the design of cooperative sustainability policies across nations.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature. Section 3 presents the data and methodology. Section 4 discusses the empirical findings. Section 5 provides concluding remarks.

2. LITERATURE REVIEW

The extensive research on EPU spillovers provides valuable methodologies, such as vector autoregressions, spillover indices, and network analysis, that can be adapted and extended to explore the complex phenomenon of sustainability uncertainty spillovers, where ESG-related risks act as sources and channels of uncertainty. This foundation is invaluable for advancing research into sustainability uncertainty spillovers, which similarly require accounting for complex interdependencies and evolving transmission channels in an increasingly interconnected global economy.

Sum (2013) uncovered a persistent and bidirectional long-term relationship between U.S. and European economic policy uncertainty (EPU), illustrating that uncertainty shocks can flow in both directions across these major economies. Colombo (2013) corroborated this interdependence, demonstrating through a Structural Vector Autoregression (SVAR) framework that the Euro area is particularly vulnerable to changes in U.S. economic policy, underscoring the region's sensitivity to external policy signals. Extending this perspective, Klößner and Sekkel (2014) explored policy uncertainty spillovers among six advanced economies, finding that more than one-quarter of domestic EPU can be traced to international sources, a share that escalated to around 50% amid financial crises, when global interconnectedness intensifies. Balli *et al.* (2017) introduced further nuance by highlighting that the transmission of policy uncertainty is significantly mediated by the strength of economic linkages, such as trade openness and institutional quality, which shape both the intensity and pathways of spillovers. In the context of emerging markets, Bhattarai *et al.* (2020) documented that policy uncertainty exerts substantial impacts on key financial indicators including stock prices, exchange rates, and capital inflows demonstrating that these effects are not confined to advanced economies. Methodologically, Antonakakis *et al.* (2018) utilized a time-varying approach to chart the evolving dynamics of uncertainty spillovers, notably identifying the European Union as a primary source of uncertainty shocks affecting the U.S. , a reversal of commonly held assumptions of U.S. dominance. Adding further depth, Gabauer and Gupta (2018) focused on U.S.-Japan dynamics and emphasized the central role of monetary policy uncertainty in facilitating cross-border risk transmission. These studies highlight the multifaceted, evolving, and increasingly global nature of policy uncertainty spillovers, while also pointing toward the importance of economic structure, institutional frameworks, and temporal dynamics in shaping these relationships.

Several studies have also delved into the regional contours of policy uncertainty spillovers, broadening the evidence base beyond advanced economies. For instance, Çekin *et al.* (2020) identified strong interdependencies in policy uncertainty among major Latin American economies

including Brazil, Chile, Colombia, and Mexico with these linkages being particularly pronounced in the years leading up to the Global Financial Crisis. Complementing this regional focus, Trung (2019) employed a Global VAR (GVAR) model to demonstrate that U.S. policy uncertainty has far-reaching disruptive effects on international trade and financial markets, reinforcing the centrality of the U.S. in global uncertainty transmission. Bai *et al.* (2019) further highlighted that the intensity of uncertainty spillovers escalates notably during episodes of financial turmoil, contributing to heightened market instability. In the Asia-Pacific context, Tang *et al.* (2021) and Osei *et al.* (2021) documented robust channels of uncertainty transmission among key regional players including China, India, Japan, and Korea suggesting that regional economic integration increases susceptibility to cross-border shocks. Adding another perspective, Abakah *et al.* (2021) showed that the transmission of policy uncertainty is often driven by country-specific factors rather than broad global trends, underscoring the significance of local context and highlighting the need for targeted, rather than universal, policy responses. These studies demonstrate that policy uncertainty spillovers exhibit considerable heterogeneity across regions, vary significantly in intensity and timing, and are shaped by both local dynamics and the broader global environment.

The COVID-19 pandemic further intensified the dynamics of uncertainty spillovers, as documented in several recent studies. Zhou *et al.* (2022) employed the spillover index approach to demonstrate that pandemic-related restrictions sharply increased cross-border uncertainty transmission, underscoring how global crises can amplify systemic risks. Ouyang *et al.* (2022) provided evidence that surges in U.S. monetary policy uncertainty during the pandemic significantly elevated systemic financial risks in China, highlighting the heightened vulnerability of emerging markets to external shocks in turbulent periods. Expanding on these findings, Guo *et al.* (2022) investigated cross-category spillovers between U.S. and Chinese policy uncertainties and uncovered that these transmission effects are distinctly time-dependent, suggesting that the direction and strength of spillovers fluctuate with evolving crisis conditions. Complementing these perspectives, Huang and Li (2024) used spatial econometric techniques to pinpoint trade, investment, and fiscal policy as the primary channels of uncertainty transmission, with financial investment particularly pronounced as a conduit during the pandemic. These studies illustrate that the COVID-19 shock not only intensified uncertainty spillovers across borders and policy domains but also reshaped the mechanisms and timing of transmission, emphasizing the need for robust, adaptive policy coordination in the face of global disruptions.

Recent studies employing advanced network analysis techniques have deepened the understanding of policy uncertainty (EPU) spillover dynamics, particularly among major economies and emerging markets. Cho *et al.* (2023) identify the U.S. and Europe as principal transmitters of EPU, with China notably emerging as a key player in transmitting policy uncertainty in the post-2020 period. This suggests a shifting geopolitical economic landscape where China plays an increasingly influential role in uncertainty propagation. Alkan *et al.* (2023) analyse contagion effects across 21 economies, confirming that the U.S., U.K., France, and Germany are primary sources of policy uncertainty spillovers. Their findings also highlight the high vulnerability of Greece and the U.K., illustrating that exposure to these shocks can differ significantly among countries. Guo *et al.* (2025) focus on spillovers between the U.S. and BRIC countries, reaffirming the strong and persistent influence of U.S. policy uncertainty on emerging market economies across various time horizons. This aligns with broader themes of U.S. monetary and fiscal policy acting as key global uncertainty drivers. Sikhwal (2024) quantifies the macroeconomic consequences of U.S. policy uncertainty on 39

emerging markets, documenting significant adverse effects on inflation rates and GDP growth, which underscores the real economy impacts beyond financial markets. Using monthly data from 2003 to 2023 and the Diebold and Yılmaz (2012) spillover index framework, Kayani *et al.* (2024) investigate the BRIC economies, finding China experiences the highest directional spillovers, making it the dominant uncertainty transmitter within the group. Brazil appears the least affected, reflecting heterogeneity within emerging markets. Adjei *et al.* (2025) extend the analysis to six emerging markets, identifying Korea as a central transmitter of EPU spillovers. They also detect strong short-term links between policy uncertainty, GDP fluctuations, and stock prices, highlighting the tight coupling between economic fundamentals and uncertainty in these economies.

These findings emphasize the importance of dynamic, regionally nuanced policy frameworks, enhanced surveillance of uncertainty transmission channels, and coordination among both advanced and emerging economies to buffer against systemic risks intensified by global policy uncertainty. These studies collectively confirm that EPU propagates through trade, financial markets, and institutional channels, shaping global economic stability. Sustainability uncertainty (ESGUI), driven by ESG factors, is similarly capable of generating cross-border ripple effects, influencing investments, market stability, and long-term growth. However, our understanding of sustainability uncertainty spillovers remains limited. Building on recent advances in understanding the multifaceted and evolving nature of policy uncertainty spillovers, as well as the intensified transmission effects observed during the COVID-19 pandemic, this paper investigates the cross-country spillovers and dynamic interlinkages of sustainability uncertainty among the BRIC economies and the U.S. This study offers novel insights into the evolving transmission mechanisms of ESG-related risks (ESGUI) between major emerging markets and the U.S., informing adaptive risk mitigation strategies and coordinated policy responses to effectively manage systemic sustainability-related risks in an increasingly interconnected and volatile global economy.

3. DATA AND MODEL

3.1. Data

This study employs the Sustainability Uncertainty Index (ESGUI) developed by Ongan *et al.* (2025), sourced from https://www.policyuncertainty.com/sustainability_index.html . The ESGUI dataset provides monthly data from November 2002 to September 2024 for 25 countries, including the BRIC economies and the U.S., capturing fluctuations in environmental, social, and governance (ESG) uncertainty over a 22-year period. By reflecting the impact of major global economic, political, and environmental events, the ESGUI offers a comprehensive measure of sustainability-related risk dynamics across economies.

The full sample period for this study spans from November 2002 to September 2024. To assess the impact of the COVID-19 pandemic and its aftermath, we define the COVID and post-COVID period as beginning in February 2020 and extending through September 2024, based on data availability.

Table no. 1 presents a summary of the ESGUI statistics across the selected economies, based on the first log-differenced series. The table is divided into two parts: Part A, which reports the statistics for the full sample period (November 2002–September 2024), and Part B, which focuses on the COVID and post-COVID period (February 2020–September 2024).

Table no. 1 – Summary Statistics

Part A : Full Sample					
	Brazil	**China**	**India**	**Russia**	**United States**
Mean	-0.001	0.004	-0.001	-0.005	-0.004
Variance	0.104	0.132	0.096	0.124	0.104
Skewness	-0.312**	-0.705***	-0.554***	0.267*	-0.044
Ex.Kurtosis	2.244***	10.158***	4.443***	3.336***	1.096***
JB	59.433***	1152.644***	229.786***	125.095***	13.244***
ERS	-4.062***	-5.706***	-2.550**	-1.295	-3.615***
Q(10)	82.623***	74.539***	78.154***	164.938***	29.388***
Q^2(10)	131.294***	50.827***	72.768***	145.518***	34.616***
Part B: COVID and Post COVID Sample					
Mean	0.001	0.005	0.007	-0.005	-0.012
Variance	0.015	0.005	0.009	0.011	0.044
Skewness	-0.892***	-0.452	-0.257	-0.286	0.097
Ex.Kurtosis	2.608***	-0.523	0.878	-0.121	1.820**
JB	23.291***	2.548	2.418	0.799	7.818**
ERS	-2.780***	-1.405	-4.974***	-0.549	-3.906***
Q(10)	15.976***	4.133	3.224	6.882	3.6
Q^2(10)	3.559	4.554	2.35	4.053	1.638

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

The mean ESGUI values near zero across the full sample suggest that sustainability uncertainty fluctuates around a neutral baseline, with no persistent trend for most countries. China's slightly positive mean value indicates a modest upward bias in uncertainty, likely due to evolving environmental policies and regulatory scrutiny. In contrast, Russia and all other economies show slightly negative means values, reflecting relatively lower or more stable uncertainty. China also exhibits the highest variance, indicating greater fluctuations, followed by Russia, the U.S., and Brazil, while India shows the lowest variability. Negative skewness in Brazil, China, and India implies more extreme negative shocks, whereas Russia shows slight positive skewness and the U.S. has an approximately symmetric distribution. All countries have significantly positive excess kurtosis, signalling fat tails and frequent large swings, with China's extreme kurtosis indicating a highly volatile environment. The Jarque-Bera test (Jarque and Bera, 1980) strongly rejects the assumption of normality for all countries at the 1% significance level, indicating notable deviations in both skewness and kurtosis. The Elliott-Rothenberg-Stock (ERS) stationarity test (Elliott *et al.*, 1996) indicates that the series is stationary for Brazil, China, India, and the U.S., but not for Russia. The weighted portmanteau tests (Fisher and Gallagher, 2012) reveal significant autocorrelation and volatility clustering in returns and squared returns [Q(10), Q2(10)] across all countries, reflecting common serial dependence and conditional heteroskedasticity in economic time series.

During the COVID and post-COVID period, notable shifts in sustainability uncertainty dynamics are observed with China, India and Brazil experiencing mild increases in uncertainty averages, while the U.S. and Russia show negative average uncertainty but with the U.S. exhibiting more volatile swings (high variance). This suggests the pandemic altered uncertainty dynamics, intensifying volatility especially in the U.S. The extreme negative skewness and fat tails seen in the full sample soften during the COVID and post-COVID sample except in Brazil and U.S. (pronounced tail risk). Stationarity properties remain largely stable. Serial dependence and volatility clustering weaken considerably during the COVID and post-COVID sample. These diagnostics justify the choice of flexible and dynamic

frameworks such as TVP-VAR models that can adapt to evolving relationships, non-normal errors, and evolving statistical properties in the data.

The Figure no. 1 provides key insights into the evolution of sustainability uncertainty (ESGUI) across the BRIC economies and the U.S. during the full sample period.

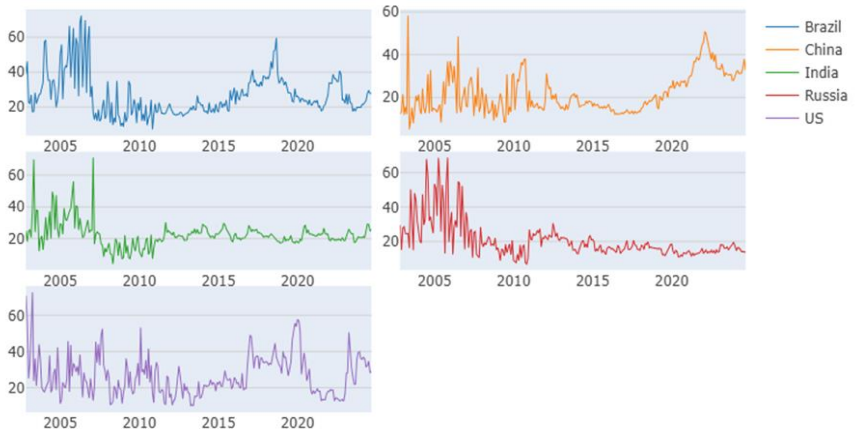

Figure no. 1 – Evolution of Sustainability Uncertainty (Full Sample)

3.2. Methodology

We analyse ESGUI spillover dynamics using the Extended Joint Connectedness measure within a TVP-VAR framework, following the methodology of Balcilar *et al.* (2021). This method builds on the connectedness framework introduced by Diebold and Yılmaz (2012), which is extensively applied in financial and macroeconomic spillover analysis.

In this study, we use a model with a lag order of one, determined by the Bayesian Information Criterion (BIC), as outlined below:

$$y_t = M_t y_{t-1} + \epsilon_t, \epsilon_t \sim N(0, \Sigma_t) \quad (1)$$

$$vec(M_t) = vec(M_{t-1}) + u_t, u_t \sim N(0, R_t) \quad (2)$$

In this model, y_t, y_{t-1} and ϵ_t are $Z \times 1$ dimensional vectors, while M_t and Σ_t are $Z \times Z$ dimensional matrices. The vectorized form of M_t, denoted as $vec(M_t)$ along with u_t, are $Z^2 \times 1$ dimensional vectors, whereas R_t is a $Z^2 \times Z^2$ dimensional matrix. This framework allows all parameters, including M_t, and the relationships between successive series to change over time. Additionally, it assumes that the variance-covariance matrices Σ_t and R_t also evolve dynamically over time.

The TVP-VMA (Vector Moving Average) model is obtained as the moving average representation (Wold representation) of a TVP-VAR model and is defined as follows:

$$y_t = \sum_{h=0}^{\infty} N_{h,t}\epsilon_{t-1}$$

where $N_0 = I_Z$ and ϵ_t denotes a symmetric white noise shock that the $Z \times Z$ time-varying covariance matrix $E(\epsilon_t \epsilon_t') = \Sigma_t$ varies with time. The TVP-VMA representation is a natural extension of the TVP-VAR model that improves our ability to analyse dynamic spillovers. By transforming the autoregressive system into a moving average representation, the model provides a clearer interpretation of how shocks propagate across variables over time, facilitates the computation of connectedness measures, and enhances its applicability for spillover analysis.

$$g\,ST_{ij,t} = \frac{\varphi_{ij,t}^{gen}(L)}{\sum_{j=1}^{L} \varphi_{ij,t}^{gen}(L)} \tag{3}$$

Here, e represents a Z×1 zero selection vector with a value of one at its i[th] position. Additionally, $\varphi_{ij,t}^{gen}(L)$ denotes the proportional decrease in the prediction error variance of variable i when accounting for future shocks from variable j. The $\sum_{j=1}^{Z} \varphi_{ij,t}^{gen}(L) \neq 1$ is adjusted to ensure a total value of 1, resulting in the final value of $gST_{ij,t}$ and given as follows:

$$X_{i\leftarrow\bullet,t}^{gen,from} = \sum_{j=1, i\neq j}^{Z} g\ ST_{ij,t} \tag{4}$$

$$X_{i\rightarrow\bullet,t}^{gen,to} = \sum_{j=1, i\neq j}^{Z} g\ ST_{ij,t} \tag{5}$$

The net total directional connectedness is expressed as: $X_{i,t}^{gen,net} = X_{i\rightarrow\bullet,t}^{gen,to} - X_{i\leftarrow\bullet,t}^{gen,from}$. If $X_{i,t}^{gen,net} < 0$ ($X_{i,t}^{gen,net} > 0$), variable *i* acts as a net receiver (transmitter) of shocks.

The Total Connectedness Index (TCI) measures the overall level of interdependence within a network of variables. A higher TCI value signifies stronger spillovers, indicating greater transmission of shocks across the system. It is expressed as follows:

$$g\,ST_t = \frac{1}{Z}\sum_{i=1}^{Z} X_{i\leftarrow\bullet,t}^{gen,from} = \frac{1}{Z}\sum_{i=1}^{Z} X_{i\rightarrow\bullet,t}^{gen,to}, \tag{6}$$

where a higher value indicates a greater degree of network spillovers.

Finally, the net pairwise directional spillovers are expressed as: $X_{i,t}^{gen,net} = gST_{ij,t}^{gen,to} - gST_{ij,t}^{gen,from}$. If $X_{ij,t}^{gen,net} > 0$, this indicates that series *i* exerts a greater influence on series *j*.

Building on the methodologies of Lastrapes and Wiesen (2021) and Balcilar *et al.* (2021), and drawing insights from Ha and Nham (2022) and Kayani *et al.* (2024), this study employs the extended joint connectedness technique with additional scaling adjustments to improve accuracy and comparability. These enhancements refine spillover estimates across different time periods and economic conditions, ensuring greater precision and consistency. The method is represented as follows:

$$X_{i,t}^{jnt,net} = X_{i\rightarrow\bullet,t}^{jnt,to} - X_{i\leftarrow\bullet,t}^{jnt,from} \tag{7}$$

$$X_{ij,t}^{jnt,net} = gST_{ji,t} - gST_{ij,t} \tag{8}$$

This analysis will help identify which economies act as shock transmitters and which are more vulnerable to receiving shocks over time.

4. DISCUSSION OF RESULTS

4.1. Averaged joint connectedness

Table no. 2 displays the averaged joint connectedness estimates for BRIC and the U.S., illustrating the interconnectedness of these economies. The rows represent each economy's contribution to the forecast error variance of others, while the columns indicate the proportion of a given economy's forecast variance that is influenced by all other economies. This provides insight into the extent of cross-country spillovers and interdependencies.

Table no. 2 – Averaged Joint Connectedness Estimates

Part A: Full Sample						
	Brazil	**China**	**India**	**Russia**	**United States**	**FROM**
Brazil	84.95	1.2	7.69	4.74	1.42	15.05
China	2.36	74.38	10.1	1.3	11.86	25.62
India	10.16	8.92	76.12	1.1	3.69	23.88
Russia	5.54	5.58	6.4	78.55	3.93	21.45
US	2.94	2.31	6.09	3.07	85.58	14.42
TO	21	18.01	30.28	10.22	20.9	TCI
NET	5.95	-7.61	6.41	-11.23	6.48	20.08
Part B: COVID and Post COVID Sample						
	Brazil	**China**	**India**	**Russia**	**United States**	**FROM**
Brazil	73.55	16.53	0.86	7.9	1.15	26.45
China	21.8	54.45	2.09	14.83	6.83	45.55
India	8.4	5.77	68.44	10.12	7.26	31.56
Russia	9.25	3.68	8.85	74.39	3.83	25.61
US	9.01	13.8	1.62	6.33	69.23	30.77
TO	48.47	39.79	13.42	39.18	19.08	TCI
NET	22.02	-5.77	-18.13	13.57	-11.69	31.99

Note: This analysis quantifies sustainability uncertainty spillovers received (FROM), transmitted (TO), and net transmitted (NET) across the Full Sample and COVID and Post-COVID Sample. Spillovers are estimated using a one-lag specification and a 10-month-ahead generalized forecast error variance decomposition (GFEVD). Diagonal elements indicate an economy's own shock-induced uncertainty, while off-diagonal elements capture cross-economy uncertainty spillovers.

In Part A of Table no. 2, which presents the results for the full sample analysis, the TCI of 20.08% suggests that, on average, 20.08% of the forecast error variance within the system is attributable to cross-economy spillovers, while the remaining 79.92% remains idiosyncratic. It suggests that while sustainability risks are still largely rooted in domestic dynamics, international influences play a non-negligible role, especially in globally integrated economies. India emerges as the most significant transmitter of sustainability uncertainty, with a TO value of 30.28, underscoring its pivotal role in propagating shocks across the system. This reflects India's growing prominence in global sustainability discussions stemming from regulatory shifts, energy transition, or environmental challenges and can significantly influence other countries, especially economies with close trade and investment ties. In contrast, Russia is the most prominent net receiver, with a NET value of -11.23, indicating that its sustainability uncertainties are primarily influenced by external factors. This could be attributed to its dependence on global fossil fuel demand and exposure to geopolitical shifts. Similarly, China registers a negative NET value of -7.61, reinforcing its role as a net recipient rather than a key source of spillovers. This suggests that despite its domestic environmental reforms, China remains highly exposed to global ESG policy shifts due to its integration in international supply chains and reliance on external markets for resource security. Conversely, the U.S. (NET = 6.48) and Brazil (NET = 5.95) act as moderate transmitters, albeit to a lesser extent than India, reflecting their roles in shaping sustainability uncertainty. The U.S.'s role may stem from its influence over global ESG regulations, corporate governance norms, and clean tech investment trends, while Brazil's role could be linked to deforestation, agribusiness policy shifts, and environmental governance debates that have global consequences. The FROM values further illustrate the susceptibility of each economy to external uncertainty spillovers. China (25.62), India (23.88), and Russia (21.45) exhibit the highest exposure, highlighting their vulnerability to sustainability-related shocks from other economies. In contrast, the U.S. (14.42) and Brazil (15.05) display lower FROM values, indicating that their sustainability uncertainties are more domestically driven. While the full sample analysis indicates moderate interconnectedness, systemic shocks such as the COVID-19 pandemic and geopolitical conflicts can significantly amplify spillover intensity. Further investigation into the crisis periods is crucial to understanding evolving spillover dynamics (Antonakakis *et al.*, 2020).

Part B of Table no. 2 presents a stark contrast to the full sample period, reflecting heightened interdependence and intensified spillover effects during the COVID and post-COVID period. The TCI has surged from 20.08% to 31.99%, signalling a sharp rise in interconnectedness among the BRIC economies and the U.S. This indicates that sustainability uncertainty has become more globally interconnected, with a larger share of forecast error variance explained by cross-country spillovers. During this period, the U.S. (NET= -11.69), India (NET= -18.13), and China (NET= -5.77) transition into net receivers of sustainability uncertainty, signifying that their risks are increasingly shaped by external factors. This marks a significant shift from the full sample period, where India was the dominant transmitter reflecting its heightened vulnerability to global ESG shocks in the aftermath of COVID-19 and energy market disruptions. This transformation may be due to India's reliance on imported energy, and climate-related vulnerabilities that are exacerbated during systemic stress. For the U.S., this could be linked to domestic policy uncertainty amid shifting federal climate commitments and global supply chain disruptions. For China, increasing ESG scrutiny and exposure to external demand shocks could explain its greater sensitivity to external

uncertainty. Conversely, Brazil (NET= 22.02) and Russia (NET= 13.57) emerge as the primary transmitters, reflecting their growing role in propagating sustainability-related shocks across the system. Brazil's expanded environmental degradation and global attention to Amazon deforestation, coupled with Russia's energy-export-centered economy and geopolitical aggression, have created significant outward spillover effects. The reversal of transmitter-receiver roles highlights the asymmetric and dynamic nature of sustainability uncertainty spillovers, underscoring how systemic shocks such as COVID-19 and geopolitical conflicts reshape spillover dynamics. The FROM values further reinforce this shift, with China (45.55), India (31.56), and Russia (25.61) facing the highest exposure to external spillovers. The "FROM" values reveal that China, India, and Russia became highly exposed to external shocks, suggesting these countries were heavily influenced by evolving ESG narratives, capital flows, and international regulatory developments during the crisis. Meanwhile, the U.S. and Brazil despite their transmitter status also experience non-negligible inflows of uncertainty, confirming the bi-directional nature of ESG spillovers. These results illustrate that systemic shocks can reconfigure the global sustainability risk network, turning transmitters into receivers and vice versa. This underscores the need for flexible, adaptive risk governance structures that are sensitive to global developments and capable of responding to rapidly evolving sustainability risks.

Further analysis of the COVID and post-COVID period is essential to understanding the evolving dynamics of spillovers. To this end, we extend our investigation by examining several dynamic measures, including the Dynamic Total Connectedness Index, Net Pairwise Directional Connectedness, Net Total Directional Connectedness, and constructing Network Diagrams illustrating interconnectedness specifically for the COVID and post-COVID period.

4.2. Dynamic total connectedness

Figure no. 2 illustrates the dynamic total connectedness (TCI) of the BRIC economies and the U.S. during the COVID and post-COVID period, providing insight into the time-varying nature of sustainability uncertainty spillovers among these economies.

In early 2020, TCI was relatively low, recorded at 19.57 in February, reflecting modest spillover effects. However, as the COVID-19 pandemic intensified globally, the interconnectedness of sustainability-related uncertainty escalated sharply. The TCI rose to 21.02 in March, surged to 36.55 in April, and peaked at an extraordinary 69.21 in August 2020 indicative of severe cross-country sustainability uncertainty spillovers. This peak corresponds with the height of the pandemic-induced economic and supply chain disruptions, highlighting how systemic global crises amplify interlinkages among national sustainability risks. Following this peak, a gradual normalization is observed. By early 2021, TCI declined and stabilized between 35 and 45, suggesting that although elevated uncertainty persisted, the extreme volatility of the initial pandemic phase had subsided. This stabilization phase signifies adaptive economic responses, effective public health measures, and supportive fiscal and monetary policies that helped economies shift toward a post-pandemic balance. During the mid-to-late 2021 period, the TCI remained within the 30–35 range, indicating moderate and sustained interconnectedness. Throughout 2022, TCI values hovered around 30–32, maintaining a relatively stable but interconnected regime. Notably, the TCI temporarily spiked to 34.65 in November 2022 potentially a reflection of market responses to escalating geopolitical tensions, particularly the Russia-Ukraine conflict and its implications for global energy markets and

supply chains. However, by December 2022, TCI dropped again to 29.02, suggesting that policy makers had gradually incorporated such shocks into their risk expectations. From 2023 onwards, a consistent decline in TCI is observed. By May 2023, the TCI had fallen to 22.38 and remained around that level for most of the year. This downward trend persisted into 2024, with values decreasing to 19.51 in August and further to 18.43 in September, returning to pre-pandemic levels. Taken together, the sharp rise and gradual fall in TCI illustrate the dynamic, shock-sensitive nature of sustainability uncertainty. The results reinforce the importance of agile policy responses and the need for global coordination during systemic crises while emphasizing the return to localized sustainability dynamics in more stable periods.

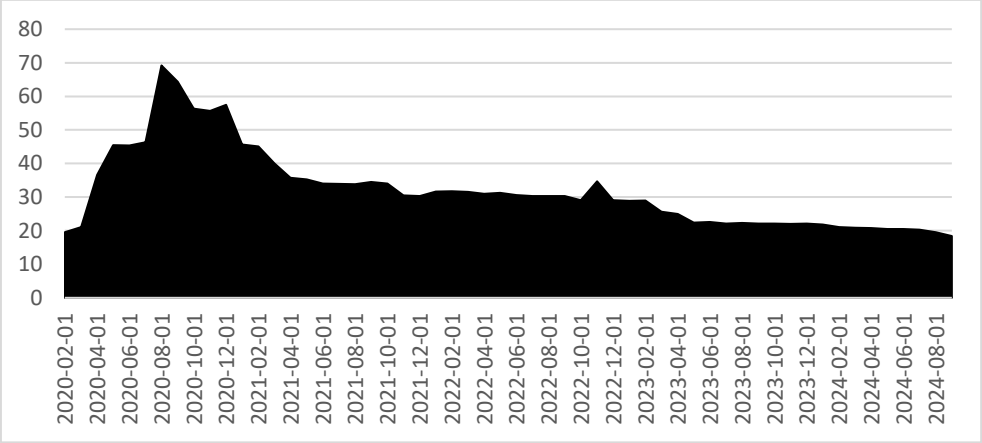

Figure no. 2 – Dynamic Total Connectedness (COVID and Post-COVID Sample)

4.3. Net pairwise directional connectedness

Figure no. 3 illustrates the Net Pairwise Directional Connectedness (NPDC) of sustainability uncertainty of the BRIC economies and the U.S. during the COVID and post-COVID period. It offers a quantitative assessment of spillover effects, identifying whether a country primarily acts as a net transmitter or net receiver of sustainability uncertainty in relation to other economies.

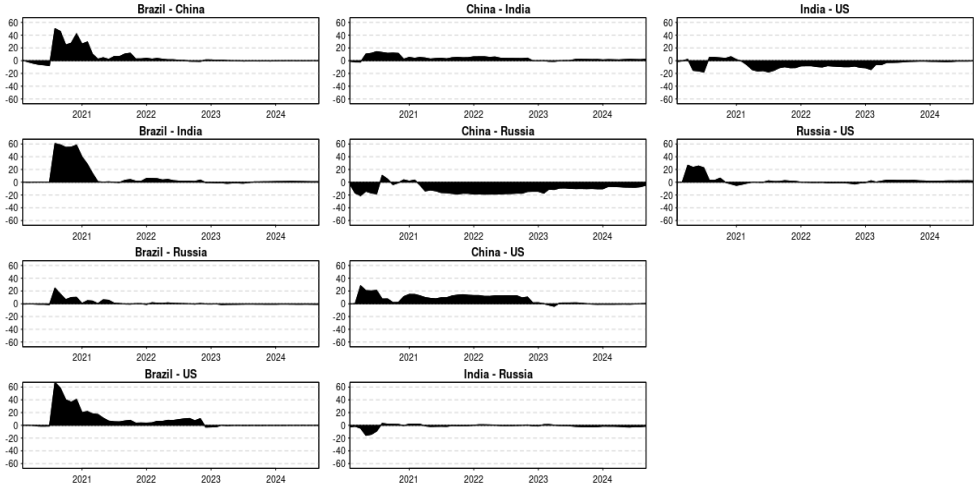

Figure no. 3 – Net Pairwise Directional Connectedness (COVID and Post-COVID Sample)

4.3.1. Brazil's trends

The NPDC values for Brazil-China, Brazil-India, Brazil-Russia, and Brazil-US were relatively low or negative, indicating that Brazil primarily absorbed uncertainty spillovers from these economies. The most significant decline occurred in June and July 2020, with Brazil-China and Brazil-US NPDC values dropping to -6.58 and -1.24, respectively. This period coincided with the initial economic disruptions caused by the COVID-19 pandemic, making Brazil highly vulnerable to external uncertainties.

A dramatic shift was observed in August 2020, when NPDC values surged across all country pairs. Brazil-China reached 50.27, Brazil-India 60.67, Brazil-Russia 24.69, and Brazil-US 67.42. This sharp increase suggests that Brazil transitioned from being a net receiver to a net transmitter of sustainability uncertainty. However, after peaking in late 2020, NPDC values declined and stabilized by mid-2021.

While Brazil maintained a net positive NPDC with India and the US indicating a sustained influence over these economies, its NPDC with Russia fluctuated around zero. The stabilization reflects economic adjustments, policy interventions, and a relative return to pre-pandemic interactions. Throughout 2023, Brazil's NPDC values remained negative or close to zero with China, Russia, and the US, indicating reduced transmission of sustainability uncertainty. Brazil-India NPDC remained slightly positive but at lower levels compared to previous years, ranging between -1.73 and 1.22.

By 2024, Brazil-India NPDC saw a slight resurgence, maintaining positive levels above 1.0. However, Brazil's NPDC with Russia remained negative, suggesting continued absorption of uncertainty from Russia rather than transmitting it. The Brazil-US NPDC fluctuated close to zero, indicating a balanced uncertainty transmission dynamic.

4.3.2. China's trends

In early 2020, China-India NPDC values were negative, suggesting that sustainability uncertainty flowed more from India to China. However, a significant shift occurred in May 2020, when NPDC turned positive and peaked at 14.16 in July, indicating that China became a net transmitter of sustainability uncertainty to India. After some fluctuations, NPDC values stabilized between 3 and 6 from 2021 to mid-2023. Since early 2024, NPDC has remained moderately positive, signifying that China continues to transmit sustainability uncertainty to India, albeit at a lower magnitude than in 2020.

The NPDC values for China-Russia were consistently negative throughout the period, indicating that Russia was the primary transmitter of sustainability uncertainty to China. The largest negative values appeared between April 2020 (-21.08) and March 2023 (-18.79), reflecting Russia's strong influence on China's sustainability uncertainty. However, a decreasing trend in negative NPDC was observed in 2024, with values rising from -10.24 in January to -4.58 in September.

For China-US, NPDC values fluctuated between positive and negative, suggesting bidirectional uncertainty spillovers. In April 2020, NPDC peaked at 28.34, indicating that China was the dominant transmitter of sustainability uncertainty to the US. This trend persisted through May-July 2020. From mid-2021 onward, NPDC remained mostly positive, with values peaking around 14-15 before gradually declining. By 2023-2024, NPDC values turned negative or hovered near zero, suggesting that the US was slightly influencing China's sustainability uncertainty rather than the reverse.

4.3.3. India's trends

India-Russia NPDC values remained predominantly negative, indicating that India was a net receiver of sustainability uncertainty from Russia. The lowest NPDC value was recorded in May 2020 (-15.71), coinciding with global trade and energy market disruptions caused by COVID-19. Brief positive NPDC values appeared in August-October 2020 and early 2022, suggesting temporary periods when India transmitted sustainability uncertainty to Russia. By 2023-2024, NPDC values continued to be negative, fluctuating between -2.68 and -1.30, reflecting persistent but reduced dependence on Russian uncertainty.

Similarly, India-US NPDC values were largely negative, signifying that India received sustainability uncertainty from the U.S. The most significant negative values were recorded in mid-2020 (-16.05 in June) and again in April-May 2021 (-14.09 and -16.21), likely linked to COVID-19's second-wave disruptions and policy uncertainties. From mid-2022 onwards, NPDC stabilized between -10 and -8, indicating sustained but reduced spillovers. However, the trend improved in 2023-2024, with values gradually rising toward zero, suggesting a diminishing dependence on U.S. sustainability uncertainty. Post-2021, NPDC values fluctuated between -2.76 and +3.20, reflecting a time-varying transmission dynamic.

4.4.4. Russia-US trends

The Russia- U.S. NPDC was predominantly positive, indicating that Russia was a net transmitter of sustainability uncertainty to the U.S. A significant spike was observed in April 2020 (26.63), May 2020 (23.25), and June 2020 (25.36), reflecting extreme uncertainty caused by the COVID-19 pandemic and oil market volatility. By 2023-2024, NPDC values hovered around 2, suggesting that Russia continued to exert moderate influence on sustainability uncertainty in the U.S.

4.4. Net total directional connectedness

Figure no. 4 illustrates the Net Total Directional Connectedness (NTDC) of the BRIC economies and the U.S. It provides a comprehensive view of each country's role in transmitting or receiving sustainability uncertainty spillovers. February to May 2020 shows substantial fluctuations, likely due to the COVID-19 pandemic's disruptions. Russia exhibited very high positive NTDC in May 2020, while India had negative values, indicating that Russia was a major transmitter and India a receiver of uncertainty during this period. The U.S., China, and Brazil also showed significant fluctuations, reinforcing the idea of global interconnectedness in sustainability uncertainty. Brazil exhibited a sharp spike in NTDC in August 2020 (203.07) and remained highly positive in the following months. This suggests Brazil transitioned from a net receiver to a dominant transmitter of sustainability-related uncertainty. The increase could be linked to environmental policies, deforestation concerns in the Amazon, and global discussions on climate policy. China's NTDC remains mostly negative throughout the dataset, implying that it consistently absorbs more sustainability uncertainty from the global network than it transmits. This pattern may be attributed to China's economic structure, large industrial emissions, and its role in global supply chains. From mid-2021 onwards, NTDC values stabilize for most countries. While India and China continue to be net receivers of uncertainty, Russia and Brazil maintain their roles as net transmitters. The U.S. exhibits fluctuations between positive and negative NTDC values, suggesting a more dynamic role within the network. Since 2023, the magnitude of these values has noticeably diminished compared to earlier periods. Brazil, which was earlier a major transmitter of uncertainty, shows NTDC values close to zero in the later part of the sample period, suggesting its influence has declined. In contrast, China and India continue to act as net absorbers of uncertainty.

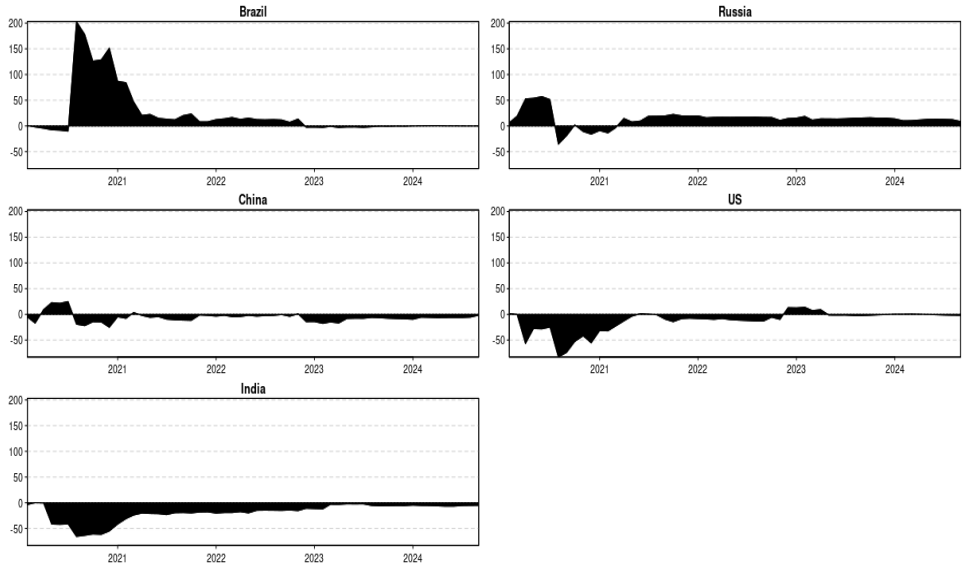

Figure no. 4 – Net Total Directional Connectedness (COVID and Post-COVID Sample)

4.5. Network diagram

The network diagram as shown in Figure no. 5 illustrates the spillover dynamics of sustainability uncertainty among BRIC economies (Brazil, Russia, India, China) and the U.S. during the COVID and post-COVID period. In this visualization, each node represents a country, while the directed edges (arrows) capture the direction and magnitude of spillover effects indicating the flow of sustainability-related uncertainty from source (transmitter) countries to destination (receiver) countries. The thickness of each edge corresponds to the strength of the spillover, with thicker lines signifying more substantial transmission. Node colours are used to distinguish roles within the network: blue nodes represent net transmitters of sustainability shocks, whereas yellow nodes indicate net recipients. The relative size of each node reflects its systemic importance, with larger nodes signifying higher levels of transmission or reception of uncertainty. This network structure allows for a clear visualization of the interdependencies and asymmetries in the propagation of sustainability risks, offering insight into which countries act as dominant influencers or vulnerable receivers within the global sustainability uncertainty framework.

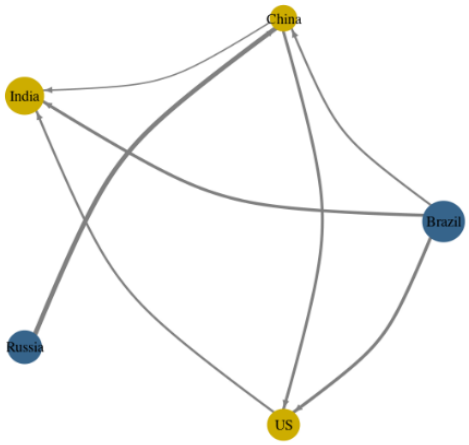

Figure no. 5 – Network Diagram (COVID and Post-COVID Sample)

5. CONCLUSION

This study applies a TVP-VAR extended joint connectedness framework to examine sustainability uncertainty spillovers among BRIC economies and the U.S. The TCI of 20.08 in the full sample period suggests moderate cross-country spillovers, with India emerging as the dominant transmitter and Russia as the primary receiver. However, during the COVID and post-COVID period, the TCI surged to 31.99, highlighting an increase in interconnectedness. Notably, India transitioned from being a major transmitter to a net receiver of sustainability uncertainty, while Brazil and Russia took on more prominent roles in transmitting shocks. This reversal underscores the asymmetric and dynamic nature of sustainability uncertainty transmission, influenced by external shocks such as the pandemic and geopolitical conflicts. India's transition from a major transmitter to a net receiver of sustainability uncertainty reflects

broader global structural shifts shaped by contemporary economic, geopolitical, and environmental dynamics. The COVID-19 pandemic severely disrupted global supply chains and economic stability, heightening India's exposure to external shocks. Simultaneously, geopolitical conflicts in Ukraine, and the Middle East have disrupted energy markets, driving up commodity prices and exacerbating inflationary risks for net energy importers like India. In contrast, Brazil and Russia's increasing roles as transmitters align with their expanding influence in global energy and commodity markets, where supply disruptions directly impact inflation, trade balances, and investment flows across economies. These dynamics underscore the interconnected nature of sustainability uncertainty and the need for enhanced macroprudential regulation, diversification of energy sources, and strengthened regional supply chains to reduce exposure to global sustainability shocks. The time-varying analysis of TCI trends reveals that sustainability uncertainty exhibited extreme volatility during early 2020, peaking at 69.21 in August. Subsequent stabilization in 2021–2022 indicates adaptive policy responses and economic recovery efforts, with a gradual decline in interdependence observed in 2023–2024. The decreasing trend suggests the emergence of more country specific and segmented policy dynamics, potentially driven by localized policy frameworks, diversification of energy sources and supply chains, and reduced systemic contagion. The NPDC analysis further elucidates the shifting transmission dynamics. Brazil, initially a net receiver, became a major transmitter of sustainability uncertainty in mid-2020 before stabilizing in 2023–2024. China and Russia exhibited persistent roles as net receivers, while the U.S. and India transitioned between transmitter and receiver roles. The findings highlight how systemic crises, such as COVID-19, can rapidly alter spillover structures and necessitate flexible risk management strategies. The findings from this study provide crucial insights into the contagion effects of sustainability uncertainty across BRIC economies and the U.S., emphasizing the dynamic and asymmetric nature of uncertainty spillovers.

The evidence underscores the need for coordinated policy responses to mitigate uncertainty spillovers (Tawiah *et al.*, 2021). The surge in interconnectedness of sustainability risks observed during the COVID and post-COVID period amplifies the potential for sustainability-related shocks stemming from environmental degradation, climate change, pandemics, and geopolitical instability to propagate swiftly and asymmetrically across national borders. Such dynamics reinforce the inadequacy of fragmented, nationally confined policy responses and underscore the necessity for coordinated, multilateral action among both developed and emerging economies, especially major actors such as the BRIC nations and the U.S. Our analysis highlights how geopolitical conflicts and supply chain disruptions with their reverberating effects on commodity prices and economic expectations can fundamentally alter spillover directions, as vividly exemplified by India's shift from being a principal transmitter to a net receiver of sustainability uncertainty during the COVID and post-COVID period. This underscores the need for policy frameworks that explicitly integrate geopolitical risk considerations alongside environmental imperatives. In light of the time-varying, nonlinear characteristics of sustainability uncertainty spillovers identified in this study, policymakers are called to move beyond static or reactive governance models. To strengthen both national and global resilience, it's crucial to build real-time risk monitoring systems and stress-test sustainability strategies against potential crisis scenarios. Just as important are greater transparency, better cross-border data-sharing, and flexible institutions that can respond quickly to emerging risks. Given that countries vary in how exposed they are and the roles they play in the system, a dual approach is needed, one that combines country-specific and regionally adapted risk management plans, while keeping national

actions aligned with broader international sustainability goals. Alignment with pivotal global initiatives, such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), will foster coherence and reinforcement between local and global sustainability ambitions. Only through collective measures can the risks of sustainability uncertainty be effectively mitigated, shielding economies from systemic shocks and steering the world toward a more stable and sustainable developmental trajectory.

This study focuses exclusively on the BRIC economies and the U.S., which, while significant, does not capture the full spectrum of global sustainability uncertainty spillovers. Future research could extend the analysis to additional major economies based on the available dataset (Ongan *et al.*, 2025), providing a more comprehensive understanding of global sustainability risk transmission. Sectoral-level analysis would provide deeper insights into industry-specific vulnerabilities and the differential impact of sustainability risks, enabling more targeted policy interventions (Olalere and Mukuddem-Petersen, 2024). Although this study acknowledges the role of geopolitical events particularly Russia's invasion of Ukraine in shaping sustainability uncertainty spillovers, a more systematic analysis of geopolitical risks, trade tensions, and institutional governance structures could provide deeper insights into the mechanisms driving sustainability risk transmission (Balli *et al.*, 2017; Yang *et al.*, 2022; Urom and Ndubuisi, 2023).

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How Can Service Convenience Reestablish Passenger Satisfaction After a Flight Delay? A Data Mining Approach

Olavo Pinto*, Amélia Brandão, Mahesh Gadekar*****

Abstract: The rapid development in aviation has transformed the way air travellers travel. Service failures, such as flight delays, significantly impact consumer satisfaction and its various dimensions. Consequently, flight delay has been identified as one of the critical factors in service failure. To improve satisfaction, airlines need to understand how consumer satisfaction can be enhanced in service failure incidents such as flight delays. As air travel recovers, understanding how service failures impact satisfaction and how they can be mitigated is crucial. Therefore, this study measures consumer airline satisfaction based on 129,880 observations of airline passengers (Study 1). It conducts data mining to predict that service convenience influences service failure perception (flight delay) and enhances consumer satisfaction (Study 2). The results indicate interesting trends. It is found that service convenience is the primary driver of delayed service failure recovery from the perspective of airline passengers. Airlines should invest in enhancing convenience and digital services, including virtual assistants, implementing automatic recovery mechanisms for flight delays, and considering the proximity of boarding gates to minimise walking distance.

Keywords: airline consumer satisfaction; flight delays; machine learning; data mining; service failure.

JEL classification: M1; M3.

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1. INTRODUCTION

Researchers and managers are deeply interested in understanding how customer satisfaction can be maximised during service failure due to flight delays. A growing body of literature has demonstrated how service failure, such as flight delay, can have negative customer experiences, customer behavioural outcomes, and financial performance and market share (Zeithaml *et al.*, 1996; Keiningham *et al.*, 2014; Sembada *et al.*, 2016; Hall and Hyodo, 2022). Airline flight delays occur regularly and are a significant cause of customer dissatisfaction. For instance, in 2021-22, the airline's flights were delayed 26-29% of the time, while in 2019, 18.6% were delayed (Buchholz, 2023). Thus, researchers and managers must find solutions to recover from service failure.

While studies have focused on countermeasures toward service failures (Das *et al.*, 2020; You *et al.*, 2020), such as apologizing and compensating in mitigating consumer anger (McCollough, 2009; Cummings and Yule, 2020; Baliga *et al.*, 2021) research suggest that service failure is one of the significant causes of customer dissatisfaction leading to adverse business outcomes and improvement in customer satisfaction can help in gaining competitive advantage in the aviation industry (Noviantoro and Huang, 2022). Given the accessibility to capturing and recording visuals and social media presence, the incident of service failure sooner becomes part of the public domain, leading to a challenging situation for the airlines. We subscribe to the opinion (e.g., Kanuri and Andrews, 2019) that researchers need to gain access to large datasets to examine variables related to service failure and suggest how service failure recovery can be achieved, leading to better profitability and higher consumer satisfaction.

In the present research, we measure consumer airline satisfaction based on 129,880 observations of airline passengers and suggest that service convenience influences perceptions of service failure (flight delay) and enhances consumer satisfaction. The data used in the present research were gathered from the website Kaggle (Klein, 2020) and are freely available. This database was selected based on its large number of responses and has been previously used in data mining analysis, as noted by Park *et al.* (2019). Using the theoretical lens of cognitive appraisal theory (Lazarus, 1991), we demonstrate that airline consumers with improved service convenience will be more satisfied in the event of flight delay. Central to this effect is the cognitive appraisal theory that supports the importance of information processing and its impact on emotion (Skavronskaya *et al.*, 2021). Specifically, the theory demonstrates the mental process of evaluating inputs to determine the form of emotional reaction in each situation (Johnson and Stewart, 2004). Cognitive appraisal theory (Lazarus, 1991) and recent studies (e.g., Kleijnen *et al.*, 2007; Chekembayeva *et al.*, 2023), highlighted the role of convenience in explaining usage intention. This learning enhances our understanding of the importance of service convenience in improving consumer satisfaction.

By identifying the link between consumer satisfaction and service convenience during the service failure of the airlines, we contribute to the customer satisfaction literature in service failure incidents (e.g., Anderson, 1998; Anderson and Mittal, 2000; Hall and Hyodo, 2022; Pantano and Scarpi, 2022). Given that the airline industry is more prone to service failures, such as delays (Palmer and Bejou, 2016), this research contributes to the existing literature on service failures in the industry (Nazifi *et al.*, 2021). Furthermore, using a large dataset of complex and empirical data, we employed a data mining method to analyse airline passenger satisfaction, particularly in the context of flight delays, and provided solutions to

offer accurate predictions. This approach aims to enhance our understanding of consumer satisfaction and mitigate negative responses to service failure incidents, such as flight delays.

2. CONCEPTUAL BACKGROUND AND HYPOTHESIS DEVELOPMENT

This study proposes a conceptual model for measuring consumer satisfaction in the airline context. It examines how service convenience influences perceptions of service failure (such as flight delays) and enhances consumer satisfaction. In the first study, the present research employs three constructs to measure consumer satisfaction, contextualised for the airline customer, drawing on the literature (Nghiêm-Phú, 2019; Park, 2019; Kosiba *et al.*, 2020). The second study, using data mining analysis, is adopted to predict consumer satisfaction based on the factors previously analysed - Convenience, Service, and Functionality, employing data mining techniques and machine learning models to predict consumer satisfaction.

2.1. Customer satisfaction and airline service

Customer satisfaction is a crucial measure for companies, and a broad research subject is the expectation of service performance and its impact on attitude and patronage intention (Oliver, 1980). It enhances knowledge of consumer behaviour, branding, and the effectiveness of communication and marketing management. Customer satisfaction measurement has undergone multiple developments and is utilised by practitioners across various industries and researchers. Moreover, when the company meets and exceeds customers' expectations, it increases customer loyalty (Chen and Chen, 2010) and repurchase intention (Park *et al.*, 2019).

Based on previous literature, this research employed three constructs to measure consumer satisfaction through the lens of airline customers (Nghiêm-Phú, 2019; Park, 2019; Kosiba *et al.*, 2020). Satisfaction is assessed using a 5-point Likert scale, consistent with previous studies (Anderson, 1998; Park *et al.*, 2019)

The first dimension, convenience, encompasses in-flight Wi-Fi, arrival and departure times, online booking ease, and gate location; notably, in-flight Wi-Fi was found to be insignificant for overall satisfaction (Nghiêm-Phú, 2019). The second dimension, service satisfaction, relates to the flight experience and covers in-flight service, onboard assistance, baggage handling, and legroom. The third dimension, functionality, focuses on seat comfort, food and drink quality, and cleanliness.

Satisfaction within the airline industry is a growing area of research. The airline industry's travel market is a mature one in most regions of the world, a truly global business, and competition strives to retain recurring customers through convenient online services (Park *et al.*, 2019). Moreover, airlines face high levels of competition, and prioritising customer satisfaction is crucial for retaining existing customers (Park *et al.*, 2019). Because the memory of past experiences influences satisfaction, a continuous relationship with airline brands is crucial (Lin, 2015). In the airline industry, customer satisfaction and loyalty are jointly affected by service quality and perceived value (Nghiêm-Phú, 2019). Studies related to airlines have identified various factors impacting airline satisfaction. For instance, airline service quality is linked to comfort, in-flight experience, physical experience, and interaction during the flight, ultimately influencing service quality (Vázquez-Casielles *et al.*, 2007; Nghiêm-Phú, 2019).

Prior studies on airline satisfaction have identified the determinants of customer satisfaction. However, these studies represented respondents who volunteered for the research, with a sample size of less than 1000. Large-scale studies were also conducted that analysed extensive customer datasets. For instance, Park *et al.* (2019) investigated the potential determinants of customer-perceived satisfaction from large datasets. This study finds large-scale customer datasets to examine determinants of customer satisfaction in specific service failures.

2.2. Service convenience

Service convenience is one of the critical determinants of customer behaviour and its role in influencing service quality and fairness (Srivastava and Kaul, 2014). Additionally, prior studies have identified service convenience dimensions that lead to improved customer perception of convenience. Because modern life and stress affect consumers in terms of time commitment, firms are expected to ensure that the services are time-saving and effortless (Lloyd *et al.*, 2014; Malhotra *et al.*, 2016). Improved service convenience affects customer engagement and overall service quality (Nguyen *et al.*, 2012). In the airline industry, service convenience refers to the environment where customers can easily and comfortably experience service and access convenient facilities (Bezerra *et al.*, 2016). Because the service associated with the airline is inseparable, requiring passengers to travel to the airport before the flight's departure physically, the consumer perception is related to various dimensions of service convenience. Specifically, consumers prefer better interactional services and service-related air travel. Similarly, airline passengers may express dissatisfaction due to the need for more WiFi facilities and in-flight entertainment (Nurhadi *et al.*, 2019).

2.3. Airline flight delay

Flight delay has attracted the attention of researchers. Because passengers' expectations of flight on-time arrival have increased, it is one of the sources of competitive advantage (Yimga, 2017). When a flight is delayed, it affects both the firm's performance and society as a whole. Statista (2025) states that flight claim companies had an economic impact of $ 208 million in Europe and North America. Consequently, flight delays affect air passengers' intention to travel again and retail spending (Fuerst *et al.*, 2011; D'alfonso and Nastasi, 2014).

Prior studies supported that the comparison of performance satisfaction between a low cost and is subject to different levels and dimensions of Satisfaction (Lin, 2015) but not for how customer class, between Business, Economy, and Economy Plus, play in different types of satisfaction with the service, while first-class and Business seem to be similarly levelled (Hwang and Lyu, 2018). In addition, the distance of flights in the industry is categorised as short-haul, medium-haul, and long-haul, according to the ranges provided by European regulators (Eurocontrol, 2018), and is often delayed in real-world scenarios. The different dimensions presented here, with the convenience and comfort provided in flight and the interaction with the airline, may have different satisfaction behaviours depending on the flight distance. A more convenient gate may be significant for a short business trip taken frequently, but less critical for a long-haul vacation trip. Moreover, the data analysis enables us to pinpoint when there is a delay in both departure and arrival. European legal procedures were used to determine a delay, which lasted from 30 minutes to 6 hours, after which it may be considered a cancellation (EUR-Lex, 2007). The departure and arrival are determined, and

the perceptions of satisfaction are registered. The different dimensions of satisfaction were analysed by comparing different delay ranges and no delay. It is expected to have a negative relationship proportional to the increasing level of delay the flight takes. Despite this, external variables may explain the different performances of customer attention, service recovery, and compensation, among others (Vázquez-Casielles *et al.*, 2007). Nevertheless, delay, one of the leading causes of customer complaints about airline services, is expected to have a role in customer satisfaction.

Furthermore, flight delays are one of the most common causes of complaints from airline customers (Mohd-Any *et al.*, 2019). Despite this, the literature suggests that training may find an optimised way to manage the incident, reading the emotional and cognitive assessment of the situation made by the customer (Vázquez-Casielles *et al.*, 2007). Additionally, regarding innovative brand experience research, schedule ranks first among the antecedents of service quality, followed by flight staff, tangibles, and ground staff (Lin, 2015). The level of satisfaction compared to the behaviour of a delay when recovered during flight, when the delay worsened during flight, and when the delay remained constant is a first approach to effective service recovery based on factual data and customer satisfaction in different dimensions.

Thus, we hypothesise that:

H1*: Satisfaction dimensions positively relate to the business customer class.*

H1.1*: Convenience dimension positively relates to the business customer class.*

H1.2*: Service dimension positively relates to business customer class.*

H1.3*: The Functionality satisfaction dimension positively relates to the business customer class.*

H2*: Satisfaction dimensions are positively related to flight distance.*

H2.1*: Convenience dimension is positively related to flight distance.*

H2.2*: Service dimension is positively related to flight distance.*

H2.3*: Functionality dimension is positively related to flight distance.*

H3*: The delay type at different points in time negatively impacts passengers' satisfaction dimensions.*

H3.1*: Convenience dimension is positively related to delay type at different points in time.*

H3.2*: Service dimension is positively related to delay type at different points in time.*

H3.3*: Functionality dimension is positively related to delay type at different points in time.*

H4*: A Recovery will have a positive and significant relationship with delay types.*

3. STUDY 1: DIMENSIONS OF AIRLINE SATISFACTION AND RELATIONSHIPS FROM BIG DATA

This first study aims to present the conceptualisation of customer satisfaction in the airline industry context and explore the different relationships with service performance. According to the extant literature, the typification of constructs is based on various dimensions of airline service provision. It is on the characterisation of the contextual airline service that the present research advances the components of customer satisfaction regarding service failure and demographics. A complete dataset was used to analyse based on the dimensions mentioned above.

The many observations present an opportunity to research consumer satisfaction in the airline context. Afterwards, the conceptual model is emphasised based on the extant literature, including both theoretical and empirical studies. Firstly, a multivariate procedure, Exploratory Factor Analysis, enabled us to identify the dimensions that contribute to customer satisfaction in the present dataset within the given context. Despite this, several considerations were developed regarding the context and previous theory, enabling the establishment of a relevant and valid model, as well as the respecification of the constructs' validity (Byrne, 2013).

Using various statistical tests, multiple evaluations were conducted to enhance the robustness and validity of the model. Covariance errors improved the model fit by addressing high scores in modification indices, as observed through the analysis of extreme outliers in the Mahalanobis distance (Byrne, 2013). Only after these considerations add robustness and validity to the conceptualisation of the model, the present research employs a Confirmatory Factor Analysis to test the proposed hypothesis (Brown, 2015), which addresses a novel and, to the author's knowledge, previously untested aspect in the extant marketing and tourism literature. A Structural Equation Modelling analysis was performed by using Amos.

3.1. Descriptive

Regarding delays, according to the U.S. Department of Transportation, the Transportation system had some delays in December 2019, which is in line with other periods (Department of Transportation's Office, 2019). According to previous studies, delays are often the leading cause of customer complaints. A plane is considered on time when it arrives at its destination within 15 minutes of the scheduled time, most of the time in U.S. and European markets (Department of Transportation's Office, 2019; Klein, 2020). The data collected pertains to each respondent's observations of departure and arrival delays. This method provided a detailed measurement of the delays experienced at both departure and arrival points. Specifically, it facilitated the analysis of delays considering regulatory provisions, helping to identify ranges of low, medium, and high delays for both departures and arrivals based on the average levels of compensation provided (EUR-Lex, 2007), as characterised in Table no. 1.

Table no. 1 - Classification of Flight Delays by Time Interval

Type of Delay	Time
No delay	0 to < 30m
Delay	30m to < 2h
Medium Delay	Two h to < 5h
High Delay	≥ 5h

The data used in the present research were gathered from the website Kaggle (Klein, 2020) and are freely available for anyone to use. The dataset contained 129.880 observations of airline passengers, of which 50.7% are female. Loyalty is described in the database as customers who reuse the airline's services, and those represent 81.7% of the observations. The age distribution is presented in Figure no. 1, using the same range as in previous research (Prentice, 2019).

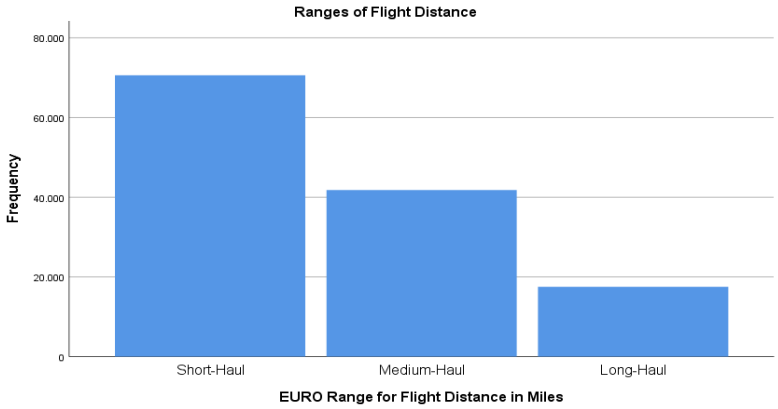
The travel type and class are variables to consider when analysing airline consumers. For the class, airlines often offer different ranges commonly allocated to other areas of the aeroplane. Each type of service typically provides differentiation in food, ambience, and entertainment, as well as a strategic location for faster seating and departure, and other amenities that can enhance the overall experience. In the dataset, these were ranked by frequency as Business (47.9%), Economy (44.9%), and Economy Plus (which offers a spacious seat), with the latter having a relatively low representation (7.2%). The type of travel describes the purpose of the trip the customer makes, with 69.1% for business purposes and 30.9% for personal/leisure reasons.

Most of the observations on the dataset did not present any delay in departure or arrival in 85.4% of the cases. According to European delimitations, and as previously stated, this corresponds to no delay on departure that's less than 30 minutes. After this, the dataset has 12.1% cases of delay. Only 2.3% of the delays go between 2 and 5 hours. After six hours, the airline must provide total compensation in accordance with European regulations. This is uncommon, and 313 observations are available in this dataset. This is 0.2%, which is a small amount.

Using the available data, a differential was calculated regarding the performance of the delay, measuring the placement in the range of delay differential between the departure and arrival of the flight. This would create scenarios based on actual flight time data, which would maintain, worsen, or recover from a delay. For this, the frequencies in the data represent 83.2% of no delay at all. However, for those who experienced a delay at departure, 11.4% would be in the same delay range on arrival. However, there are many observations where this delay would worsen after departure (2.9%), and in these cases, the delay would be compensated (2.5%). For example, some flights where the departure would cause a delay at the low end would eventually compensate during the flight.

In defining the distance travelled, the maximum ranges of 1,500 km for short-hauls and 4,000 km for medium-hauls were adopted (Eurocontrol, 2018), cataloguing the observations in this way, even though this may not apply to every region due to its specificities. The dataset presented the distance travelled by the respondent, and using the range mentioned earlier, 54% of the observations were in the short-haul distance. Medium-haul travels were 32.2%, and long-haul represented only 13.5% of the observations.

Table no. 2 presents all the component variables available in the dataset for customer satisfaction with airline services. It includes the item mean, the standard error, skewness, and kurtosis for all the variables. These used a 1-5 Likert scale, similar to research with customer satisfaction concepts (Lin, 2015; Antwi *et al.*, 2020; Kosiba *et al.*, 2020). In the present study, these items were allocated to 3 different dimensions of constructs, using at least three items each. This decision was made using available knowledge from previous theories and literature, as well as an exploratory factor analysis.



Source: authors' contribution

Figure no. 1 – Ranges of Flight Distance

Table no. 2 – Components of consumer satisfaction

Item	Mean	SE	Skewness	Kurtosis
Inflight WiFi service	2.81	1.359	-0.25	-1.159
Departure/Arrival time convenient	3.22	1.281	0.123	-1.039
Online booking	2.88	1.278	-0.058	-1.032
Gate location	2.98	1.326	-0.149	-1.158
Food and drink	3.21	1.253	-0.344	-0.907
Online boarding	3.33	1.319	-0.486	-0.923
Seat comfort	3.44	1.333	-0.366	-1.063
Inflight entertainment	3.36	1.287	-0.421	-0.89
Onboard service	3.38	1.298	-0.318	-1.055
Legroom service	3.36	1.18	-0.677	-0.384
Baggage handling	3.63	1.266	-0.367	-0.83
Check-in service	3.31	1.176	-0.691	-0.36
Inflight service	3.64	1.313	-0.3	-1.016
Clean	3.29	1.244	0.162	-0.959

Source: authors' contribution

Additionally, a binary variable distinguishes between satisfied and unsatisfied customers, in conjunction with the constructs presented. Table no. 3 presents the frequency of those observations in the dataset.

Table no. 3 – Frequency of Satisfaction vs. No Satisfaction

Item	Frequency	Per cent
Not Satisfied	73.452	56.6%
Satisfied	56.428	43.4%

Source: authors' contribution

3.2. Principal component analysis

The previous conceptualisation of satisfaction with airline services was considered for the development of the present study. Additionally, the exploratory factor analysis performed on the large dataset allowed for a test of the most significant factors influencing customer satisfaction.

After several EFA, the final model is provided by Principal Component Analysis, with the rotation method Varimax with Kaiser Normalisation. The first factor in the final model is convenience, which explains 22.67% of the variance and has four components with factor loadings ranging from .747 to .874. Next is a service that explains 22.26% of the total variance, characterised by four elements, with factor loadings ranging from 0.633 to 0.839. Finally, Functionality. Functionality explains 20.93% of the variance and consists of 3 items with factor loadings ranging from .854 to.892 These three factors explain 65.66% of the model's total variance.

Table no. 4 – Factor loadings and commonalities from a principal component analysis with rotation method varimax for 11 items

Item	Convenience	Service	Functionality
Online booking	0.874		
WiFi Inflight	0.767	0.139	0.170
Time Conve.	0.759		
Gate Location	0.747		
Inflight Serv.		0.839	
Baggage		0.827	
Onboard Serv.		0.787	
Leg Room		0.633	
Clean			0.892
Seat Comfort			0.857
Food & Drinks			0.854

Note: Factor loadings < 0.1 are omitted.

Source: authors' contribution

After an inspection of the Homogeneity of Variances, Tamhane's variance analysis was performed due to Levene's test failure. A Principal Component Analysis uncovered the components of the final model, saving the regression factor scores into new variables. The Kaiser-Meyer-Olkin Measure (KMO) and Sample Adequacy are very good, with a value of 0.787, which is above the recommended value of 0.6. Anti-image – Measures of Sample Adequacy (MSA) indicate that all diagonals are well above the recommended value of 0.5, with the lowest being 0.672 for "Ease of Booking Online" and the highest being 0.848 for "Leg Room". Additionally, Bartlett's Test of Sphericity performed well ($\chi 2$ (55) = 506497, $p < .001$). When performing further adjustments to the model, excluding Online boarding, in-flight Entertainment, and Check-in service, the KMO value signals 0.741.

Table no. 5 – Regression Analysis Results

Item	β	t	p	R^2_a	VIF
Convenience F(4,129875)=10280017	**-**	**-**	***	**.997**	
Online	.363	1507	***	-	2.4
Gate Location	.310	1629	***	-	1.5
Time Convenience	.302	1568	***	-	1.5
WiFi Inflight	.285	1323	***	-	1.9
Service F(4,129875)=5276489	**-**	**-**	***	**.994**	
Inflight Service	.348	1164	***	-	1.9
Baggage Handling	.343	1170	***	-	1.8
Onboard Service	.323	1182	***	-	1.5
Leg Room Service	.258	1069	***		1.2
Functionality F(3,129876) = 5081207	**-**	**-**	***	**.992**	
Clean	.383	986	***	-	2.3
Food & Drinks	.385	1104	ns	-	1.9
Seat Comfort	.374	1045	ns	-	2.0

Note: *** indicates p-value < .001, ** indicates p-value < .01, * indicates p-value < .05, ns = non-significant.
Source: authors' contribution

The dependent variables within the same construct underwent linear regression analysis for the final Model Proposed, as presented in Table no. 5. Concerning Multicollinearity, all the VIF values were two or well below that, which is very well below the 10-cut-off value proposed in the literature.

3.3. Reliability and validity

Factoring in different constructs, the satisfaction items are highly correlated and sufficiently distinct from one another, achieving statistical significance, thereby representing various dimensions of customer satisfaction in the airline industry. The correlation matrix within the construct is always positively correlated (Pearson Correlation > .5) and significant (p-value < .001).

Table no. 6 – Parameter estimates for the CFA model (Factor Loadings)

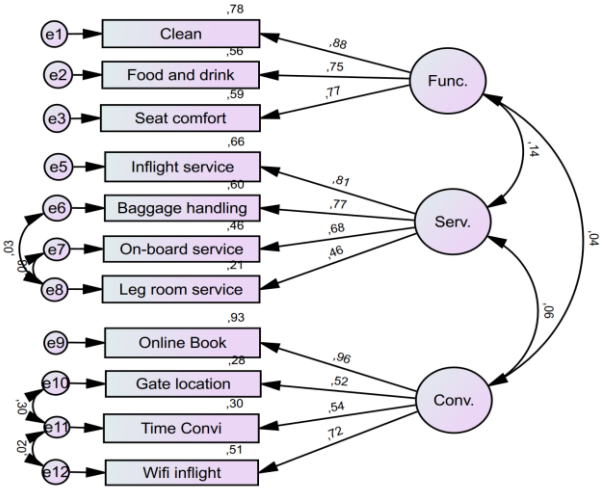
			Estimates	S.E.	C.R.	P
Regression weights						
Seat comfort	<---	Func.	.877	.003	274.77	***
Food and drink	<---	Func.	.853	.003	268.37	***
Cleanliness	<---	Func.	1.000			
Baggage handling	<---	Serv.	1.000			
Inflightwifiservice	<---	Conv.	.723	.004	187.66	***
TimeConvenient	<---	Conv.	.600	.004	157.04	***
EaseofOnlinebooking	<---	Conv.	1.000			
Gate location	<---	Conv.	.544	.003	157.38	***
In-flight service	<---	Serv.	1.050	.005	225.14	***
Legroomservice	<---	Serv.	.658	.005	141.99	***

			Estimates	S.E.	C.R.	P
Regression weights						
Onboard service	<---	Serv.	.959	.004	215.52	***
Seat comfort	<---	Func.	.877	.003	274.77	***
Food and drink	<---	Func.	.853	.003	268.37	***
Cleanliness	<---	Func.	1.000			
Baggage handling	<---	Serv.	1.000			

Source: authors' contribution

A closer examination of the modification indices was conducted to improve the model, and the link between high M.I. errors within the same constructs was identified to enhance reliability. Further, the Check-in Service and Online Boarding failed to measure in a new construct due to the high correlation of the items with measures outside the factor. These three variables were dropped, and a goodness-of-fit of the model was achieved: $\chi 2$ (37) = 14783.607, p-value < .001; CFI = 0.971; NNFI = 0.971; RMSEA = 0.055. The factor loadings for each variable are in Table no. 6.

The model proposed reached composite reliability (> .6), AVE (> .5), and Cronbach's α (> .7) as per Table no. 7.



Source: authors' contribution

Figure no. 2 – Measurement Model Results

Table no. 7 – Reliability and validity tests

	Cronbach's α (> 0.7)	CR (> 0.6)	AVE (> 0.5)
Functionality	0.841	0.843	0.6
Convenience	0.797	0.792	0.5
Service	0.775	0.782	0.5

Source: authors' contribution

Also, there is discriminant validity with no intercorrelation outside the factors and a high convergent validity in the proposed factors (> 0.69) (Table no. 8).

3.4. Results

Analyse Variances using One-Way ANOVA. The dependent variable used was the Recovery Delay, which we developed by combining the departure and arrival delays, given the significant number of occurrences in the dataset. It used a significance level of 0.05 (α = .05).

All the ANOVA tests were significant since they had a $p < .001$. This means a substantial difference between the proposed groups can be found in at least one relation.

Post-hoc tests were performed to investigate further the differences between groups following significant ANOVA tests. Levene's test was performed, and in everyone, it presented a $p < .001$, except for the Service with Delay Performance test, which offered a $p < .05$. In every situation, this required using a post hoc test in which the variances could not be assumed equal, so all the further tests used Tamhane's T2.

Table no. 8 – Convergent and Discriminant Validity Results

	CR	AVE	Conv.	Serv.	Func.
Conv.	0.792	0.5	0.71		
Serv.	0.782	0.5	0.06	0.69	
Func.	0.843	0.6	0.05	0.14	0.80

Source: authors' contribution

Business groups of customers consistently scored higher on all satisfaction constructs.

Between these two types of travel, the dataset shows a statistically significant difference as per one-way ANOVA in the Convenience dimension ($F(1, 129878) = 19.02$, $p < .001$) for Service ($F(1, 129878) = 564.58$, $p < .001$) and for Functionality ($F(1, 129878) = 1837.72$, $p < .000$).

The group of loyal customers provided by the dataset also proved to be significantly different from those who are not faithful to any airline. These customers present in the dataset show statistically significant differences between groups for convenience as per one-way ANOVA ($F(1, 129878) = 111.99$, $p < .000$) for Service ($F(1, 129878) = 11.57$, $p = .001$) and Functionality ($F(1, 129878) = 1543.22$, $p < .001$). This data shows that loyal customers are significantly more satisfied in every dimension measured.

After the initial analysis, two One-Way ANOVA results with post hoc tests further revealed which group had an impact on the direction of each dimension of satisfaction (dependent variable). First, Table no. 9 provides the one-way ANOVA for a class type and the range of distance travelled.

For class type, business, economy, and Economy plus groups, after performing one-way ANOVA, were determined to be significantly different in Convenience ($F(2, 129877) = 11.67$, $p < .001$), Service ($F(2, 129877) = 3840.68$, $p < .001$) and Functionality ($F(2, 129877) = 1895.40$, $p < .001$).

Table no. 9 – ANOVA Tamhane multiple comparisons table for customer class and travel distance

Independent	***Dependent***		
	Convenience	**Service**	**Functionality**
Cust. Class	***p***	***p***	***p***
Business & EcoPlus	0.944*n.s.*	< .001*	< .001*
Eco & Business	< .001*	< .001*	< .001*
Eco & EcoPlus	< .01**	< .001*	< .01**
	F(2, 129877) = 11.67, p < .001	F(2, 129877) = 3840.68, p < .001	F(2, 129877) = 1895.40, p < .001
Tr. Distance	**Convenience**	**Service**	**Functionality**
Short - Long	0.495*n.s.*	< .001*	< .001*
Medium - Short	< .001*	< .001*	< .001*
Medium - Long	0.715*n.s.*	< .001*	< .001*
	F(2, 129877) = 6.70, p < .001	F(2, 129877) = 609.52, p < .001	F(2, 129877) = 750.72, p < .001

Source: authors' contribution

Table no. 10 – ANOVA Tamhane multiple comparisons table for delay and delay performance

	Dependent		
	Convenience	**Service**	**Functionality**
Independent Delay	*p*	*p*	*p*
No Delay – Delay	< .001*	< .001*	< .001*
No Delay – Medium Delay	.136*n.s*	< .001*	< .001*
No Delay – High Delay	.604*n.s*	.316*n.s*	.765*n.s*
Delay – Some Delay	1*n.s*	.983*n.s*	579*n.s*
Delay – High Delay	.203*n.s*	1*n.s*	1*n.s*
Some Delay – High Delay	.197*n.s*	.998*n.s*	.997*n.s*
	F(3, 129876) = 7.79, p < .001	F(3, 129876) = 52.52, p < .001	F(3, 129876) = 33.77, p < .001
Delay Performance	**Convenience**	**Service**	**Functionality**
Maintain - Recover	.816*n.s.*	.242*n.s.*	.657*n.s.*
Maintain - Worsen	.996*n.s.*	.826*n.s.*	1*n.s.*
Maintain – No Delay	< .001*	< .001*	< .001*
Recover - Worsen	.995*n.s.*	.076*n.s.*	.752*n.s.*
Recover – No Delay	.948*n.s.*	< .01**	< .05***
Worsen – No Delay	.438*n.s.*	< .001*	< .001*
	F(3, 129869) = 6.63, p < .001	F(3, 129869) = 55.59, p < .001	F(3, 129869) = 34.31, p < .001

Source: authors' contribution

Due to being proven significant, a Tamhane post hoc inspection uncovered that satisfaction with convenience was significantly higher for Business ($p < .001$) and Economy Plus ($p < .01$) compared to Economy. No statistically significant difference was found between Business and Economy Plus ($p = .994$).

In analysing service and functional satisfaction, the relationships between the two groups were statistically significant in both dimensions. On both Business ($p < 0.001$) and Economy Plus ($p < 0.001$), the fares were found to be higher and lower, respectively, than those of Economy. Business was also significantly higher ($p <0.001$) than Economy Plus.

About the range of distance travelled by the flight, according to the distances considered by European agencies, the One-Way ANOVA was found to be significantly different in all

three dimensions: Convenience ($F(2, 129877) = 6.70$, $p < .001$); Service ($F(2, 129877) = 609.52$, $p < .001$) and Functionality ($F(2, 129877) = 750.72$, $< .001$).

The Tamhane T2 test, when analysing the Convenience satisfaction dimension, presented no statistically significant difference between either Short ($p = 0.495$) or Medium-haul ($p = 0.715$) and Long-haul. Medium-haul is significantly higher in satisfaction for convenience when compared to Short-haul ($p < .001$).

The post hoc test for distance travelled on service satisfaction and functional satisfaction shows that the relationships between the two groups were statistically significant in both dimensions. On both, Short-haul ($p < .001$) was found to be lower, and Long-haul ($p < .001$) was found to be higher, regarding Medium-haul travel distances. Long-haul travel was also significantly higher ($p < .001$) than short-haul travel on the Service and Functional Satisfaction dimensions.

Four different measures of delay typified as no delay, delay, medium Delay, and high Delay, the one-way ANOVA were determined to be significantly different in Convenience satisfaction($F(3, 129876) = 7.79$, $p < .001$), Service satisfaction ($F(3,129876) = 52.52$, $p < .001$) and Functionality satisfaction ($F(3, 129876) = 33.77$, $p < .001$). After a Tamhane post hoc inspection revealed that the satisfaction with Convenience, Service, and Functionality was significantly higher for No Delay ($p < .001$) compared to the first level of delay, no statistically significant difference was found between any other relation in Convenience Satisfaction, with all $p > .05$. For satisfaction with Service and Functionality, however, No Delay is significantly higher ($p < .001$) than Medium Delay. As shown in Table 10, no other group comparison is statistically significant ($p > .05$).

One-way ANOVA was also used to find significant differences between delay performances based on the previously defined ranges (Table 10). All the three factors where significant: Convenience ($F(3,129869) = 6.63$, $p < .001$); Service ($F(3,129869) = 55.59$, $p < .001$) and Functionality ($F(3,129869) = 34.31$, $p < .001$).

The Tamhane T2 test, when analysing the Convenience satisfaction dimension, presented no statistically significant difference between ‘Recover’ ($p = .816$) and ‘Worsen’ ($p = .996$) and ‘Maintain the Delay’. There is also no statistically significant difference when comparing Recover ($p = .995$) with Worsen delay Maintain the Delay, nor with Recover ($p = .948$) and Worsen (0.438) and No Delay.

For the Service Satisfaction dimension, there was no statistically significant difference between Recover ($p = 0.242$), Worsen ($p = 0.826$) and Maintain the Delay. There is also no statistically significant difference when comparing Recover ($p = .076$) with Worsen delay.

Similarly, there was no statistically significant difference in functionality satisfaction between Recover ($p = .657$) and Worsen ($p = 1$) and Maintained the Delay. Also, there is no statistically significant difference when comparing Recover ($p = .752$) with Worsen delay.

The Tamhane post hoc test, when analysing the three dimensions, convenience, service, and functionality satisfaction, all proved to be significantly lower on Maintain ($p < .001$) compared to No Delay.

The same is true for Service satisfaction and functionality satisfaction, where “Recover” ($p < .01$) and “Worse” ($p < .001$ and $p < .05$, respectively) are significantly lower than “No Delay.”

The present test revealed no significant difference in the tendency for recovery or worsening delays during flights. However, there is a substantial difference between those delayed flights and those that depart on time.

3.5. Findings & Discussion

Approaching a real and immense customer satisfaction database presents an opportunity to further conceptualise the dimensions present in the airline industry. Data showed that satisfaction is higher for business customers than for economy class. Economy Plus has higher satisfaction ratings than Economy in terms of convenience and functionality, but lower satisfaction with service. Satisfaction increases in service and functionality as the travel distance increases, except for convenience satisfaction, which drops in satisfaction from short to medium haul. The customer satisfaction regarding convenience is not significantly different for long-haul travel distances. There is a significant difference between those flights with delays and those that depart and arrive on time, supporting the fact that all dimensions of satisfaction have a significant negative relationship with delay.

Table no. 11 – Summary of Hypotheses Testing Results

Hypothesis	Observations	Test result
H1.1	Convenience dimension positively relates to business customer class	Not Supported
H1.2	Service dimension positively relates to business customer class.	Supported
H1.3	Functionality satisfaction dimension positively relates to business customer class.	Supported
H2.1	Convenience dimension is positively related to flight distance.	Not Supported
H2.2	Service dimension is positively related to flight distance.	Supported
H2.3	Functionality dimension is positively related to flight distance	Supported
H3.1	The type of delay negatively impacts passengers' Convenience dimensions	Not Supported
H3.2	The type of delay negatively impacts passengers' Service dimensions	Not Supported
H3.3	The type of delay negatively impacts passengers' Functionality dimension	Supported
H4	A Recovery will have a positive significant relationship with types of delay.	Not Supported

4. STUDY 2: DELAY SERVICE FAILURE DATA MINING PERFORMANCE

This study is followed by a data mining analysis that aims to predict user satisfaction based on the previously analysed factors: Convenience, Service, and Functionality, employing data mining techniques and machine learning models to predict consumer satisfaction. The analysis performed the following tests: Logistic Regression, Gaussian Naive Bayes, K-Nearest Neighbours, Decision Tree Classifier, Random Forest Classifier, Gradient Boosting Classifier, Multi-layer Perceptron (MLP) Classifier, and Support Vector Classifier (SVC), and evaluation metrics with Accuracy, ROC-AUC, F1 Score, Precision, and Recall. Measuring Delay Differential as a predictive performance indicator, the relationships between the three factors become more evident. The analysis utilises 20,353 records, representing 16% of the total observations in the original dataset, and considers only occurrences with positive Delay Differential, excluding those without this service failure.

The correlation matrices, representing variables with higher negative correlations in blue and those with stronger positive correlations in red, are presented in Figure no. 3. This allowed us to understand the patterns and dependencies of the factors in the dataset.

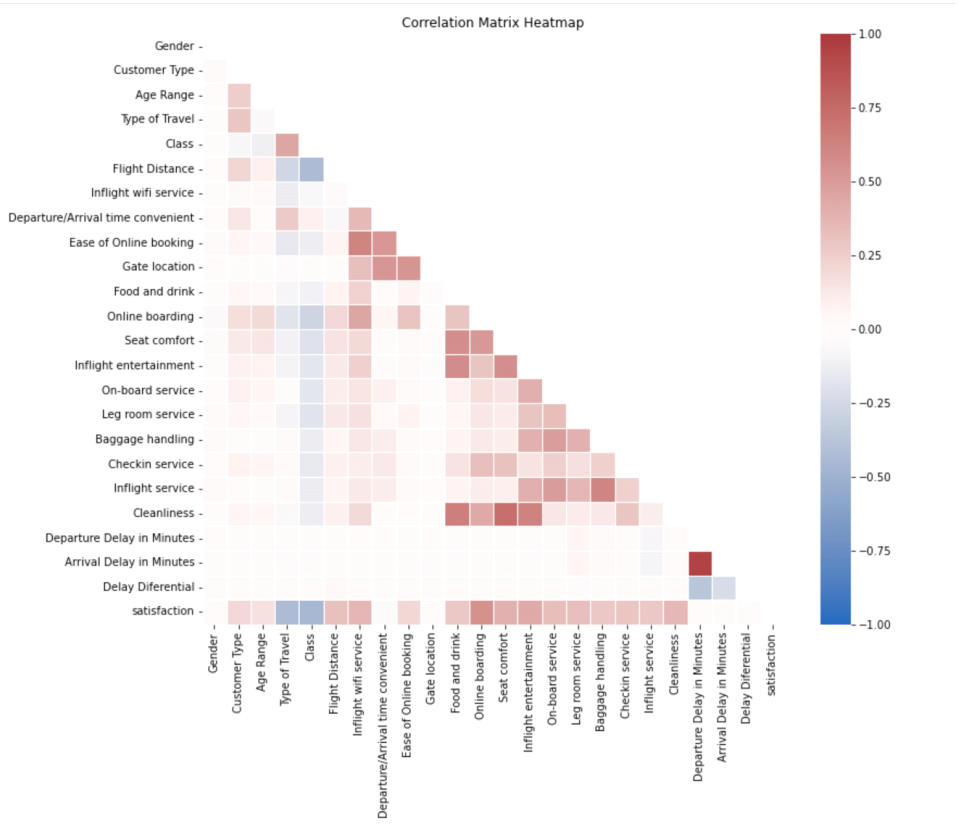


Figure no. 3 – Correlation Matrix

To predict user satisfaction, machine learning models were trained and evaluated using the Convenience, Service, and Functionality factors. Tables no. 12 and no. 13 present the results of the regression analysis. Table no. 12 represents the predictive performance without the "delay differential" feature, while Table no. 13 includes it. Including the "delay differential" feature negatively impacted the predictive performance of the analysis, highlighting model-building limitations for future research.

Table no. 12 – Regression without delay differential [Out 36]

	Factor	Model	Accuracy	Roc-Auc	F1	Precision	Recall
0	Convenience	LogisticRegression	71.64%	65.28%	54.56%	62.34%	48.52%
1	Convenience	GaussianNB	73.56%	68.16%	57.19%	66.22%	50.33%
2	Convenience	KNeighborsClassifier	85.64%	75.95%	79.08%	80.36%	78.53%
3	Convenience	DecisionTreeClassifier	87.60%	87.12%	82.99%	80.07%	86.13%
4	Convenience	RandomForestClassifier	87.58%	87.15%	82.97%	80.00%	86.27%
5	Convenience	GradientBoostingClassifier	87.47%	87.21%	82.97%	79.33%	86.97%
6	Convenience	MLPClassifier	87.59%	87.14%	82.98%	79.96%	86.29%
7	Convenience	SVC	87.02%	86.83%	82.70%	77.73%	88.35%

	Factor	Model	Accuracy	Roc-Auc	F1	Precision	Recall
8	Service	LogisticRegression	75.10%	71.56%	60.40%	68.30%	54.22%
9	Service	GaussianNB	76.93%	76.96%	68.88%	65.33%	72.90%
10	Service	KNeighborsClassifier	83.06%	81.68%	74.40%	78.76%	70.67%
11	Service	DecisionTreeClassifier	84.28%	81.01%	76.41%	79.85%	73.39%
12	Service	RandomForestClassifier	84.47%	81.84%	76.90%	79.39%	74.47%
13	Service	GradientBoostingClassifier	83.49%	81.32%	75.51%	78.16%	73.32%
14	Service	MLPClassifier	85.17%	81.66%	77.28%	82.57%	72.62%
15	Service	SVC	84.27%	81.49%	76.25%	80.23%	73.00%
16	Functionality	Logistic Regression	74.13%	69.75%	59.42%	66.11%	54.01%
17	Functionality	GaussianNB	72.56%	72.33%	64.94%	58.79%	72.56%
18	Functionality	K Neighbors Classifier	78.48%	75.17%	64.58%	75.78%	56.45%
19	Functionality	DecisionTreeClassifier	80.81%	77.35%	71.25%	74.93%	68.03%
20	Functionality	RandomForestClassifier	80.91%	77.71%	71.50%	74.64%	68.75%
21	Functionality	GradientBoostingClassifier	80.11%	77.07%	69.91%	74.38%	65.97%
22	Functionality	MLPClassifier	80.57%	77.11%	71.00%	75.01%	67.77%
23	Functionality	SVC	79.16%	75.22%	67.17%	75.26%	60.69%

Table no. 13 – Regression with delay differential [Out 39]

	Factor	Model	Accuracy	Roc-Auc	F1	Precision	Recall
0	Convenience	LogisticRegression	70.59%	63.62%	52.03%	60.78%	45.64%
1	Convenience	GaussianNB	73.73%	68.27%	57.55%	66.58%	50.72%
2	Convenience	KNeighborsClassifier	85.00%	83.80%	79.06%	76.69%	82.65%
3	Convenience	DecisionTreeClassifier	87.31%	87.07%	82.77%	79.17%	86.76%
4	Convenience	RandomForestClassifier	87.36%	87.12%	82.78%	79.15%	86.91%
5	Convenience	GradientBoostingClassifier	87.37%	87.23%	82.85%	79.18%	86.90%
6	Convenience	MLPClassifier	87.52%	87.40%	83.10%	79.66%	86.45%
7	Convenience	SVC	86.16%	82.37%	80.96%	78.28%	84.28%
8	Service	LogisticRegression	75.74%	70.99%	61.86%	69.01%	56.13%
9	Service	GaussianNB	77.10%	76.27%	69.12%	65.55%	73.26%
10	Service	KNeighborsClassifier	81.47%	79.61%	71.34%	77.77%	65.96%
11	Service	DecisionTreeClassifier	83.50%	80.92%	75.62%	77.64%	73.99%
12	Service	RandomForestClassifier	83.96%	81.53%	76.54%	77.95%	75.13%
13	Service	GradientBoostingClassifier	83.46%	81.16%	75.71%	77.67%	74.01%
14	Service	MLPClassifier	85.13%	82.42%	77.14%	82.17%	72.77%
15	Service	SVC	83.78%	81.09%	75.75%	79.00%	73.07%
16	Functionality	LogisticRegression	74.42%	69.51%	59.79%	66.73%	54.28%
17	Functionality	GaussianNB	72.78%	72.35%	64.97%	59.23%	72.14%
18	Functionality	KNeighborsClassifier	75.72%	73.24%	67.42%	65.49%	71.11%
19	Functionality	DecisionTreeClassifier	79.86%	76.82%	69.24%	74.26%	65.07%
20	Functionality	RandomForestClassifier	80.02%	76.82%	69.86%	73.89%	66.63%
21	Functionality	GradientBoostingClassifier	79.99%	77.05%	69.47%	74.72%	65.02%
22	Functionality	MLPClassifier	80.07%	77.24%	69.93%	73.97%	67.82%
23	Functionality	SVC	78.63%	74.51%	66.40%	74.15%	60.19%

The results from Table no. 12 show the predictive performance of the models when the Delay Differential is excluded and not considered.

Table no. 14 – The predictive performance of the three factors

Factor	Accuracy	Roc-Auc	F1	Precision	Recall
Convenience	83.13%	80.86%	75.14%	74.94%	76.29%
Functionality	77.69%	74.69%	67.14%	70.30%	65.28%
Service	81.77%	79.25%	72.89%	75.84%	70.54%

Table no. 13 presents the Delay Differential and its impact on the predictive performance of the models. Results show a noticeable decrease in predictive performance compared to Table no. 1, suggesting that Delay Differential is irrelevant in predicting the factors under analysis.

Subsequently, a machine learning analysis was conducted, as represented in Tables no. 3 and no. 4. The model displays Accuracy, ROC-AUC, F1 Score, Precision, and Recall. Accuracy demonstrates the ability to predict user satisfaction, while the ROC-AUC suggests that the models' discrimination is satisfactory. The F1 Score reflects the performance between precision and Recall, where precision indicates the proportion of correct optimistic predictions, and Recall, the model's ability to identify valid positive instances. These display the predictive performance for Convenience, Service, and Functionality, considering a Delay Differential. Convenience has emerged as the most critical factor, accounting for over 80% of user satisfaction.

The results of Table no. 14 show the predictive performance of the three factors. Convenience achieved an accuracy of 83.13%, a ROC-AUC score of 80.86%, an F1 Score of 75.14%, a precision of 74.94%, and a recall of 76.29%. Functionality achieved an accuracy of 77.69%, a ROC-AUC score of 74.69%, an F1 Score of 67.14%, and a precision of 70.30%. The Recall was 65.28%. The service yielded an accuracy of 81.77%, a ROC-AUC score of 79.25%, an F1 Score of 72.89%, and a precision of 75.84%. The Recall was measured at 70.54%. The convenience factor has the highest accuracy and overall predictive capabilities among the three factors, indicating that the models perform well in assessing user satisfaction. The service factor is close to Convenience, with a Functionality factor that has relatively lower accuracy and predictive power.

Table no. 15 – The Delay Differential and the analysis for Convenience and Functionality

Factor	Accuracy	Roc-Auc	F1	Precision	Recall
Convenience	83.51%	80.61%	75.68%	75.75%	76.42%
Functionality	78.34%	75.21%	67.47%	71.86%	64.28%
Service	82.10%	79.69%	73.25%	76.57%	70.57%

Table no. 15 considers the Delay Differential, and the analysis for Convenience, Functionality, and Service factors only shows small changes, indicating that the feature has a limited impact on the model. The models achieved an accuracy of 83.51%, a ROC-AUC score of 80.61%, an F1 Score of 75.68%, and a precision of 75.75%, as well as a recall of 76.42%. Functionality achieved an accuracy of 78.34%, a ROC-AUC score of 75.21%, an F1 Score of 67.47%, and a precision of 71.86%, a recall of 64.28%. The service yielded an accuracy of 82.10%, an ROC-AUC of 79.69%, an F1 Score of 73.25%, a precision of 76.57%, and a Recall of 70.57%.

4.1. Findings & Discussion

These methods align with existing research on travel consumer satisfaction, utilising data mining and machine learning techniques to predict user satisfaction (Noviantoro and Huang, 2022). This fact lends credibility to the present and future findings, thereby validating the research conclusions. The analysis reveals the significance of user satisfaction prediction and emphasises the central role of convenience factors in influencing user experiences.

For the first time, the analysis incorporated Delay Differential as a feature, which contributed to a detailed and deeper analysis of consumer satisfaction in the travel industry. This highlighted the importance of Convenience factors in attaining flight features that enhance user experience and satisfaction impacts. A data-oriented managerial application can feature increased results. At the same time, future research can expand upon the present findings by exploring alternative features and analysing additional factors influencing user satisfaction. Extending this analysis to different datasets, industries, and contexts can enhance research validation and confirm applications.

5. GENERAL DISCUSSION & CONCLUSION

Given the importance of consumer satisfaction in the airline industry, studies have highlighted the consequences of customer dissatisfaction and adverse behavioural outcomes. Flight delays are one of the leading causes of complaints from airline customers (Mohd-Any *et al.*, 2019). Thus, improving customer satisfaction can help gain a competitive advantage in the aviation industry (Noviantoro and Huang, 2022). In this study, we measure consumer satisfaction based on 129,880 observations of airline passengers. The study employs three constructs to measure consumer satisfaction, contextualised for the airline customer, drawing on the literature (Nghiêm-Phú, 2019; Park, 2019; Kosiba *et al.*, 2020). The study utilises data mining analysis, employing data mining techniques and machine learning models to predict consumer satisfaction. The study used a machine learning model to predict customer satisfaction regarding flight delays. Service convenience was found to play a crucial role in enhancing customer satisfaction in service failure incidents.

The study makes three significant theoretical contributions. First, the study contributes to consumer satisfaction literature in the event of service failure incidents by demonstrating that service convenience enhances consumer satisfaction in the event of flight delays. Thus, this study complements earlier studies on service failure incidents (e.g., Nazifi *et al.*, 2021).

Second, because the airline industry is regarded as one of the most susceptible industries to service failure, enhancing consumer satisfaction in such a crisis is essential. The study contributes to previous research (e.g., Anderson, 1998; Anderson and Mittal, 2000; Hall and Hyodo, 2022; Pantano and Scarpi, 2022). Third, using a large dataset in Studies 1 and 2, the theory utilises complex and empirical data in the context of flight delays and provides predictions for enhancing satisfaction in service failure incidents within the airline industry. This approach is intended to improve our understanding of consumer satisfaction and reduce negative responses in service failure incidents, such as flight delays.

This paper has practical implications for the airline service industry, specifically in mitigating failures in service encounters, such as when a flight delay occurs during departure and/or arrival.

First, airline companies should invest in enhancing passenger satisfaction through increased convenience. Therefore, they should prioritise the digitalisation of the service for virtual assistants, augmented reality, Artificial intelligence, and virtual reality. Second, Wi-Fi in-flight can also reduce the delay in flight service. For example, offering an extra hour of Wi-Fi usage. Third, airline managers should consider the gate location. Some passengers are stressed and frustrated even before the flight departs, as some companies neglect to address these passengers' negative experiences. Fourth, companies should recover the delay difference and the consequences of passenger dissatisfaction by implementing automatic recovery strategies when a delay occurs. A limited voucher with a flight value can serve as a financial stimulus for the company's brand. This can turn a rage passenger into a loyal one.

This study suggests future research directions. First, the focus of the study can be expanded towards consumers from diverse cultural backgrounds, which would impact consumer satisfaction dimensions. Specifically, investigating cultural moderators and their role in affecting customer satisfaction could also be assessed. Given the rise of emergent technologies such as AI assistants and AI delay prediction, it would be interesting for researchers to examine their impact on consumer satisfaction. Third, because this study approach is more inductive, the theoretical base is integrated after reviewing consumer satisfaction from the datasets. Despite the challenge in finding many examples of real-world Big Data, this study can be replicated in different datasets, primarily if more information regarding context can be determined. This could lead to further theoretical development under new assumptions. A longitudinal study could help examine frequent delays in consumer behavioural outcomes apart from satisfaction, such as brand loyalty and repurchase intention. Additionally, analysing demographic and psychographic profiles could help analyse how flight delays affect consumer satisfaction.

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Complementarity Relationship between Foreign Direct Investment, Human Capital Threshold and Economic Growth: Empirical Evidence for the MENA Region

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Abstract: The complementarity between foreign direct investment (FDI) and human capital constitutes a key interconnected factor that plays a crucial role in encouraging the growth and economic development of nations. This paper processes data from the Middle East and North Africa (MENA) region from 2000 to 2023 to determine the moderating effect of human capital between FDI and economic growth and to establish the human capital threshold which guarantees the advantages of the IDE. It uses the generalized moments method (GMM) and the regression threshold (TR) as part of the dynamic panel data model as estimation strategies. The results note the absence of significant contribution of FDI and human capital to economic growth. After the interaction between FDI and human capital, they justify the significant positive effect of foreign direct investment. However, the coefficient of the interaction variable is significantly negative. This implies that the MENA workforce is unable to transfer the benefits of foreign direct investment. For this reason, this paper resorted to applying the regression threshold to determine the minimum threshold of human capital that guarantees the positive effect of FDI on economic growth. It established a threshold of human capital of 74.58%. It therefore becomes necessary for the MENA region to develop human capital to strengthen its absorption and capacity to diffusion of new technologies in order to reap the full benefits of foreign direct investment.

Keywords: foreign direct investment; human capital threshold; economic growth; GMM.

JEL classification: F21; J24; O40.

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1. INTRODUCTION

Leaving aside the internal resources of growth and economic development such as human capital development, natural resource availability, financial and institutional development, poor and developing countries seek to improve and develop their economies by implementing strategies to attract external resources, including the entry of FDI.

FDI contributes to the growth and economic development of host countries through several transmission channels. To begin with, it increases physical productivity through the transfer of new technologies to physical capital (Christopher and Prosper, 2017; Haini *et al.*, 2024). In addition, it improves the state of the trade balance of host countries by encouraging exports (Hye and Lau, 2015; Séna and Michael, 2017). Moreover, FDI affects economic growth by improving the income of employees through the creation of new jobs (Teresia and Charles, 2018). In addition, FDI promotes growth and economic development by encouraging domestic investment in host countries. Indeed, FDI flows accompany other investments in complementary sectors (Makiela and Ouattara, 2018; Nguyen, 2022). In addition, FDI can result in the transfer of new knowledge to the human capital of host countries (Anetor, 2020). Indeed, the transfer of new knowledge can increase labour productivity. As for the determinants of the contribution of FDI to economic growth, it is said to be determined by the degree of the technological gap between the sending and receiving countries of FDI (Christopher and Prosper, 2017; Obeng-Amponsah and Owusu, 2025), the type and ebb of FDI (Chen *et al.*, 2024) and institution development (Shittu *et al.*, 2020), financial development (Rajab and Zouheir, 2021; My-Linh, 2022; Rajab and Zouheir, 2023) and human capital development.

The development of human capital was considered a target. It ensures economic growth and development through the accumulation of skills and knowledge, and the qualification of the workforce (Affandi *et al.*, 2019; Martin *et al.*, 2021; Tanddrayen Ragoobur and Nasroo, 2022). The development of human capital plays a very important role in the attractiveness of foreign investors. Indeed, it adapts easily with new strategies and new technologies (Kheng *et al.*, 2017). In addition, it absorbs and disseminates new technologies incorporated by FDI to host countries that can enhance the effect of FDI on economic growth.

According to the library of previous research, some studies have neglected to determine the threshold of human capital that ensures the benefits of foreign direct investment. That is, academic research studies have studied the distinct contribution of FDI and human capital to economic growth, studies have analyzed the effect of complementarity between FDI and human capital on economic growth, studies have analyzed the effect of complementarity between strange direct investment and human capital on economic growth. This complementarity is explained by the role played by labor in the absorption and diffusion of new technologies incorporated by foreign direct investment (Kheng *et al.*, 2017). Moreover, some studies have led to the determination of the threshold of human capital that guarantees the benefits of FDI (Friday, 2020; Rajab and Zouheir, 2023; Tsaurai, 2023).

This research study is organized as: Section 2 is devoted to the presentation of literature review. After that, Section 3 presents the theoretical framework. Section 4 deals with the data and methodology. Section 5 discusses the results and discussions. Sections 6 present the conclusion and policy recommendations.

2. LITERATURE REVIEW

According to the results of previous empirical studies, domestic development in host countries plays a very important role in absorbing the benefits of FDI, including financial development. In this regard, My-Linh (2022) examined the mediating role of banking and stock market development in the effect of FDI on economic growth in a sample of 6 countries of the Association of Southeast Asian Nations from 2002 to 2019. The system GMM results and the regression threshold show the positive and significant contribution of FDI to economic growth before and after interaction. This relationship is explained by the development of the financial system of the sampled countries. Again, they set a threshold for the banking sector of 85.64% and the stock market of 21.95%.

Then, Matušovičová and Matušovičová (2023) focus on the correlation between FDI and GDP for 96 quarters from 1999 to 2022. The regression results of a multiple linear model show the significant positive impact of the 5% FDI threshold on economic growth. Indeed, the linear relationship between FDI and GDP is explained by the good preparation of the preconditions for the entry of foreign resources.

Moreover, based on reviews of the theoretical and empirical literature, FDI affects the growth and social well-being of host countries. In this regard, Keita and Baorong (2022) tested the effect of FDI on social welfare in the Guinean context from 1990 to 2017. The results show that FDI positively affects economic development in the short and long term. They noted that it is necessary for Guinean officials to encourage the entry of foreign resources to see healthy economic growth conducive to well-being.

On the other hand, the link between foreign direct investment and economic growth can be explained not only by the increase in total factor productivity but also by the accumulation of the stock of physical capital. Indeed, Makiela and Ouattara (2018) emphasized the relationship between FDI and economic growth in a sample of developed and developing countries from 1970 to 2007. They justified that the effect of FDI is determined by the accumulation of stock. According to these results, they found it important for developing countries to accumulate foreign resources as soon as possible in order to strengthen their impact on growth.

Thus, the allocation of FDI to economic growth can be achieved through various transmission channels, such as export promotion, transfer of new technologies and knowledge, increased competition, export promotion, creation of new jobs, and accumulation of physical capital stock, etc. However, this allocation is not always certain. In this regard, Gökçeli *et al.* (2022) assessed the impact of FDI on national investment and economic growth in the OECD (Organization for Economic cooperation and development) over the period 1990 to 2017. The results of the GMM a fixed effect show the significant positive association between FDI and economic growth. Moreover, they justify that the FDI of developed countries contributes to the increase of the economic growth of the host countries, while FDI from developing countries has no significant impact. In fact, the absence of the significant contribution of FDI to economic growth is explained by the small technological gap between FDI sending and receiving countries.

In fact, Musakwa and Odhiambo (2023) processed annual time series data from 1970 to 2020 to test the causality between FDI, foreign aid and economic growth in Kenya. The results of the ECM-based Granger causality test show the presence of a two-way causality between foreign aid and short-term economic growth and a one-way causality of foreign aid to

economic growth. Moreover, they showed that there is no causal relationship between FDI and economic growth in the short and long term. Indeed, the absence of the causal relationship between FDI and economic growth is explained by the poor preparation of preconditions for the attractiveness of FDI.

Moreover, in the light of the results of academic research, the effect of FDI on economic growth depends on the degree of technical progress of the host countries. In this context, Obeng-Amponsah and Owusu (2025) examined the role of technology in the association of foreign direct investment, employment and economic growth in Ghana from 1995 to 2017. The results of the autoregressive distributed lag ARDL show the negative effect of FDI on growth. Again, they show the positive impact of technology in the short and long term on economic growth. Moreover, they show that technology weakens the negative effect of FDI in the short term. According to these results, they concluded that it is important for poor countries to encourage technological progress in order to promote economic growth and reduce the negative effects of FDI.

In addition, Haini *et al.* (2024) examined the effect of FDI from Japan, China, India, South Korea, Hong Kong and Taiwan on productivity and economic growth in the Association of Southeast Asian countries from 1995 to 2022. The results of the GMM in system show the significant positive impact of FDI on economic growth. In addition, they show that FDI from Japan, Korea and Hong Kong has a significant positive effect on economic growth. However, the flows of Chinese, Indian, and Taiwan origin have a non-significant effect. This result is explained by the small technological gap between the two poles. Again, Haini *et al.* (2024) have found that the benefits of FDI cannot be derived only through the contribution of capital but also through the transmission of new knowledge and new technologies from foreign companies.

To conclude the relationship between FDI and economic growth, FDI promotes economic growth through several transmission channels such as the transfer of new technologies, new knowledge, export promotion, creation of new jobs, etc.

As regards the subject of human capital and economic growth, the contribution of the workforce to the improvement of economic growth is explained by the qualification of the workforce as a result of the accumulation of knowledge and skills. The latter can increase the total productivity of the factors of production and consequently the encouragement of growth and economic development.

In fact, the economic growth of emerging countries is mainly based on the good quality of the workforce. In this regard, Zhang *et al.* (2023), estimated the effect of cognitive and non cognitive productivities on the basis of Chinese macro-data at the provincial level and micro-data on individual work from 2008 to 2017 by using a general equilibrium model of human capital (Xiang & Yeaple, 2018). They found that improving the human capital index leads to convergence of economic growth in the Chinese provinces. This relationship is explained by the fact that the regions in question do not have the same quality of the workforce.

Theoretically, the good quality of the workforce is explained by the development of the education and health sector and the implementation of training. In this angle, Tanddrayen Ragoobur and Nasroo (2022) examined the relationship between human capital and Mauricenne economic growth from 1983 to 2019. The results of the vector error correction model (VECM) and the impulse response function and variance decomposition show that secondary education and health rate indices are explanatory factors of long-term economic growth. So, in light of these results, they see that it is important for poor countries to invest in education and health to promote economic growth.

In addition, on the basis of theoretical and empirical studies, the allocation of human capital to economic growth is explained by the high quality of the educational service, the good quality of the health service, the delivery of training, cognitive skills, etc. In this regard, Affandi *et al.* (2019) discussed the link between the quality of education and Indonesian economic growth. They used the result of the national exam as a proxy for the quality of education. They showed that cognitive skills are a more important factor in Indonesia's economic growth. In addition, he noted that the effect of the exam result on economic growth varies across regions.

According to previous academic research, the development of the education and health sector are the determinants of the qualification and accumulation of human capital. In this context, Zemed and Lakhwinder (2023) examined the effect of human capital accumulation on long-term economic growth in Ethiopia. After the processing of time series data, covering the period 1980/1981 to 2019/2020 by co-integration and error correction test, Zemed and Lakhwinder (2023) showed that secondary school enrolment and life expectancy have a significant positive effect on Ethiopian growth. However, the effect of the primary school enrolment rate and the mortality rate has a non-significant negative effect.

On the other hand, the significant contribution of education sector development to economic growth is not always certain. In this regard, Mohamed (2023) studied the cointegration relationship between education and patents and economic growth in Scandinavian countries over the period 1990 to 2019. He used the cointegration test of Westerlund (2007) and the transversely increased autoregressive distributed shift (CS-ARDL) and the non-causality test of Dumitrescu and Hurlin (2012). The results show a stable long-term cointegration relationship between education, life expectancy and economic growth. Moreover, they justify that the number of patents in the Scandinavian countries has a positive effect on economic growth. However, education spending has a negative effect on economic growth.

To conclude the topic of human capital and economic growth, we can conclude that Affandi *et al.* (2019); Tanddrayen Ragoobur and Nasroo (2022); Zemed and Lakhwinder (2023) have justified the contribution of human capital to economic growth. on the other hand, others have neglected this contribution Mohamed (2023).

With regard to the complementary relationship between foreign direct investments, human capital and economic growth, based on previous studies, it is said that the qualification of the workforce plays a very important role in strengthening the contribution of FDI to economic growth. From this perspective, Su and Liu (2016) examined the effect of human capital and FDI on economic growth in 32 Chinese cities from 1991 to 2010. The GMM results show a significant effect of FDI on economic growth. Moreover, they noted that the complementarity between FDI and human capital affects economic growth. This complementarity is explained by the qualification of the Chinese workforce. That is, it is capable of absorbing and differentiating new technologies incorporated by foreign direct investment.

Furthermore, Dankyi *et al.* (2022) studied the relationship between foreign direct investment, human capital, urbanization, renewable energy, carbon dioxide emissions, and economic growth. They demonstrated the positive effects of human capital, FDI, renewable energy, and urbanization on economic growth. Furthermore, they noted that quality, inclusive, and equitable education was a significant explanatory factor in economic growth and FDI in economic community of West African states countries from 1990 to 2017.

On the other hand, theoretical and empirical reviews have shown that the complementarity between FDI and human capital can justify under certain conditions. In this regard, Friday (2020) examined the mediating role of human capital in the relationship of FDI and economic growth for the 28 sub-Saharan African countries during the period 1999 to 2017. The GMM system results show the significant negative impact of FDI on growth. Indeed, this relationship is explained by the poor preparation of the preconditions for the entry of foreign direct investment. Moreover, they justify the non-significant negative impact of human capital. The absence of this contribution is explained by the underdevelopment of human capital in sub-Saharan African countries. Friday (2020) noted that the effect of complementarity between FDI and human capital is negative but significant. In addition, it established a minimum human capital threshold of 63.91% to ensure significant positive complementarity.

In fact, Rajab and Zouheir (2023) examined the complementary relationship between FDI and human capital and their effect on the economic growth of a sample of 15 least developed African countries from 2000 to 2019. The results of the GMM in system show the significant negative contribution of foreign direct investment. However the effect of human capital is negative not significant. In fact, the lack of significant allocation of human capital to economic growth is explained by the underdevelopment of human capital. Moreover, they showed the significant negative impact of complementarity between FDI and human capital on economic growth. Rajab and Zouheir (2023) used the regression threshold and set a threshold of 61.57% of human capital that saves the benefits of foreign direct investment.

Finally, on the basis of the results of previous studies, the development of human capital through accumulation and qualification facilitates the adoption and improvement of capacities for the transformation of new technologies and knowledge, research, innovation, etc. These operations require a minimum human capital threshold.

3. THEORETICAL FRAMEWORK

This study examines the complementarity relationship between FDI and human capital and its interaction effect on economic growth from an endogenous growth perspective. Indeed, the function below presents the Cobb Douglas type production function.

$$Y_t = K_t^{\propto} H_t^{\beta} (A_t L_t)^{1-\alpha-\beta} \quad (1)$$

with:

Y: real gross domestic product
K: the physical capital stock
H: the stock of human capital
L: the labour factor,
A: technological efficiency
t: time.

It is supposed $\alpha + \beta < 1$.

The function of the work is L_t. Indeed,

$$L_t = L_0 e^{nt} \quad (2)$$

The technological function is A_t. Indeed,

$$A_t = A_0 e^{gt} F^{\theta} \quad (3)$$

with:

n: the rate of exogenous labour force growth,

g: the growth rate of technical progress

F: the proportion of A that relates to FDI

FDI is assumed to improve overall productivity through two direct and indirect channels:

– The direct channel is that technology embedded in FDI directly improves the average productivity of host countries.

– The indirect channel is that the inflow of FDI generates positive spinoffs in the form of technology transfer. They increase the average productivity of local businesses and consequently the improvement of the average productivity of host countries.

Theoretically, the benefits of FDI depend on the absorption capacity of the host countries. It is measured by the stock of human capital. Thus, to capture the direct and indirect positive externality of FDI on productivity, the elasticity θ is considered to be the function of the human capital stock.

$$\theta = \theta_0 + \theta_1 f(h) \quad (4)$$

The savings rate is assumed to be exogenously determined by government policy and individual preferences. In this case:

The human capital stock can be expressed in function K:

$$K = s_k Y_t - \delta k \quad (5)$$

with:

s_k : presents the proportion of income in the investment of physical capital.

δ : is the depreciation rate.

The physical capital stock can be expressed in function H:

$$H = s_h Y_t - \delta h \quad (6)$$

with:

s_h : Represents the proportion of income in human capital investment.

It is assumed:

– k : the stock of physical capital per unit of labor.

Indeed, $k = \frac{K}{AL}$ and,

– h : the stock of human capital per unit of work.

Indeed, $h = \frac{H}{AL}$.

Therefore:

$$\mathcal{K} = s_{\mathcal{K}} y_t - (n + g + \delta)\mathcal{K} k_t \quad (7)$$

$$\hbar = s_{\hbar}\, y_t - (n + g + \delta)\hbar_t \quad (8)$$

It is supposed:

– the level of physical capital per work unit is constant. It is noted h^* .

– the level of human capital per work unit is constant. It is noted $\hbar^*$.

In fact,

$$h^* = \left(\frac{s_{\mathcal{K}}^{1-\beta} s_{\hbar}^{s}}{n + g + \delta}\right)^{\frac{1}{1-\alpha-\beta}} \quad (9)$$

$$\hbar^* = \left(\frac{s_{\mathcal{K}}^{\alpha} s_{\hbar}^{1-\alpha}}{n + g + \delta}\right)^{\frac{1}{1-\alpha-\beta}} \quad (10)$$

To obtain the per capita income in the stationary state, we replace equation (9) in (10) and add the log. So,

$$\log \frac{Y_t}{L_t} = \log A_t - \frac{\alpha+\beta}{1-\alpha-\beta} \log\,(n + g + \delta) + \frac{\alpha}{1-\alpha-\beta} \log s_{\mathcal{K}} + \frac{\beta}{1-\alpha-\beta} \log s_{\hbar} \quad (11)$$

To simplify equation (11), the technological benefits of FDI are replaced, and θ in equation (3) by $\theta = \theta_0 + \theta_1 f(h)$

When we integrate equation (11) into (10) and we replace A_t by $A_t = A_0$, we get equation (12). With:

$$A_t = A_0 e^{gt} F^{\theta_0 + \theta_1 \log(h)}$$

Equation (12) refers to income as a function of demographic rate, rate of investment in physical and human capital and FDI.

$$\log \frac{Y_t}{L_t} = \log A_0 + g_t + \theta_0 \log(F) * \log(\hbar) - \frac{\alpha}{1-\alpha} \log(n + g + \delta) + \frac{\alpha}{1-\alpha} \log s_{\mathcal{K}} \frac{\beta}{1-\alpha} \log(\hbar) \quad (12)$$

Equation (12) presents the steady state of the economy i.

y^* is the per capita income in the stationary state.

y_t is the per capita income in t.

So the rate of convergence to a stationary state is written in equation (13).

$$\frac{dlog\ y}{dt} = \eta\ (\log y^* - \log y_t \tag{13}$$

with:

$$\eta = (n + g + \delta)1 - \alpha - \beta$$

When integrating equation (13) from t_0 to t, is obtained equation (14):

$$\log y_t = (1 - e^{-\eta t}) \log y^* + e^{-\eta t} \log y_0 \tag{14}$$

When replacing the $\log y^*$ in equation (12) and rewrite the equation we get the equation below.

$$\begin{aligned} \log\left(\frac{Y}{L}\right)_t = \log\left(\frac{Y}{L}\right)_0 = & -(1 - e^{-\eta t}) \log\left(\frac{Y}{L}\right)_0 - (1 - e^{-\eta t})\left(\frac{\alpha}{1-\alpha}\right) \log\ (n + g + \delta) \\ & + (1 - e^{-\eta t})\left(\frac{\alpha}{1-\alpha}\right) \log s_{\mathcal{K}} + \frac{\beta}{1-\alpha} \log(\hbar) + \log A_0 + g_t \\ & + \theta_0\ (\ (1 - e^{-\eta t}) \log(F) + \theta_1 (1 - e^{-\eta t}) \log(F) * \log(\hbar) \end{aligned} \tag{15}$$

Equation (15) presents the determinants of endogenous growth over a long period. Otherwise economic growth is determined by the rate of population growth, the rate of physical capital, human capital stock, FDI and its interaction with human capital. The equation below presents the regression equation of a dynamic panel data.

$$\begin{aligned} \log(y_{it}) = \log(y_{i0}) = & \ \alpha_0 + \alpha_1 \log(y_{i0}) + \alpha_2 \log(n_{it} + g + \delta) + \alpha_3 \log(s_{\mathcal{K}it}) + \alpha_4 \log(h_{it}) \\ & + \alpha_5 \log(FDI_{it}) + \alpha_6 \log(FDI_{it}) * \log(h_{it}) + u_{it} \end{aligned} \tag{16}$$

where: u_{it}: error term

According to equation (16), this study specified two models. Indeed:

– The first econometric model estimates the contribution of FDI and human capital to economic growth.

– The second econometric model addresses the impact of complementarily between FDI and human capital on economic growth. These econometric models are formulated in equations (17) and (18).

$$\begin{aligned} GDP_{it} = & \ \alpha_0 + \alpha_1 GDP_{it-1} + \alpha_2 FDI_{it} + \alpha_3 HC_{it} + \alpha_4 GCF_{it} + \alpha_5 TOP_{it} + \alpha_6 POP_{it} + \alpha_7 INF_{it} \\ & + \alpha_8 XDEBT_{it} + \alpha_9 GXP_{it} + u_{it} \end{aligned} \tag{17}$$

where:

GDP is the growth of GDP per capita,
FDI is FDI,
HC is the human capital,
GCF is gross capital formation,
TOP is the commercial opening,

POP is population growth,
INF is inflation,
XDEBT is external debt,
GXP is the final consumption expenditure of general government,
and u_{it}: $error\ term$.

$$GDP_{it} = \alpha_0 + \alpha_1 GDP_{it-1} + \alpha_2 FDI_{it} + \alpha_3 (FDI_{it}.HC_{it}) + \alpha_4 HC_{it} + \alpha_5 GCF_{it} + \alpha_6 TOP_{it} + \alpha_7 POP_{it} + \alpha_8 INF_{it} + \alpha_9 XDEBT_{it} + \alpha_{10} GXP_{it} + u_{it} \quad (18)$$

where: $FDI_{it}.HC_{it}$ is the interplay between FDI and human capital.

This study also aims to establish the minimum threshold of human capital at which the interaction between human capital and FDI positively affects economic growth. The threshold equation is specified in equation (19):

$$GDP_{it} = u + FDI_{it}(HC_{it} < y_{it})\beta_1 + FDI_{it}(HC_{it} > y_{it})\beta_2 + u_i + e_{it} \quad (19)$$

where: g is the threshold parameter that divides the equation into two regimes with coefficient β_1 and β_2.
u_i is the individual effect.
and u_i is the stochastic term.

Table no. 1 presents the definition and measurement of variables.

Table no. 1 – Definition and measurement of the variables

Variables	Description	Measurement	Expectation	Source
GDP	Economic growth	GDP per capita growth.	Negative	WDI (2023)
FDI	Foreign direct investment	The percentage ratio of FDI net inflows in the reporting economy to GDP.	Positive/ Negative	WDI (2023)
HK	Human capital	Secondary school enrollment (% gross).	Positive	WDI (2023)
GCF	Gross capital formation	The ratio of GCF divided by GDP.	Positive	WDI (2023)
TOP	Trade openness	The percentage ratio of sum of exports plus imports of goods to total output.	Positive	WDI (2023)
POP	Population growth	It is computed as the annual growth rate.	Negative	WDI (2023)
GXP	Government consumption expenditure	It is consist of total expenses and the net acquisition of non-financial assets.	Positive	WDI (2023)
INF	Inflation	It refers to the general increase in consumer prices.	Negative	WDI (2023)
XDEBT	External debt	It comprises of debt, liabilities in the form SDRs, currency and deposit, debt securities, loans, insurance and pension.	Negative	WDI (2023)

According to previous theoretical and empirical literature reviews, each variable can exert a significant or non-significant positive or negative effect. Indeed, this study anticipated a positive or negative effect of FDI on economic growth.

Based on theoretical and empirical studies, the contribution of FDI to economic growth is uncertain. So, the first assumption is that FDI does not affect economic growth. In addition, according to the results of previous studies, it is easy to assume the second hypothesis as human capital affects economic growth. On the other hand, in light of the arguments established on the relationship between human capital, FDI and economic growth, the third hypothesis is that complementarity between human capital and FDI does not strengthen economic growth.

4. DATA AND METHODOLOGY

This research study treats the MENA region database from 2000 to 2023. Countries are selected based on data availability, including Tunisia, Algeria, Saudi Arabia, Bahrain, Djibouti, United Arab Emirates, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Morocco, Mauritania, Oman, Qatar and Syria.

This study assumes the heterogeneity between the countries of the MENA region. Because, the countries of the MENA region have radically different economic structures, levels of development and institutional qualities.

Because of the problem of heterogeneity between countries, variables, and the problem of bias omitted, this study used the econometric technique of Arellano and Bond (1991); Arellano and Bover (1995) and Blundell and Bond (1998). In addition, she used a dynamic panel and regression threshold data model proposed by Hansen (2000). Indeed, the model allows you to determine the threshold of HC so that its interaction effect with the FDI becomes positive. In addition, it adds increased flexibility to the functional form and, at the same time, it is not as sensitive to the curse of dimensional problems as non-parametric methods Kourtellos *et al.* (2016).

5. RESULTS AND DISCUSSIONS

5.1. Descriptive statistics

Table no. 2 presents the descriptive statistics of the variables.

Table no. 2 – Descriptive statistics

Variable	Mean	SD	Minimum	Maximum	Skewness	Kurtosis	JB	P.JB
GDP	2.26	2.77	-2.86	5.56	-0.65	0.51	3.68	0.041
FDI	22.68	9.24	9.98	89.06	4.23	3.81	1.92	0.009
HC	94.03	33.45	0.00	98.21	8.29	3.09	55.39	0.000
GCF	44.39	18.79	12.94	69.58	-9.83	9.99	5.37	0.345
TOP	93.54	31.18	33.09	149.86	-1.68	12.81	22.67	0.029
POP	4.46	1.09	3.29	9.57	9.07	0.94	3.90	0.092
INF	10.45	0.91	-12.02	22.73	2.37	11.31	79.21	0.000
XDEPT	59.36	52.47	0.00	89.14	9.48	2.29	8.03	0.081
GXP	78.47	16.39	0.71	94.02	1.02	10.01	0.02	0.069

Source: calculated by author's using STATA 15

According to Table no. 2, GDP per capital growth in the MENA region averaged 2.26 with a standard deviation of 2.77. In contrast, all values are between -2.86 and 5.56. In fact, the shape of the distribution is asymmetric extended to the right where the Skewness statistic > 0. In addition, it is leptokurtic where the Kurtosis is equal to 0.51. The form of the GDP distribution rejects the null hypothesis of the normal distribution for a risk level of 5%.

In addition, Table no. 2 shows that the variable "FDI" recorded an average growth rate of 22.68 of GDP with a standard deviation of 9.24. In addition, the values are bounded between 9.98 and 89.06. This variable takes a form of asymmetric distribution extended to the right where the Skewness statistic is equal to 1.81 > 0. It is leptokurtic because the Kurtosis is positive. Overall, this variable rejects the null assumption of normality because p value is well below 5%.

In addition, Table no. 2 shows that the variable 'POP' recorded an average growth rate of 4.46 with a standard deviation of 1.09. Moreover, the minimum and maximum values are 3.29 and 9.57 respectively. This variable takes a form of asymmetric distribution extended to the right because, the Skewness statistic is equal to 9.07 > 0. Furthermore, it is leptokurtic due to the fact that the Kurtosis > 0. Overall, this variable rejects the null hypothesis of normality due to the fact that the p value is largely less than 5%.

Overall, human capital has an overall average of 94.03 with a standard deviation of 33.45. The maximum and minimum values are 98.21 and 0.00. In addition, the human capital variable takes an asymmetrical distribution to the right. It is leptokurtic where the Kurtosis is equal to 3.09. The distribution of this variable rejects the null assumption of normality for a risk level of 5%.

In addition, Table no. 2 shows that trade opening has recorded an average growth rate of 93.54. Again, the average growth rate of domestic investment is equal to 44.39. The variable "inflation" recorded an average growth rate of 10.45. In addition, public expenditure recorded an average growth rate of 78.47. Also, the MENA region recorded an average public debt ratio of 59.36 of GDP.

5.2. Stationarity Test

To justify the stationarity of the series, we used the Hadri LM test (2000). Indeed, the null hypothesis of Hadri LM (2000) proposes that all series are stationary. However, the alternative hypothesis is that some series are not stationary. In fact, the null hypothesis is written: H0: T-statistic > 0 vs the alternative hypothesis: H1: T-statistic < 0. The table below displays the results of the stationarity test.

Table no. 3 – Hadri LM Test

	GDP	**FDI**	**HC**	**GCF**	**TOP**	**POP**	**INF**	**XDEPT**	**GXP**
Level									
Hadri LM	-2.055 (0.014)	28.107 (0.003)	11.735 (0.321)	9.019 (0.092)	32.904 (0.000)	-8.063 (0.000)	12.319 (0.035)	1.795 (0.011)	25.943 (0.000)
1st Difference									
Hadri LM	-13.724) (0.001)	-10.980 (0.005)	-1.159 (0.034)	-19.413 (0.009)	-0.156 (0.000)	-18.344 (0.000)	-5.491 (0.019)	-1.133 (0.009)	-27.238 (0.000)

Source: STATA 15

According to Table no. 3, at that level, none of the variables are stationary except for the variables "economic growth" and "population." In this case, we reject H_0 for all the other variables. In the first difference, all series become stationary. So, we assert that all variables are integrated in order 1.

5.3. Effect of FDI on Economic Growth

Table no. 4 presents the results of the GMM econometric estimation.

Table no. 4 – The effect of FDI on economic growth

Variables	Estimation	Probability
GDP per capital growth (-1)	-0.093	(0.062) *
FDI inflow as % of GDP	-0.014	(0.144) n.s
Human capital	0.043	(0.281) n.s
GCF as % of GDP	0.084	(0.031) *
Trade openness	0.253	(0.000) ***
Population growth rate	0.103	(0.973) n.s
Inflation	-0.082	(0.009) ***
External debt as % of GDP	-0.146	(0.052) *
Government expenditure as % of GDP	0.248	(0.006) ***
AR (1)	0.012	
AR(2)	0.154	
Hansen Test	0.197	
Diff-in-Hansen (excluding group)	0.229	
Diff-in-Hansen (H0 = exogenous)	0.286	
Number of observations	391	
Number of countries	17	
Number of instruments	23	

Note: The probability is reported in parentheses. *; ** and *** indicate significance at 10, 5 and 1% levels, respectively. SGMM model is estimated by using the Blundell and Bond (1998) dynamic panel SGMM estimations and Roodman (2009) STATA xtabond2 command.

Source: calculated by author's using STATA 15

Hansen's null hypothesis assumes that the estimation instruments are valid. Indeed, with a coefficient of 0.197 from the Hansen test, we do not reject the null hypothesis. This signals that the estimation instruments are valid.

The results in Table no. 4 show that the coefficient of the variable "FDI" is negative. And it is statistically insignificant. This means that the entry of FDI into the MENA region does not encourage economic growth. This result is expected. But, it confirms the results of previous studies by Bakari and Sofien (2019); Friday (2020); Simionescu *et al.* (2021); Obeng-Amponsah and Owusu (2025). Indeed, the economic justification for the absence of the contribution of FDI to economic growth may explain the poor precondition of the attractiveness of foreign resources. Otherwise, it is the poor preparation of the conditions necessary to benefit from the benefits of foreign direct investment.

In addition, the sign associated with the variable "human capital" is positive insignificant. In this case, it is said that human capital does not explain economic growth in the MENA region. However, the result is not as expected. But, it is consistent with the results of previous research

Rizal and Nurruhwati (2018); Mohamed (2023). On the other hand, this result may explain the poor skills of the MENA workforce and the persistent brain drain in the region.

As for the variable "gross fixed capital formation", the results justify that gross fixed capital formation is an engine of economic growth in the MENA region. Indeed, this result corroborates the previous empirical justifications and conforms to the economic logic. This result is explained by the continuous accumulation of the stock of physical capital through investment in the private sector.

Then, the coefficient associated with the variable "commercial opening" is positive of 0.253 and statistically significant at the 1% threshold. This indicates that the trade opening of the MENA region is a factor of economic growth. Indeed, the result corroborates the results of previous studies of Hye and Lau (2015); Yeboah (2023). In fact, one plausible explanation for this is that most MENA countries are integrating into the global economy. This integration creates dynamic comparative advantages in terms of potential to improve productivity and consequently economic growth.

As for the coefficient of the population variable, it is positive not significant. That is, the population of the MENA region does not designate a factor of economic growth. This relationship corroborates the results of previous studies Friday (2020).

On the other hand, the inflation rate has a negative effect of -0.082 and is statistically significant at the 1% threshold on economic growth. In fact, the inverse relationship between inflation and economic growth is explained by the general rise in prices in the MENA region that can increase production costs within companies, create production-related difficulties.

Moreover, the debt ratio has a significant negative effect on economic growth. A plausible explanation for this is that a considerable share of external debt has not been allocated to productive projects. Generally, this strategy discourages long-term economic efficiency.

The results also showed that public spending contributes to economic growth in the MENA region. This result is consistent with economic logic. Indeed, this relationship is explained by economic growth in the MENA region and is based on heavy state intervention.

The results show that the effect of the previous year's growth rate on current growth is negative and statistically significant. Indeed, the inverse relationship can be explained by the convergence hypothesis. This indicates that poor and developing countries are converging more rapidly towards a steady average growth rate compared to developed countries.

5.4. Effect of the interaction between FDI and human capital on economic growth

The relationship of complementarity between FDI and human capital and its effect on economic growth is determined by the nature of the effect of the interaction variable FDI.HK. Table no. 5 presents the results of the regression of equation (18).

Table no. 5 – Interaction effect between FDI and human capital

Variables	Estimation	Probability
GDP per capital growth (-1)	-0.058	(0.093)*
FDI inflow as % of GDP	0.016	(0.049)**
FDI.HK	- 0.037	(0.011)**
Human capital	0.127	(0.338) n.s
GCF as % of GDP	0.297	(0.009)**
Trade openness	0.248	(0.063)*
Population growth rate	-0.021	(0.507) n.s
Inflation	-0.044	(0.000)***
External debt as % of GDP	-0.021	(0.072)*

Variables	Estimation	Probability
Government expenditure as % of GDP	0.0207	(0.006)***
AR (1)	0.039	
AR(2)	0.293	
Hansen Test	0.217	
Diff-in-Hansen (excluding group)	0.222	
Diff-in-Hansen (H0 = exogenous)	0.539	
Number of observations	391	
Number of countries	17	
Number of instruments	23	

Note: The probability is reported in parentheses. *; ** and *** indicate significance at 10, 5 and 1% levels, respectively. SGMM model is estimated by using the Blundell and Bond (1998) dynamic panel SGMM estimations and Roodman (2009) STATA xtabond2 command.

Source: calculated by author's using STATA 15

Table no. 5 shows that the contribution of FDI to economic growth becomes positive and statistically significant. In addition, theoretically, the interaction variable designates the capacity of the workforce of host countries to absorb and disseminate new technologies linked to foreign direct investment. In fact, the sign associated with the variable the interaction is negative and it is significant. This means that human capital is essential to strengthen the effect of FDI on economic growth. In addition, it assumes the underdevelopment of human capital that is to say that the hand the MENA region is unable to absorb and disseminate new technologies incorporated by foreign direct investment. In this case, it becomes relevant to find the level of human capital that could be considered as a minimum for the impact of the interaction variable becomes significant positive.

5.5. Results of the dynamic panel regression threshold

Table no. 6 shows the results of the regression threshold.

Table no. 6 – Regression Threshold Results

Estimated human capital threshold		
y	74.58	
95% confidence interval	[74.59; 74.57]	
Impact of regime-independent regressor		
GDP per capital growth (-1)	-0.154	(0.009)***
FDI inflow as % of GDP	-0.085	(0.054)**
Human capital	-0.102	(0.386) n.s
GCF as % of GDP	0.093	(0.029)**
Trade openness	-0.071	(0.000)***
Population growth rate	0.109	(0.832) n.s
Inflation	-0.099	(0.000) ***
External debt as % of GDP	-0.002	(0.019)**
Government expenditure as % of GDP	0.115	(0.047)**
Constant	0.072	(0.013)**
Observations		391
Number of countries		17

Note: the dependent variable is GDP per capita growth. The probability is reported in parentheses. *; ** and *** indicate significance at 10, 5 and 1% levels, respectively.

Source: calculated by author's using STATA 15

Table no. 6 shows a human capital level of 74.58 for the MENA region of (74.59; 74.57) with a 95% confidence interval. This means that if the level of human capital decreases below 74.58%, The MENA region could not benefit from the potential benefits of FDI entry and as a result, FDI does not affect economic growth. For this, it is important for the MENA region to develop human capital so that FDI fully plays its role as a factor creating economic growth.

6. CONCLUSION AND POLICY RECOMMENDATIONS

This study addressed the effect of the complementary relationship between foreign direct investment-human capital on economic growth in the MENA region over the period 2000-2023 by the generalized moment method and the dynamic regression threshold.

This study justifies the absence of the significant effect of FDI and human capital on economic growth in the MENA region from 2000 to 2023. Moreover, when adding the interaction variable FDI.KH, the effect of FDI on economic growth becomes significant positive. However, the effect of the variable FDI.KH is significant negative. This means that the MENA workforce is not able to absorb and transform new technologies incorporated by foreign direct investment. As a result, this study used the regression threshold to find the minimum human capital threshold and set a level of 74.58%. Otherwise, when the MENA region's human capital threshold falls below 74.58%, it will not be able to benefit from the benefits of foreign direct investment.

According to the results obtained, this research study uses two recommendations. Indeed, as this research has justified that human capital does not meet the requirements of the impact of FDI on economic growth, MENA leaders need to develop skills strategies for the workforce in order to fully absorb and disseminate the benefits of foreign direct investment, therefore, strengthening economic growth. In addition, MENA country leaders must prioritize the knowledge and skills required by strategic sectors of the economy, including training and education. This means that it is important for the MENA region to restructure the education system to facilitate the matching of a skilled workforce with economic activities requiring the same qualifications.

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Challenging the Efficient Market Hypothesis: Multifractal Insights into Price – Volume Cross-Correlations in the S&P 500

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Abstract: This study investigates the multifractal behaviour of prices, trading volume, and their cross-correlations in the S&P 500 index over the 2004–2024 period. To this end, we employ an integrated framework that combines the Bai–Perron structural break test with Multifractal Detrended Fluctuation Analysis (MFDFA) and Multifractal Detrended Cross-Correlation Analysis (MFDCCA). MFDFA is employed to detect scale-dependent long-range dependence and multifractality within individual time series, while MFDCCA extends this framework to examine multifractal cross-correlations between price and trading volume across different time scales. The structural break analysis reveals five endogenous break points, leading to six distinct market segments and allowing market dynamics to be examined on a segment-specific basis. The empirical evidence shows that both price and volume series display multifractal behaviour throughout the sample, although the intensity of multifractality varies across segments. By contrast, price–volume cross-correlations tend to exhibit broader and more asymmetric multifractal spectra, pointing to stronger nonlinear dependence and greater structural complexity in joint dynamics. Importantly, these results should not be interpreted as evidence of a permanent breakdown in market efficiency. Rather, they suggest that deviations from weak-form efficiency are time-varying and closely linked to changing market conditions, in line with the Adaptive Market Hypothesis and the Fractal Market Hypothesis. Overall, the joint analysis of price, volume, and their multifractal cross-structure within a structural-break-aware setting offers new insights into segment-dependent information transmission and the evolving nature of market efficiency in a major benchmark index.

Keywords: Bai-Perron; long memory; adaptive market hypothesis; price-volume cross-correlation; structural breaks.

JEL classification: G14; C22; C58.

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1. INTRODUCTION

The efficiency of capital markets is a subject that has been extensively discussed in the financial economics literature. Under the Efficient Market Hypothesis (EMH) developed by Fama (1965, 1970), market prices are believed to reflect all available information, thereby precluding the possibility of investors achieving systematic abnormal returns. According to the weak form of the EMH, past price information is insufficient to predict future price movements and therefore prices follow a random walk (Samuelson, 1965). This perspective has served as the foundational basis for numerous conventional financial theories.

Nevertheless, as demonstrated in the extant behavioural finance literature, which has evolved considerably since the 1980s, it has become evident that individuals do not invariably act in a manner that is consistent with rationality. Concurrently, market prices have been shown to deviate from time to time due to factors such as emotions, biases, and bounded rationality (Kahneman and Tversky, 1979; Shiller, 2003). This perspective posed a challenge to the deterministic nature of the EMH, suggesting that market behaviour should be explained by more complex structures.

In this context, the Adaptive Market Hypothesis (AMH), developed by Lo (2004), provides an important conceptual leap. According to AMH, market efficiency is not a static phenomenon; rather, it is a time-varying and evolutionary process. In essence, while a market may exhibit efficiency during certain periods, it may deviate from efficiency during other periods.

Concurrently, the non-linear and complex nature of financial time series has garnered mounting attention. In this regard, Peters (1994) and subsequent studies have posited that financial time series may manifest characteristics such as self-similarity and long memory, which may contradict the EMH. The concept of "long memory" in financial markets signifies the tendency of past price movements to exert influence on future price movements. This phenomenon can be interpreted as a manifestation of market inefficiency (Mandelbrot, 1972; Peters, 1994; Di Matteo, 2007).

In this framework, fractal geometry and multifractal analysis methods emerge as potent instruments for elucidating the intricate dynamics of financial time series. The notion of fractal structures was initially articulated by Mandelbrot (1963). It was observed that a multitude of natural phenomena (e.g., snowflakes, river deltas, tree branches) exhibit a propensity to manifest as similar forms to themselves. The observation of similar structures in financial time series (Wang *et al.*, 2009) is important for understanding complex market dynamics that cannot be explained by classical models. The fractal dimension is determined by how the object or time series fills its space (Peters, 1996). The Fractal Market Hypothesis (FMH) emphasises the impact of liquidity and investment horizon on investors' behaviour (Peters, 1994). Peters (1994, 1996) points out that the next data in a financial time series is not completely independent of the previous ones, i.e. previous data may be a carrier of information.

On the other hand, besides price series, other market indicators such as trading volume can also be a carrier of information (Karpoff, 1987; Gopikrishnan *et al.*, 2000). The relation between trading volume and security prices has been studied for over 40 years since (Osborne) suggested in 1959 that the variance of security prices could be modelled as a diffusion process whose variance depends on the number of transactions (Stošić *et al.*, 2015). The interplay between price and volume provides important clues about market microstructure and investor behaviour. Therefore, analysing not only prices but also trading volume in terms of

multifractal structure allows for a more holistic assessment of market efficiency (Jiang *et al.*, 2019; Açikgöz *et al.*, 2024).

This study contributes to the literature by offering a structural-break-aware joint multifractal analysis of prices, trading volume, and their cross-correlations for the S&P 500 index over the 2004–2024 period. Existing studies have typically focused either on price dynamics alone or on price–volume relationships examined through linear or single-scale frameworks. In contrast, the present study combines Multifractal Detrended Fluctuation Analysis (MFDFA) and Multifractal Detrended Cross-Correlation Analysis (MFDCCA) within a framework that explicitly incorporates endogenously identified structural breaks using the Bai–Perron procedure. Specifically, MFDFA captures the presence of multifractality and long-memory behaviour in individual financial series, whereas MFDCCA allows the investigation of scale-dependent cross-correlations between price and volume dynamics. This approach allows market dynamics to be analysed at the segment level and provides a clearer view of how information is transmitted through prices, trading activity, and their interaction under different market conditions. The findings do not indicate a permanent breakdown of the Efficient Market Hypothesis. Instead, they reveal time-varying departures from weak-form efficiency, reflected in persistent and heterogeneous multifractal structures. These patterns are consistent with the Adaptive Market Hypothesis and the Fractal Market Hypothesis. Overall, the evidence shows that price–volume cross-correlations tend to display stronger and more heterogeneous multifractal characteristics than individual series, underscoring the role of joint dynamics in shaping market behaviour and offering new insights into the evolving nature of market efficiency. While existing multifractal studies on the S&P 500 largely focus on price dynamics in isolation or on single-scale correlations, empirical evidence on the joint multifractal structure of price and trading volume – particularly in the presence of structural breaks – remains limited.

The primary objective of this study is to examine the joint multifractal dynamics of price and trading volume in the S&P 500 index, with particular attention to how these dynamics evolve across structurally distinct market regimes.

The empirical findings reveal persistent multifractality and non-linear cross-correlations between price and volume, whose intensity and asymmetry vary across structural break segments, providing evidence inconsistent with the strict form of the Efficient Market Hypothesis.

Accordingly, the analysis is guided by the following research questions:

***Q1**: Do price and trading volume series of the S&P 500 exhibit multifractal and scale-dependent dynamics across market segments identified by endogenous structural breaks?*

***Q2:** Does the multifractal structure of price–volume cross-correlations differ systematically from those of individual price and volume series, and does it exhibit stronger nonlinearity and heterogeneity?*

***Q3:** Do segment-specific multifractal patterns provide evidence of time-varying departures from weak-form market efficiency, in line with the Adaptive Market Hypothesis and the Fractal Market Hypothesis?*

The present study is predicated on the assumption that information flow may give rise to multifractal structures in volume dynamics, as well as its subsequent impact on market price. Consequently, the analysis relies on Multifractal Detrended Fluctuation Analysis (MFDFA) to

capture scale-dependent long-range dependence in non-stationary time series, together with Multifractal Detrended Cross-Correlation Analysis (MFDCCA), which extends this framework to examine multifractal cross-correlations between pairs of non-stationary series. Using this combined approach, the multifractal properties of price and trading volume are analysed alongside the structure of their interaction. In this parallel, our research will generate information that will assist policymakers in comprehending market functionality and will benefit market participants, such as investors and portfolio managers, who aim to make forecasts.

While the methodological foundation of this study is closely related to the multifractal framework employed by Patil and Rastogi (2020), the present analysis departs from that approach in several important respects. Rather than concentrating exclusively on price-based measures of efficiency, it explicitly incorporates trading volume and examines price–volume cross-correlations within a multifractal setting. In addition, the analysis moves beyond static price dynamics by exploring how joint multifractal structures evolve across endogenously identified structural breaks. The sample period is also extended to cover more recent episodes, including the Covid-19 shock and the subsequent post-pandemic recovery, which allows for a broader and more realistic assessment of segment-dependent market efficiency. Together, these extensions offer additional insights into information transmission mechanisms and the changing complexity of market dynamics that are not fully captured in earlier studies. Although the study adopts an integrated MFDFA–MFDCCA framework combined with the Bai–Perron structural break procedure, it is worth noting that alternative multifractal methodologies could further strengthen robustness assessment. For instance, future research may draw on cross-multifractal spectrum (CMFS) approaches or complementary structural break detection techniques to validate and extend the segment-dependent price–volume interactions documented here. Such extensions would enable a deeper examination of nonlinear dependence across market segments, while leaving the core findings of the present study unchanged. Accordingly, rather than replicating an existing framework, the present study extends prior multifractal analyses by explicitly incorporating trading volume and price – volume interactions into a regime-dependent setting, thereby offering a broader perspective on market efficiency dynamics.

2. LITERATURE REVIEW

Research on the efficiency of capital markets has historically been shaped around the Efficient EMH and criticisms against this hypothesis. Fama (1965) argues that financial markets are characterized by weak efficiency, thereby implying that historical price movements are inadequate for predicting future prices. However, subsequent years have witnessed the emergence of alternative approaches that contend with the notion of market prices being entirely random. A seminal example of this phenomenon is the AMH, proposed by Lo (2004). According to this hypothesis, markets adapt to time-varying conditions; therefore, efficiency is not constant but cyclical. In this framework, studies suggesting that financial series may contain not only short-run but also long-range dependence have also become prominent in the literature. In particular, Peters (1994) advanced the notion that financial time series may exhibit fractal characteristics and investigated the "self-similarity" phenomenon by implementing the fractal geometry concept initially developed by Mandelbrot (1989) The objective of this study is to examine financial data.

A considerable body of research has been dedicated to the empirical evaluation of this theoretical framework through the utilization of numerical methodologies. For example, Wang *et al.* (2009), in their study on the Shenzhen Stock Exchange, used the MFDFA method and found that the Hurst exponent changes over time and the market becomes increasingly efficient. Similarly, Oprean-Stan *et al.* (2014), in their research examining the market structures of different countries through R/S analysis, found that the Brazilian market is closest to the random walk hypothesis, whereas the Chinese, Estonian and Romanian markets have fractal characteristics. Hiremath and Narayan (2016) also investigated the time-varying efficiency level on Indian stock markets and found that long memory varies over time and the market tends towards efficiency. In a different approach, Kumar *et al.* (2017) test the FMH using wavelet-based analysis on nine Asian foreign exchange markets and show that short-term investor behaviour increases significantly during crisis periods. Lin *et al.* (2018), analysed a total of 34 indices from different continents, and showed that market structures are geographically differentiated with detrended cross-correlation coefficient, and small and large fluctuations have independent identities. On the other hand, Moradi *et al.* (2021), in their analysis conducted with the L-Co-R algorithm in Tehran and London stock markets, found that while a fractal structure was detected in the Iranian market, this structure was not observed in the London market. Tiwari *et al.* (2019) examined a total of 10 developed and emerging markets with the MFDFA method and found that most of these markets have a multifractal structure and that efficiency increases not in the short term but rather in the long term. Ji *et al.* (2020) analysed the change in efficiency in the soy futures market during the trade tensions between the US and China with the DMCA and MFDFA methods and found that markets became more persistent but less correlated during the conflict period.

Among the recent studies Metescu (2022), applied R/S analysis on the price series of a publicly offered company in the Romanian market and supported the validity of the FMH with the Hurst exponent values obtained. Karaömer (2022), tested long memory with ARFIMA and ARFIMA-FIGARCH models in the markets of Mexico, Indonesia, Nigeria and Turkey, known as MINT countries, and argued that market returns in these countries are predictable and have a fractal structure. Açikgöz *et al.* (2024) examined the relations between green bonds and commodity markets with the MFDCCA method and found that both return and volatility-based cross-correlations between these assets are long-term and power law dependent. Moreover, persistence in small fluctuations and antipersist tendencies in large fluctuations are found to be dominant. Among recent studies, Masseran and Safari (2025) used MFDFA and MFDCCA methods to analyse the multifractal properties of exchange rates and reported that their results revealed that MYR/USD, MYR/RMB, MYR/GBP and MYR/CAD exchange rates exhibit scale-invariant properties, indicating the existence of a multifractal structure in these temporal series. According to the study, some pairs, including MYR/USD-MYR/CAD, MYR/USD-MYR/GBP, MYR/RMB-MYR/GBP, MYR/RMB-MYR/CAD and MYR/GBP-MYR/CAD, show weaker multifractal features in their cross-correlations. Finally, Kojić *et al.* (2025) conduct a comprehensive examination of the complexity, efficiency, and sectoral interdependencies associated with the S&P Global BMI indices amid significant global events, notably the Covid-19 pandemic and the Russia-Ukraine conflict. Their findings underscore substantial disparities in information efficiency across various sectors. Furthermore, the MFDCCA highlights the fragile nature of cross-correlations in relation to geopolitical risk. Notably, the consumer staples and energy sectors

exhibit stable persistence, whereas the Information Technology sector demonstrates heightened sensitivity in terms of its complexity.

Despite the growing body of research on multifractality and market efficiency, several important gaps remain. Much of the empirical literature continues to focus primarily on price dynamics, with trading volume either omitted altogether or examined in isolation, even though it plays a central role in the transmission of market information. Studies that do consider price–volume relations typically rely on linear correlation measures or single-scale approaches, which are not well suited to capturing nonlinear and scale-dependent interactions. Moreover, although multifractal techniques such as MFDFA or MFDCCA are increasingly used, structural breaks are seldom incorporated explicitly, especially in analyses of major benchmark indices like the S&P 500. Although Patil and Rastogi (2020) study presents research within the framework of price, volume, price-volume cross-correlation, and structural breaks, these researchers examined the Sensex index for the Indian market, not the S&P 500. Beyond this contribution, the broader literature includes studies that connect trading activity to market efficiency and dependence structures, yet typically without combining all three elements – (i) price and volume jointly, (ii) multifractal cross-correlation, and (iii) endogenous regime segmentation via structural breaks – within a single S&P 500 setting.

By jointly examining the multifractal behaviour of prices, trading volume, and their cross-correlations within a structural-break-aware framework, this study seeks to address these limitations and to provide a segment-specific perspective on market dynamics and efficiency over a long time horizon.

3. METHODOLOGY

Various quantitative methods have been developed in the literature to analyse long memory structures and market efficiency in financial time series. Lo (2004) argued that the R/S method commonly used by Peters (1994, 1996) seems to be highly sensitive to short-term autocorrelation and non-stationarity, which may lead to biased estimation of long memory parameters. To overcome the disadvantages, Peng *et al.* (1994) introduced DFA (Detrended Fluctuation Analysis) to study the fractal structure of molecular chains of deoxyribonucleic acid (DNA). Based on the DFA method, Kantelhardt *et al.* (2002) proposed the multifractal detrended fluctuation analysis (MFDFA) for the first time to describe the multifractal features of time series under different time scales (Cao *et al.*, 2018). DFA and its multifractal generalisation MFDFA have since been widely used to detect long-range auto-correlations in financial markets, including stock markets, foreign exchange market and gold market (Ma *et al.*, 2013).

Various techniques have been developed to analyse fractal and multifractal properties in time series. According to Stošić *et al.* (2015), MFDFA and MFDCCA have shown to be powerful tools for analysing the multifractal behaviour of non-stationary time series.

In this study, it is aimed to detect structural breaks with the procedure developed by Bai and Perron (2003) and to apply MFDFA and MFDCCA to determine the long memory in each time series to be obtained with these results.

3.1. Bai and Perron structural break test

In analysing financial markets, the accurate identification of structural breaks is critical for understanding market dynamics and examining changes in market efficiency over time.

This study builds on the methods developed by Bai and Perron (2003) to identify and analyse structural breaks. Then, using the sequential test procedure and the method of estimating break dates proposed by Bai and Perron (2003), potential break points in market data will be identified. The identification of structural breaks allows us to understand how market efficiency changes over time and reveals how market efficiency differs before and after structural breaks. It also analyses the relation between structural breaks and AMH and shows how markets adapt to changes in market conditions.

The Bai and Perron (2003) procedure tests for fluctuation due to stability in the regression modelling given in the figure below:

$$y_i = X_i^T \beta + u_i \quad (1)$$

The procedure starts with the assumption that there are *m* breaks, which equals *m+1* sub-sections to identify breaks, and y_i is the dependent variable observed at time *i*.

$$y_i = X_i^T \beta + u_i, \qquad (i = i_{(j-1)} + 1, \dots, i_j, \qquad j = 1, \dots, m + 1) \quad (2)$$

The coefficients are transitioned from one balanced regression to another, as shown in Equation (2). The process selects sub-sections that yield the minimum Residual Sum of Squares (RSS) and the lowest Bayes Information Criterion (BIC) value. j is the number of sub-sections, β is the vector of coefficients (Bai and Perron, 2003; Patil and Rastogi, 2020). Following standard practice in the structural break literature, the breakpoint test was implemented using a constant-only specification. The trimming parameter was set to 0.15 in order to ensure a sufficient number of observations within each segment, while the maximum number of structural breaks was restricted to five and determined endogenously based on information criteria. This configuration ensures statistically reliable segmentation. More specifically, the Bai–Perron procedure is applied within a mean-shift (constant-only) regression framework, where the dependent variable is modelled as a piecewise constant process subject to multiple structural breaks. This specification focuses on detecting changes in the unconditional mean of the series, which is particularly suitable for identifying regime shifts in financial time series. Following Bai and Perron (2003), a trimming parameter of 0.15 is adopted to ensure that each segment contains a sufficient number of observations for reliable estimation. The maximum number of structural breaks is determined endogenously based on information criteria, with the selected specification identifying up to five breakpoints. Break dates are selected using a sequential testing procedure based on supF-type statistics, allowing for a statistically consistent identification of multiple structural breaks.

3.1.1. MFDFA and MFDCCA

Prior to the implementation of the MFDFA and MFDCCA procedures, the financial time series are transformed following standard practice in the multifractal literature. Let P_t denote the closing price of the S&P 500 index at time *t*. The logarithmic price series is defined as $X_t = \ln(P_t)$, which serves as the primary input for the multifractal analysis. Trading volume is denoted by V_t, and its logarithmic transformation, which is used in the subsequent analysis, is defined as $Y_t = \ln(V_t)$ to mitigate scale effects and heteroskedasticity. Both transformed series are demeaned prior to analysis to ensure compatibility with the mean-shift framework adopted in the structural break procedure. In the MFDFA framework, the integrated profile is constructed from each transformed series and analysed separately to capture scale-dependent

long-range dependence. In the MFDCCA framework, the joint multifractal behaviour is examined by applying the procedure to the paired series (X_t, Y_t) allowing the investigation of scale-dependent cross-correlations between price and trading volume.

In the analysis of financial markets, the effects of market efficiency and structural breaks can be examined by using multiple fractal analysis methods as frequently encountered in the literature. In this study, MFDFA and MFDCCA methods are used to examine the multidimensional structure of market efficiency and cross-correlations between different financial series in detail (Kantelhardt *et al.*, 2002; Podobnik and Stanley, 2008; Patil and Rastogi, 2020). Detrended Fluctuation Analysis (DFA) was introduced by Kantelhardt *et al.* (2002) to effectively address the challenges associated with time series data that exhibit trends. The methodology of MFDFA further refines this approach by calculating the detrended residuals of a time series that resembles a random walk. This technique involves partitioning the series into segments of equal size, ensuring that these segments remain non-overlapping. Building upon this foundation, MFDCCA was developed by Zhou (2008), drawing insights from the earlier work of Podobnik and Stanley (2008), thereby extending the capabilities of MFDFA into the realm of multivariate time series analysis. Jiang *et al.* (2019) then described this method (Patil and Rastogi, 2020). In this study, price and volume series will be analysed with MFDFA and cross-correlation of price and volume will be examined with MFDCCA.

3.1.2. MFDFA

The MFDFA method is designed to unveil the multifractal nature of time series by examining the degree of fluctuations occurring at varying time scales. In this method, scale-dependent fluctuation functions are calculated by removing the trends in the series and the Hurst exponent and multifractal spectrum are obtained from these functions.

The MFDFA methodology involves the computation of trended residuals derived from a random walk-like time series, which is systematically partitioned into non-overlapping segments of uniform length. Within each segment, the root mean square of the residuals is determined, and the resultant mean is designated as the trend-free fluctuation function for that particular subsegment. This approach facilitates the examination of the intrinsic fluctuation characteristics of the time series under study, thereby enhancing the understanding of its multifractal nature. In addition, the qth order of the trend-free fluctuation function of this subsegment sub-section is calculated. The relation between the segment size and the fluctuation function is subject to a power law. This power law relation is captured in the Hurst exponent and described by a very fractal spectrum. The above steps are performed using the following equations:

1. The detrended residuals are computed using the following equation:

$$\varepsilon(i) = \mathcal{X}_t - (\widehat{\mathcal{X}}) \tag{3}$$

2. The fluctuation function is computed as the RMS (Root-Mean-Square) of the trend-reduced residuals:

$$[F_v(s)]^2 = \frac{1}{s}\sum_{j=1}^{s}\left[\varepsilon\big((v-1)s\big) + j\right]^2 \tag{4}$$

3. The q. order of the fluctuation function is computed for a a specified value of q.

$$[F_v(s)]^q = \frac{1}{s}\sum_{j=1}^{s}\left[\varepsilon\left((v-1)s\right)+j\right]^q \quad (5)$$

4. The Law of Power relation is defined;

$$F_q(s) \sim s^{h(q)} \quad (6)$$

The singularity spectrum ($f(\alpha)$) characterizes the fractal dimension of these multifractals, where α is represents the singularity strength. This fractal dimension is formulated in terms of $f(\alpha)$ can be computed using the following equation:

$$f(\alpha) = q\alpha - \tau(q) \quad (7)$$

where $\tau(q)$ is expressed in terms of the generalised Hurst exponent (*H(q)*). *H(q)* is calculated;

$$H(q) = \lim_{q' \to q}\left[\frac{\tau(q')+1}{q'}\right] \quad (8)$$

or;

$$\tau(q) = q^* h(q) - 1 \quad (9)$$

as above (Patil and Rastogi, 2020).

3.1.3. MFDCCA

MFDCCA, a bivariate extension of MFDFA, is employed to unveil multifractal correlations between two distinct time series. This method is particularly effective in analysing complex relations between market prices and trading volumes.

In the application of the MFDCCA method for analysing price-volume cross-correlation, a series of procedural steps analogous to those employed in the MFDFA framework are undertaken. The fluctuation function is computed utilizing the following equation:

$$F_v^2(q,s) = \frac{1}{s}\sum_{k=1}^{s}\left[\mathcal{X}_v(k) - \widehat{\mathcal{X}_v(k)}\right]\left[Y_v(k) - \widehat{Y_v(k)}\right] \quad (10)$$

The q. cross-correlation between the series is calculated as follows;

$$F_{xy}^2(q,s) = \left[\frac{1}{m}\sum_{v=1}^{m} F_v^q(s)\right]^{\frac{1}{q}} \quad (11)$$

and scaling relation,

$$F_{xy}(q,s) \sim H_{xy}(q) \quad (12)$$

is expressed as in equation (12) (Jiang *et al.*, 2019; Patil and Rastogi, 2020).

In this context, the study analyses both the effects of structural breaks on market efficiency and the multiple fractal correlations between price and trading volume in detail by

applying MFDFA and MFDCCA methods in each segment after the structural breaks determined by the Bai and Perron (2003) procedure.

4. DATA

The financial time series analysed in this study consists of daily closing prices and daily trading volume data of the S&P 500 index. The data set covers the period between 5 January 2004 and 31 December 2024, and contains 5282 daily observations in total. This wide time span makes it possible to observe the dynamic behaviour of markets in different segments, especially crisis periods, recovery processes and stationary period within the same data set. Data are obtained from Bloomberg Data Terminal. Raw price and volume data have been transformed by taking their natural logarithms in order to facilitate the series to meet the stationarity assumption and to obtain more reliable results in the analyses (All variables are log-transformed with natural logarithm, i.e. ln, e-based logarithm). At this point, the formula $r_t = [ln(P_t) - ln(P_{t-1})]$ for price and $V_t = [ln(V_t) - ln(V_{t-1})]$ for volume were used. Unnormalized log returns (PriceLNC) and volume changes (VolumeLNC) are employed in the MFDFA analyses for the entire dataset. This approach provides a more accurate analysis by preserving the natural structure of multifractal features and is widely used in the literature (Kantelhardt *et al.*, 2002; Carbone *et al.*, 2004; Oświęcimka *et al.*, 2006). The sufficient length of the data set made this choice possible. On the other hand, in cross-correlation-based MFDCCA analyses, normalized series are used in order to detect the common structural patterns of variables of different magnitudes more reliably. Furthermore, in all analyses (MFDFA and MFDCCA) for each segment obtained as a result of structural break tests, normalized price and volume series are employed to ensure cross-scale comparability and to reduce bias in moment calculations. Thus, methodological integrity is maintained in all segment-based analyses.

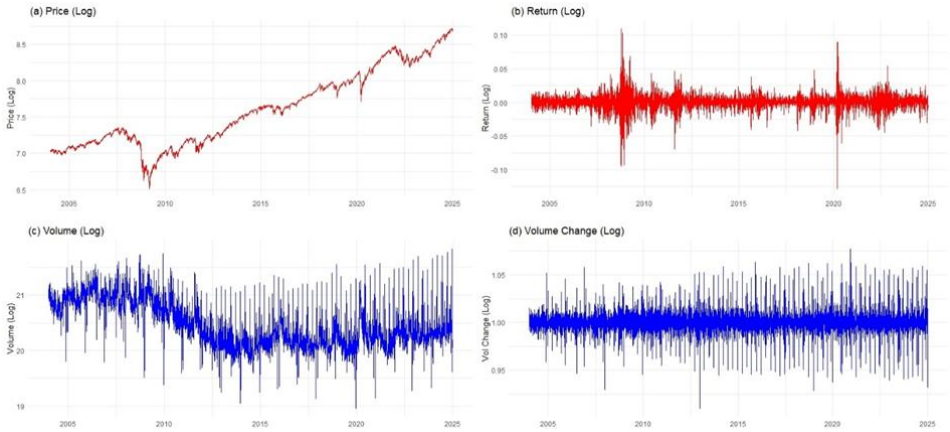


Figure no. 1 – Visualisation of the data

Figure no. 1 visualises the behaviour of the key variables in the data set over time after log transformation. The graphs provide important clues about the basic structure of the series.

In Panel (a), the logarithmic price series (Price (Log)) exhibits a long-term trend. During the 2008 global financial crisis, sharp declines are observed, followed by a recovery and a continuous upward trend. The 2008 mortgage crisis is one of the most significant structural breaks in the series. On the other hand, the impact of the Covid-19 pandemic that emerged in early 2020 was limited and the index recovered in a short time.

The logarithmic return series (Return (Log)) in Panel (b) exhibits a high-frequency volatility, with a significant increase in volatility during the crisis periods (2008 and 2020). This reveals the impact of financial stress on price volatility.

An analysis of the log volume series (Volume (Log)) in Panel (c) reveals a decreasing trend over time, followed by a flat trend and high volatility. The fluctuations in the volume data become more pronounced especially during crisis periods, and periodic increases and decreases stand out in the structure of the series.

In Panel (d), the logarithmic volume change series (Volume Change (Log)) exhibits a more stable but still volatile structure. Although shorter-term fluctuations are observed compared to prices, no clear trend is observed. This feature suggests that the series is characterized by weak continuity and more homogenous variance.

Table no. 1 - Summary statistics of the data

Variable	N	Min	Max	Median	Mean	SE_Mean	95% CI (Lower)	95% CI (Upper)	SD
PriceLN	5282	6.51698	8.71445	7.55227	7.59959	0.00713	7.58561	7.61358	0.51845
VolumeLN	5282	18.9560	21.8333	20.3422	20.4510	0.00574	20.4397	20.4622	0.41718
PriceLNC	5282	-0.12765	0.10957	0.00071	0.00032	0.00016	-0.00001	0.00064	0.01191
VolumeLNC	5282	0.90976	1.07757	0.99975	1.00007	0.00017	0.99974	1.00041	0.01257
PriceLNC_NORM	5282	-10.7428	9.1720	0.03283	0.00000	0.01376	-0.02697	0.02697	1.00000
VolumeLNC_NORM	5282	-7.18325	6.1635	0.02579	0.00000	0.01376	-0.02697	0.02697	1.00000

Note: SE and CI stand for the Standard Error and Confidence Interval of the mean

Table no. 1 presents summary statistics of the main series used in the analysis. The variables are grouped into three main categories: logarithmic level series (PriceLN, VolumeLN), logarithmic difference series (PriceLNC, VolumeLNC) and normalised logarithmic difference series (PriceLNC_NORM, VolumeLNC_NORM). This classification is important to accurately reflect the effects of the applied transformations on the analysis approach.

PriceLN and VolumeLN are obtained by taking the natural logarithm of the raw price and volume data. This transformation stabilises the variance and makes the distribution more symmetric, provided the data are positive. The high standard deviation values observed (~0.52 and ~0.42, respectively) indicate that price and volume levels vary over a wide range over time.

PriceLNC and VolumeLNC are logarithmically differenced series and represent the log return and log volume change, respectively.

The mean of PriceLNC is close to zero (0.00032), indicating that the return series does not have a statistically significant positive central tendency. The mean of VolumeLNC is very close to 1 (~1.00007), indicating a systematic central tendency due to the transformation. These difference series are the main input for direct MFDFA analyses.

PriceLNC_NORM and VolumeLNC_NORM are the z-score transformed (normalized) versions of the above difference series. This transformation is used especially in MFDCCA analyses to ensure comparability between series at different scales. This transformation is

calculated as the ratio of the deviation of each observation from the mean of its series to its standard deviation and is obtained using the following formula:

$$Z_i = \frac{x_i - \bar{x}}{s} \tag{13}$$

where x_i is the observation of the series i. s is the standard deviation of the series. This type of normalisation has been used to improve inter-scale comparability between series, reduce bias in moment calculations and facilitate the accurate detection of structural patterns between variables, especially in MFDCCA. Z-score normalization has been widely applied, especially in the context of financial time series analyses. (Oświęcimka *et al.*, 2006; Podobnik and Stanley, 2008; Zhou, 2008).

The means of these normalised series are structured as zero and standard deviations as 1. The 95% confidence intervals are at the level of ±0.02697 and these values show that there is no outlier problem in the distribution of the series.

These descriptive statistics indicate that the data set is suitable for non-linear time series analyses. Especially in MFDFA and MFDCCA analyses, knowing the statistical distribution properties of the data is critical to assess the reliability of the multifractal measurements obtained. In addition, preventing variance bias in segment-based analyses with normalised series was considered as a methodological requirement for the consistency of moment-based measurements.

The fact that the data set belongs to the S&P 500 index enables the findings of this study to have implications for both the financial markets of advanced economies and global market behaviour. Since the S&P 500 reflects the performance of the 500 largest publicly traded companies in the United States, it is considered an important indicator of global investor sentiment and behaviour. Moreover, as it is a frequently analysed indicator in the literature, this study has the potential to contribute to the comparative studies conducted in different countries and in different periods.

Before analysing each segment, MFDFA and MFDCCA methods were applied for the whole series. Then, the data were sub-segmented according to the structural break points obtained by the Bai and Perron (2003) procedure and MFDFA and MFDCCA analyses were performed on each segment. This methodological distinction enables more accurate modelling of the time-varying market structure and more meaningful results within the framework of the Adaptive Market Hypothesis (Lo, 2004).

In conclusion, the data set used is considered to be structurally sound and suitable for statistical analyses, allowing to examine the multifractal nature of both long-term and cyclical market behaviour.

5. EMPIRICAL RESULTS

This section presents the empirical results obtained from the MFDFA and MFDCCA analyses for the full sample as well as for the structural segments identified by the Bai–Perron break test. The discussion does not aim to reproduce detailed graphical patterns; instead, it concentrates on the main multifractal features that distinguish prices, trading volume, and their cross-correlations across segments. Segment-specific figures and summary statistics are reported for reference, while shared patterns and segment-dependent differences are brought together in the Cross-Segment Synthesis subsection.

5.1. Structural fracture analysis

As previously stated, the methodology established by Bai and Perron (2003) was employed to identify structural breaks in the data set under consideration. The "strucchange" package in the R Studio program was utilized for the calculation. The optimal number of structural breaks was determined using the BIC criterion, and the analysis identified five break points, resulting in six segments, as illustrated in Figure no. 2.

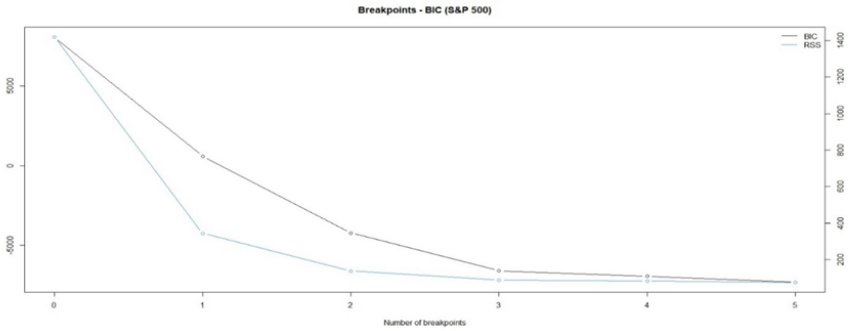


Figure no. 2 – BIC and residual sum of squares

According to the structural break analysis applied with the Bai and Perron (2003) procedure, the optimal number of breaks is determined by taking into account the Bayes Information Criterion (BIC) and Residual Sum of Squares (RSS) values. The structural break dates obtained were determined as follows: November 12, 2007 (before the 2008 Global Financial Crisis), January 5, 2011 (European Debt Crisis), March 3, 2014 (Ukraine-Russia tensions and the US Federal Reserve's tapering of asset purchases), July 11, 2017 (Trump-era global policy uncertainties), and November 12, 2020 (post-Covid-19 recovery). The sample under analysis was divided into six distinct sub-periods, and multifractal analyses were conducted on each segment.

Table no. 2 – Descriptive statistics for segments

Variable	N	Min	Max	Median	Mean	SE Mean	95% CI Mean	SD
2004-01-05-2007-11-12	971	6.9691	7.3557	7.1274	7.1455	0.0033	0.0065	0.1027
2007-11-12-2011-01-05	792	6.5170	7.3238	7.0128	7.0051	0.0061	0.0120	0.1716
2011-01-05-2014-03-03	792	7.0024	7.5280	7.2440	7.2718	0.0046	0.0089	0.1282
2014-03-03-2017-07-11	845	7.5042	7.8053	7.6394	7.6429	0.0024	0.0047	0.0700
2017-07-11-2020-11-12	843	7.7131	8.1834	7.9496	7.9586	0.0032	0.0063	0.0927
2020-11-12-2024-12-31	1038	8.1768	8.7144	8.3823	8.4018	0.0041	0.0080	0.1314

Note: Mean and standard error values indicate *Standard Error (SE)* and *Confidence Interval (CI)*, respectively. The CI value was calculated at 95% confidence interval.

Basic descriptive statistics of the log-transformed price series (PriceLN) for each structural break period are presented in the Table no. 2. The upward trend in the mean values over time reflects the long-term upward trend of the index. The higher standard deviation and lower mean values observed especially in the 2007-2011 period reveal the effects of the 2008 global financial crisis. These segment-based statistics allow for a comparative assessment of the structural characteristics of each period prior to multifractal analysis.

Figure no. 3 shows the segments obtained with the detected structural break dates.

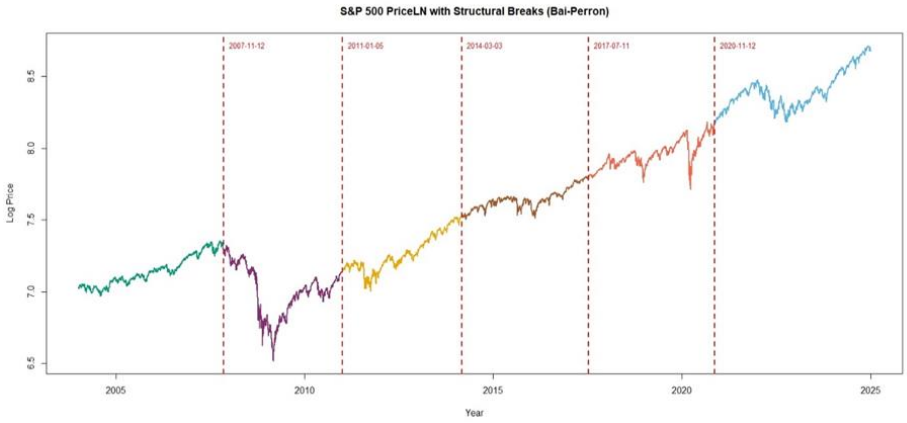


Figure no. 3 - Segments visualisation

5.2. Multifractal analysis

In this study, multifractal analyses were performed using the MFDFA package defined in the R programming language (Laib *et al.*, 2019) and the MFDCCA function created specifically for the study. In all segment-based analyses, the series were first de-averaged and normalized with the scale() function. Then, in accordance with the classical multifractal analysis approach, the cumulative sums of these normalised series were taken and integrated. This transformation enables the structural features to be revealed more accurately, especially in high-frequency and noisy series such as log-price and log-volume change. In both MFDFA and MFDCCA analyses, normalised PriceLNC and VolumeLNC series were used, and this choice allowed consistent and comparable analysis results to be obtained at multiple scales, regardless of whether the series is whole or segment-based. Multifractal analyses were performed separately for each segment obtained as a result of structural break tests. In each analysis, the segment length s (scale) value, which determines the scale size, was limited to 100 different scales distributed logarithmically in the range from 8 to N/2. The approach of logarithmically distributing the segment length is a common practice (Kantelhardt *et al.*, 2002; Ihlen, 2012; Al-Yahyaee *et al.*, 2018). These scales are designated as segments that do not overlap each other. The moment degree q is chosen in the range of -5 to +5, (Zhou, 2009; Ihlen, 2012; Takaishi, 2022), while the polynomial degree m used for detrending is classically 1 (linear detrending) (Suárez-García and Gómez-Ullate, 2014; Patil and Rastogi, 2020). While calculating the fluctuation functions in all MFDFA and MFDCCA analyses, the second-

moment approach commonly used in the literature was adopted. In this approach, intra-segment residual variances or cross-covariances were squared and *Fq(s)* functions were calculated over generalised moments with *q-parameter*. On the other hand, absolute value-based fluctuation calculations, which are frequently encountered in MFDCCA analysis and used in some alternative applications to overcome the problem of negative *F(q)* values, are not preferred in this study. Stošić and Stošić (2025) made a comprehensive study on this subject. The second-moment (q = 2) formulation adopted in this study follows standard practice in multifractal analysis and is widely used to ensure stable estimation when higher-order moments become numerically unreliable (Kantelhardt *et al.*, 2002; Zhou, 2008; Jiang and Zhou, 2011). The squaring approximation provides both theoretical continuity and a more stable calculation of the functions *τ(q), h(q), α* and *f(α)*.

For each segment, multiple plots consisting of four panels are presented:

Panel (a): MFDFA analyses for the price series (PriceLNC)

Panel (b): MFDFA analyses for the volume series (VolumeLNC)

Panel (c): MFDCCA outputs analysing the price-volume cross relation

Panel (d): Comparative presentation of multifractal spectra of three structures

Panels (a) and (b) contain four subplots:

Fluctuation Function: Visualises the fluctuation intensity of the time series at different values of *q* and *s*. Negative *q* is sensitive to small fluctuations, positive *q* to large fluctuations.

Hurst Exponent h(q): Indicates the persistence of the series. $h(q) < 0.5 \rightarrow$ anti-persistence; $h(q) = 0.5 \rightarrow$ randomness; $h(q) > 0.5 \rightarrow$ persistence (long memory).

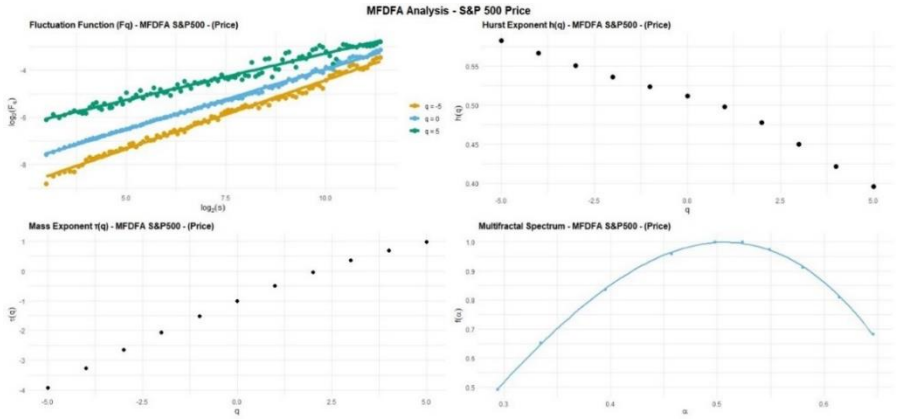
Mass (Renyi) Exponent τ(q): Multifractality is present if the plot of *τ(q)* against *q* is not linear.

Multifractal Spectrum f(α): Represents the intensity of local variations and the diversity of distributions in the series. The width of the spectrum indicates the degree of multifractal effects and the range α indicates the heterogeneity of the series.

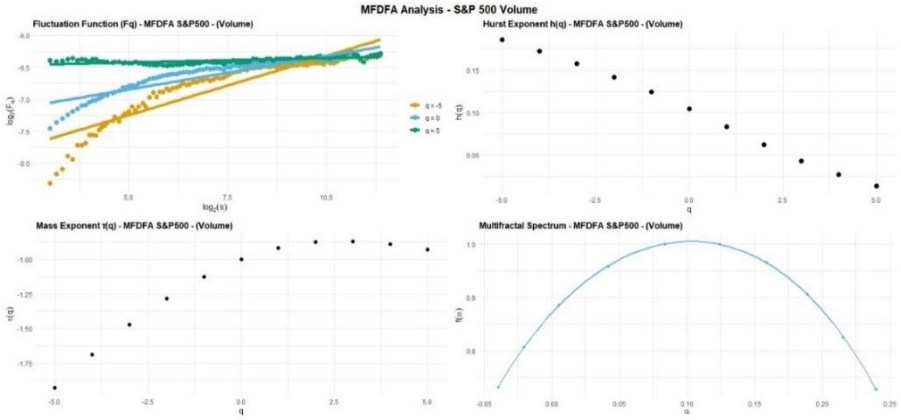
A shift of the multifractal spectrum to the left is commonly interpreted as an indication of anti-persistent behaviour, whereas a shift to the right reflects persistent dynamics (Kantelhardt *et al.*, 2002; Zhou, 2008). Moreover, the spread of *h(q)* and *α* values reveals the heterogeneity and structural complexity of the series.

5.3. Whole data set

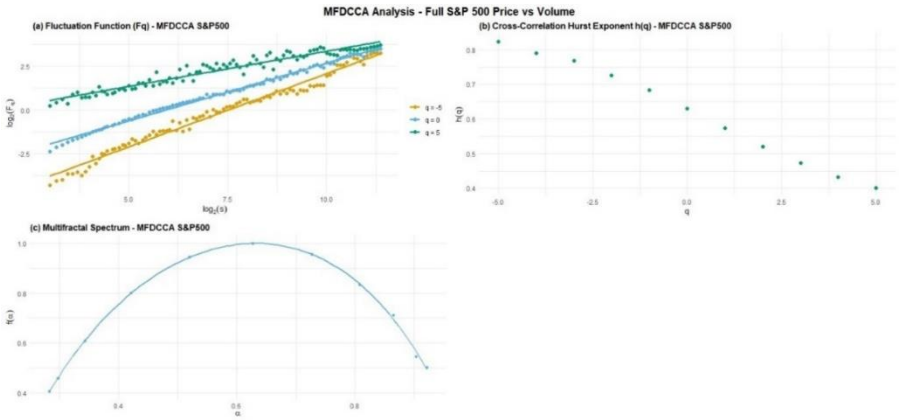
The outputs produced as a result of the analyses run for the entire data set and the graphs obtained as a result of their visualisation as described in the previous section are as follows.



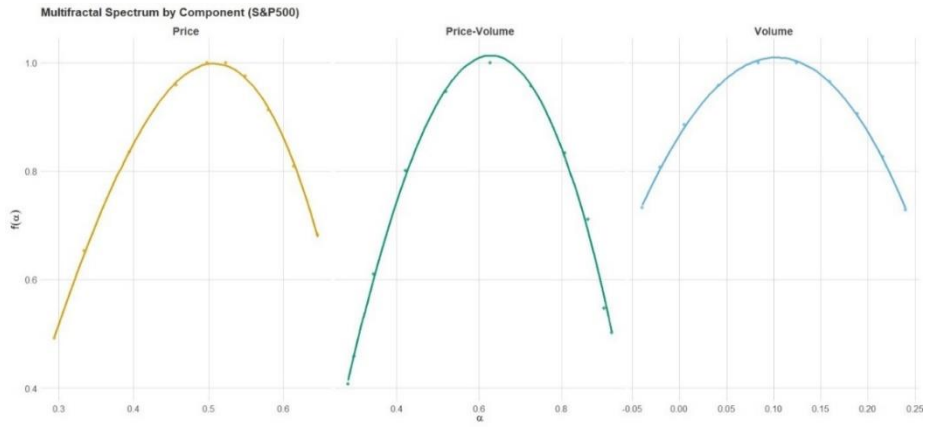
(a) - Price Spectrum



(b) - Volume Spectrum



(c) - Price- Volume Cross-Correlation Spectrum



(d) - Spectrum Comparison

Figure no. 4 – Whole data-price, volume and price-volume cross-correlation

The multifractal spectrum of the price series shown in Figure no. 4a reveals that for positive q values representing large fluctuations, the Hurst exponent remains below 0.5 and therefore the series exhibits anti-persist properties. This is also supported by the fact that the slopes in the fluctuation function graph are less steep for $q=5$ and steeper for $q=-5$. These results suggest that the price series tends to exhibit an anti-persistent behaviour for large fluctuations. For small fluctuations, the fact that the value of $h(q)$ is quite close to 0.5 implies that the price series can also take on a random structure from time to time.

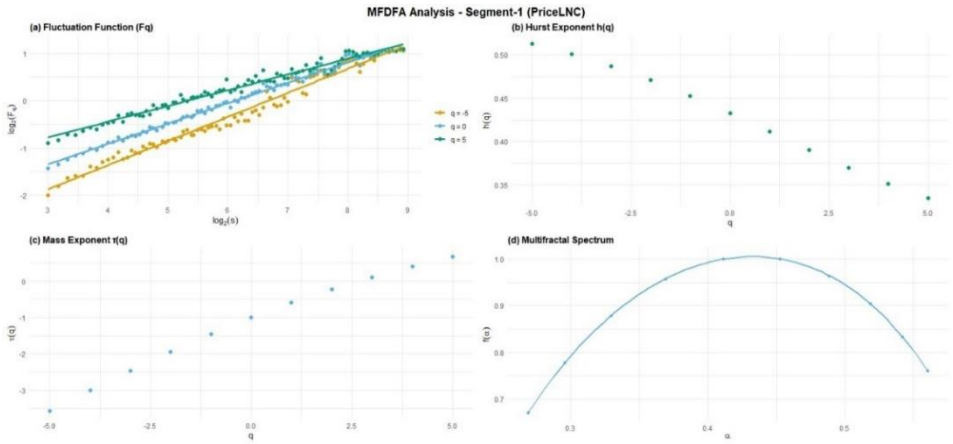
Figure no. 4b shows the results for the volume series, where it is observed that $h(q)$ values are generally below 0.2 for both large and small fluctuations. This indicates that the volume series is markedly anti-persist in both low and high scale fluctuations. Furthermore, the multifractal spectrum has a narrower and left-shifted form, implying that the volume series shows lower multifractal density.

The results of the cross-correlation analysis between price and volume in Figure no. 4c show that the interactions of both series have an anti-persist character. The $h(q)$ curve remains below 0.5 for all q values, indicating that there are no traces of long-range memory in the fluctuations in the cross structure and that inverse relations are prominent. The width of the spectrum curve indicates that the interactions between price and volume span a wider range of singularities and exhibit a more pronounced multifractal behaviour than the volume series.

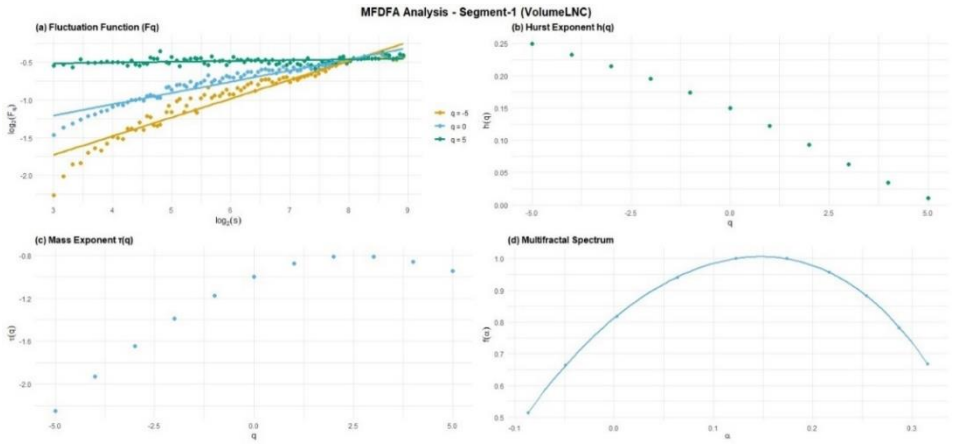
Finally, the comparative multifractal spectrum panel in Figure no. 4d shows that the price–volume cross-correlation exhibits a broader spectrum width than both the individual price and volume series. This indicates that the interaction between prices and trading activity is characterised by higher multifractal intensity and greater fluctuation diversity than either series in isolation. Moreover, the left-skewed asymmetry of the spectra suggests that anti-persistent behaviour dominates across all analysed series, consistent with the interpretation of multifractal scaling properties outlined by Kantelhardt *et al.* (2002) and Zhou (2008). Taken together, these findings indicate that the long-memory structure of price and volume dynamics in the S&P 500 index evolves over time and exhibits scale-dependent departures from the strict assumptions of weak-form market efficiency, particularly during periods of elevated volatility.

5.4. Segment 1 - segment 6

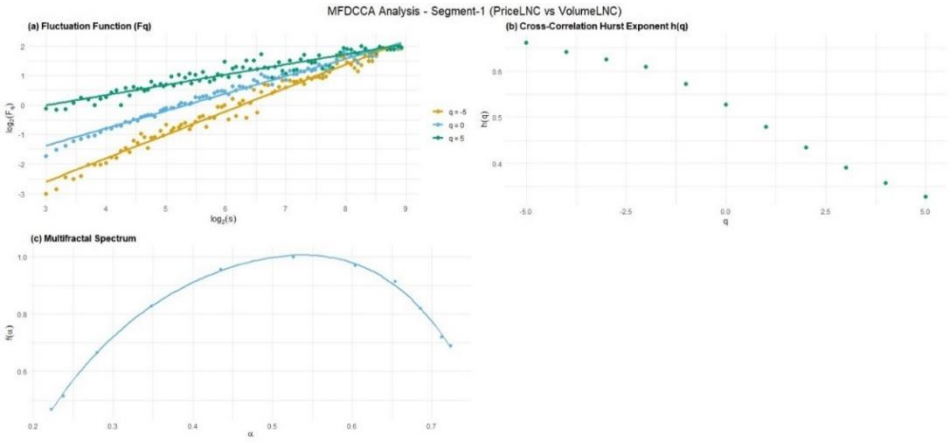
This subsection examines the multifractal characteristics of prices, trading volume, and their cross-correlations across the structural segments identified by the Bai–Perron procedure. Rather than dwelling on detailed graphical patterns, the discussion highlights the key features that distinguish each segment. A broader comparison across segments is then developed in the following subsection.



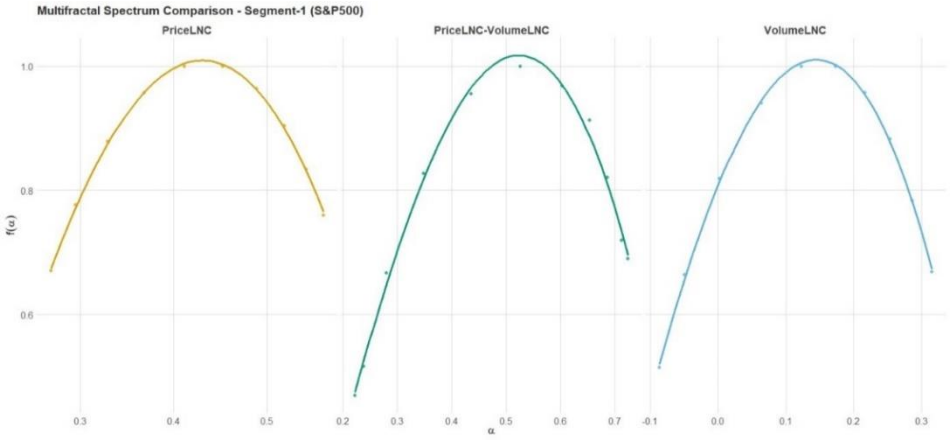
(a) - Price Spectrum



(b) - Volume Spectrum



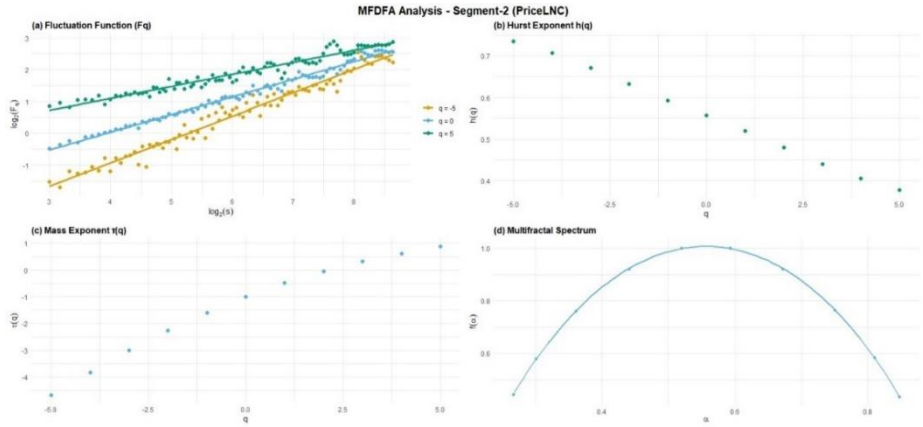
(c) - Price- Volume Cross-Correlation Spectrum



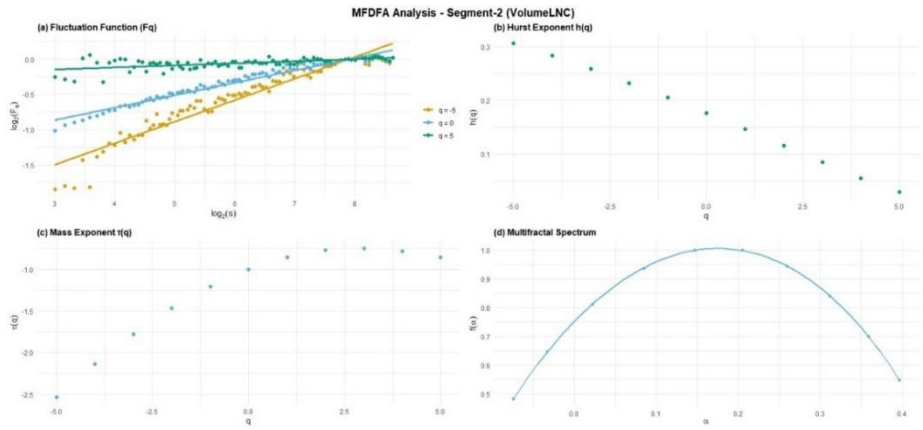
(d) - Spectrum Comparison

Figure no. 5 – Segment 1

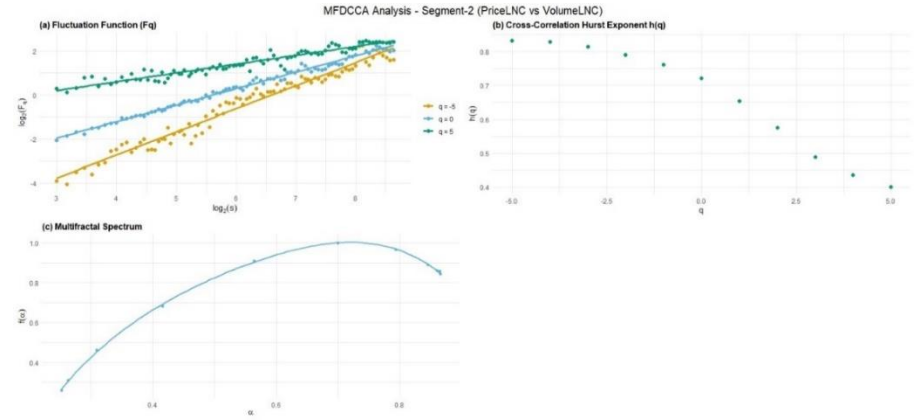
Segment 1 represents a period prior to the global financial crisis, characterised by relatively stable market conditions. During this period, price dynamics exhibited a moderate multifractal structure, and scale-dependent behaviour indicated differing responses between small and large fluctuations. On the other hand, trading volume largely exhibits anti-persistent structure characteristics, indicating that transactions are short-lived and rapidly reversible. Nevertheless, as can be seen in Figure no. 5 and Table no. 3, the price-volume cross-correlation reveals a broader and more asymmetric multifractal structure than price alone or volume alone. This suggests that even during relatively calm financial market conditions, information transmission and market adjustment processes appear to be more strongly reflected in nonlinear joint price–volume dynamics than in isolated market variables. In terms of market efficiency, these findings suggest that deviations from weak-form efficiency, while limited in magnitude during stable periods, are more readily observable in the joint price–volume domain than in individual series.



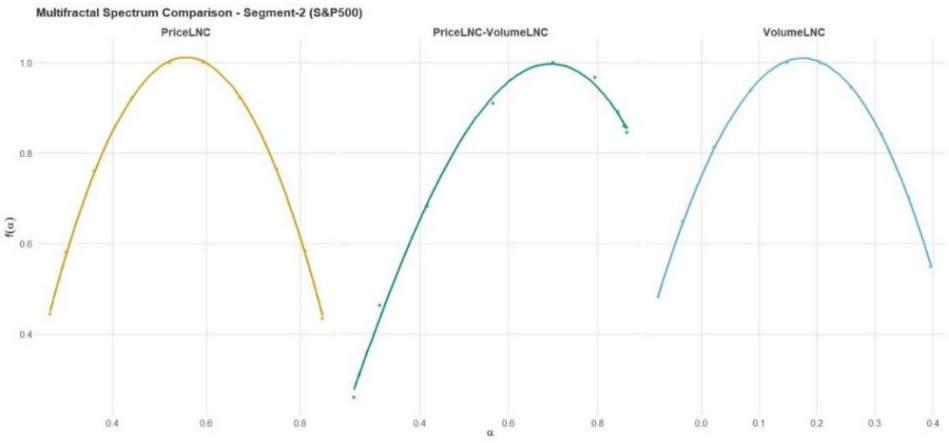
(a) - Price Spectrum



(b) - Volume Spectrum



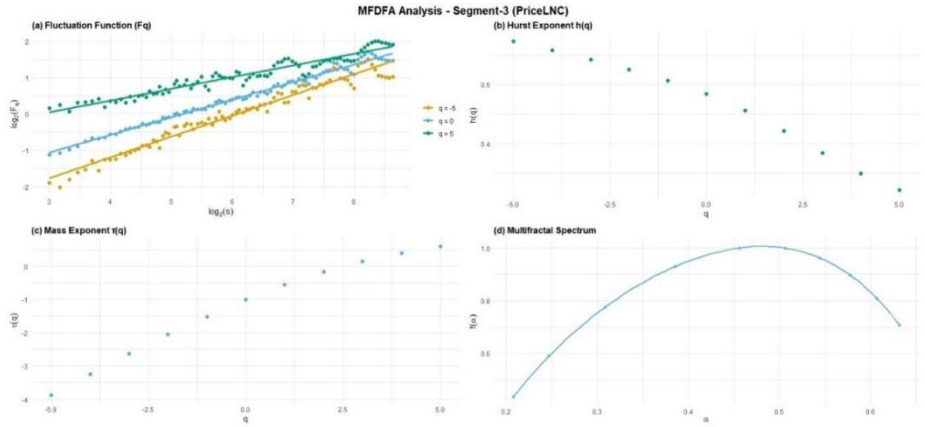
(c) - Price- Volume Cross-Correlation Spectrum



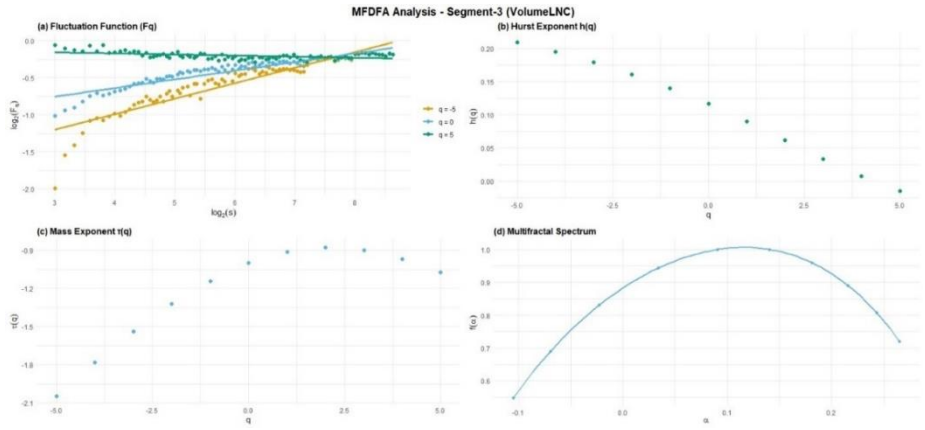
(d) - Spectrum Comparison

Figure no. 6 – Segment 2

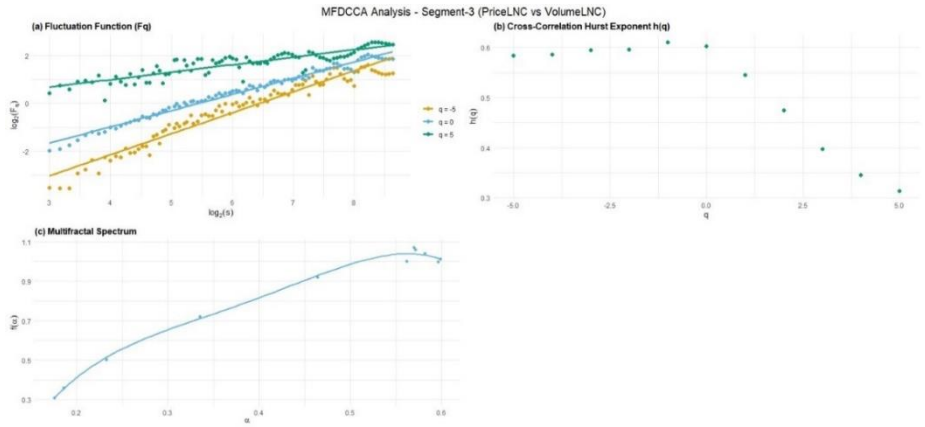
Segment 2 covers a period encompassing the outbreak of the US-centred Mortgage Crisis, during which multifractal heterogeneity intensified in market dynamics. Markets tend to exhibit unstable reactions under increasing stress. This period reflects these reactions as a segment where price movements exhibit scale dependency and behavioural differences are observed between small and large fluctuations. Trading volume continues to be predominantly anti-persistent and points to trading activity that is prone to short-term and rapid reversals despite high uncertainty. The most striking feature is the behaviour of price-volume cross-correlations. As shown in Figure no. 6 and summarised in Table no. 3, these correlations exhibit a much broader and more asymmetric multifractal structure than either prices or volumes alone. Compared to the pre-crisis period, the strengthening of this shared multifractality indicates that crisis conditions have amplified the non-linear information transfer between prices and trading activity, and that cross-dynamics are more informative than isolated series when assessing systemic market stress. In AMH terms, this segment reflects a regime where market efficiency is temporarily weakened rather than permanently impaired, and adaptive behaviours become more visible through price-volume interactions.



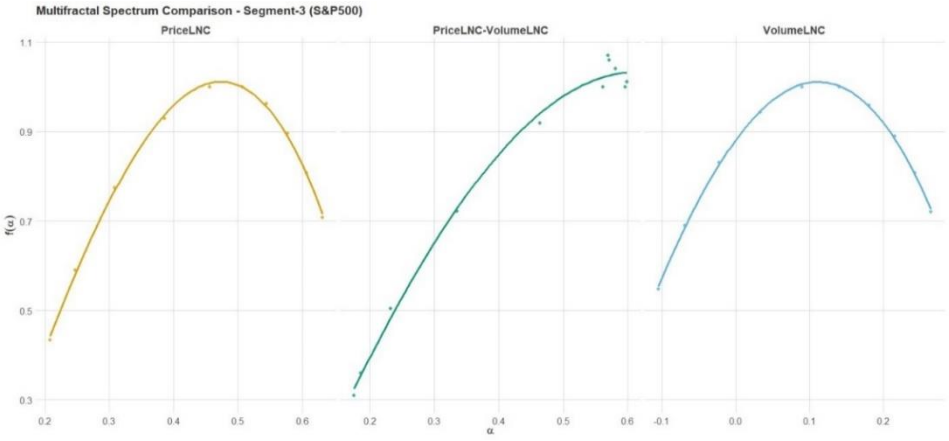
(a) - Price Spectrum



(b) - Volume Spectrum



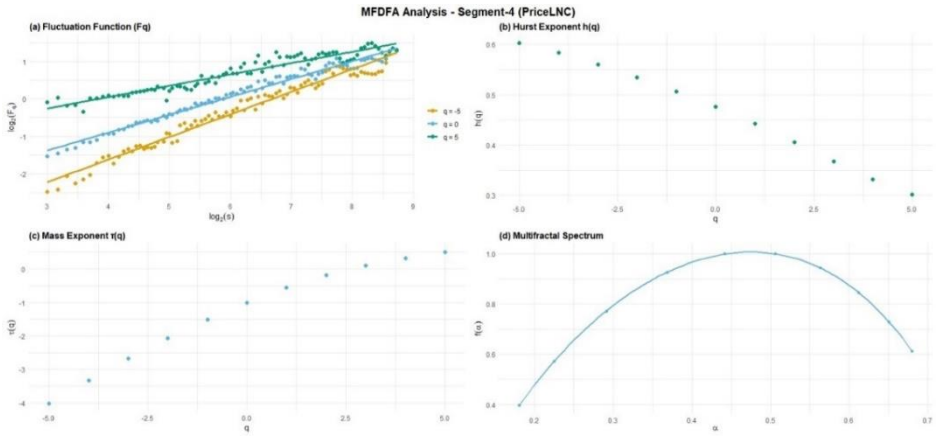
(c) - Price- Volume Cross-Correlation Spectrum



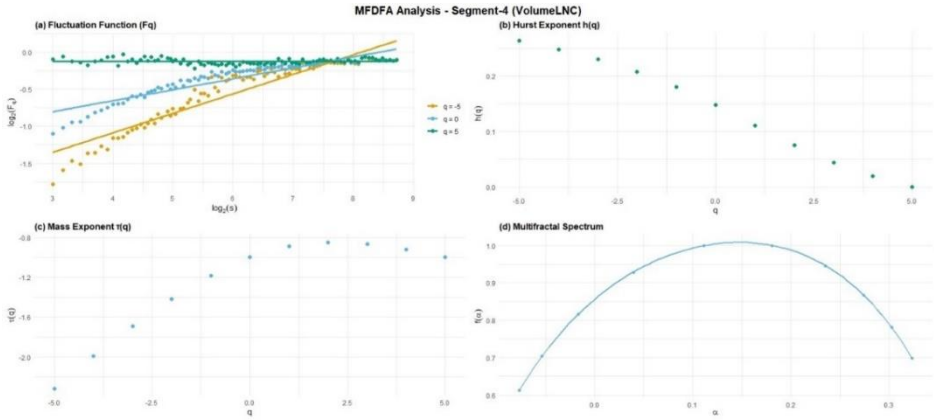
(d) - Spectrum Comparison

Figure no. 7 – Segment 3

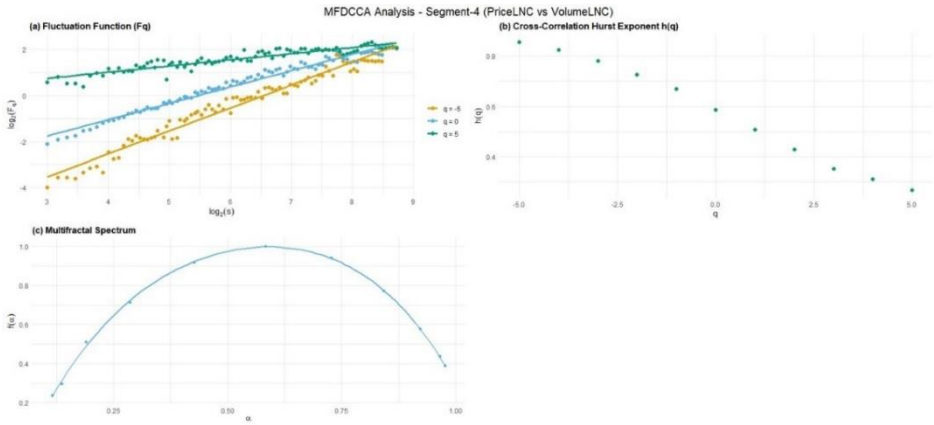
Segment 3 exhibits characteristics consistent with the post-crisis recovery phase of markets, showing partial stability in price behaviour when compared to crisis periods. As market stress begins to subside, it displays a more balanced multifractal structure, indicating a gradual decrease in volatility. However, in terms of trading volume outputs, the anti-persistent structure appears to be continuing. This indicates that there has been no clear transformation in investor behaviour. Nevertheless, a partial normalisation is observed in individual series, and the price-volume cross spectrum continues to remain broad accordingly. It also exhibits a more balanced degree of asymmetry (Figure no. 7; Table no. 3), indicating that non-linear information transmission continues beyond the crisis. The persistence of these complex co-dynamics implies that, despite the reduction in volatility pressures, non-linear information transmission continues to shape market behaviour beyond the acute crisis phase.



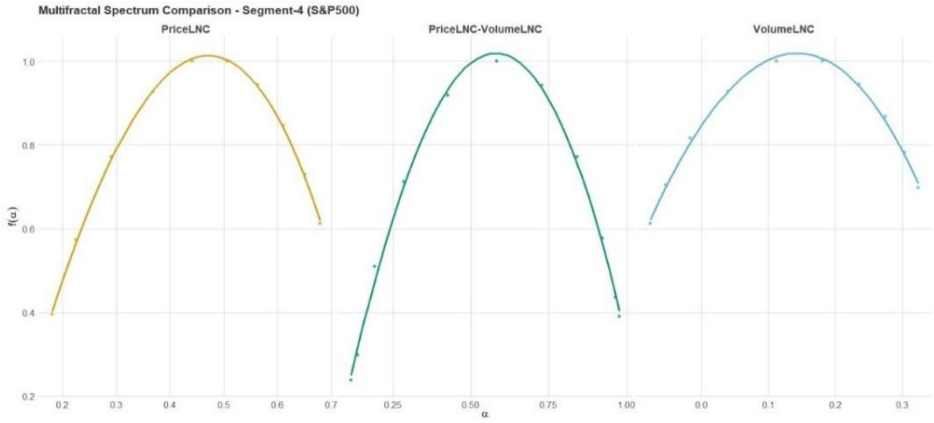
(a) - Price Spectrum



(b) - Volume Spectrum



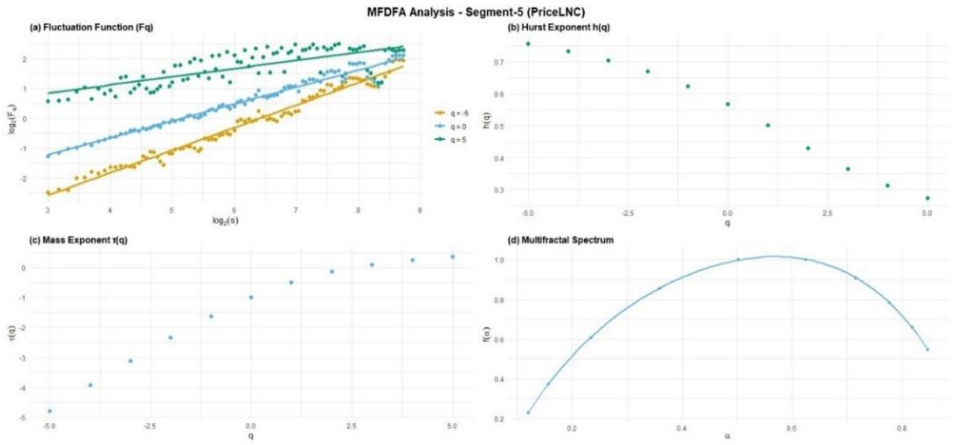
(c) - Price- Volume Cross-Correlation Spectrum



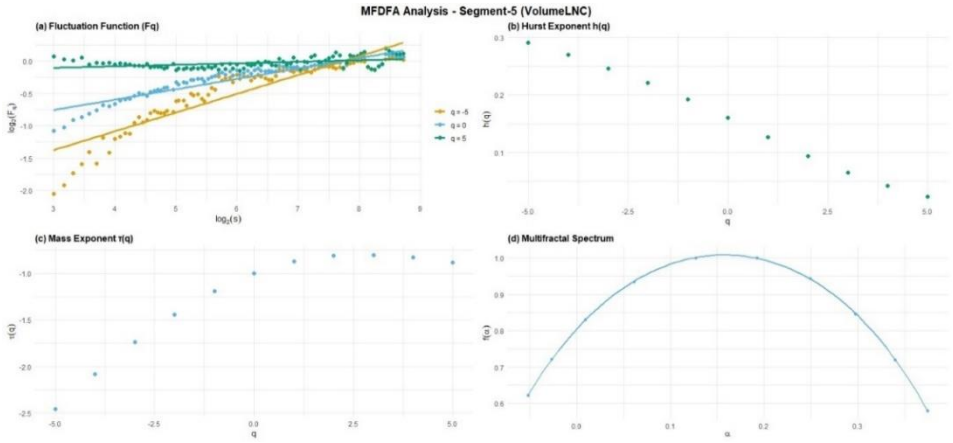
(d) - Spectrum Comparison

Figure no. 8 – Segment 4

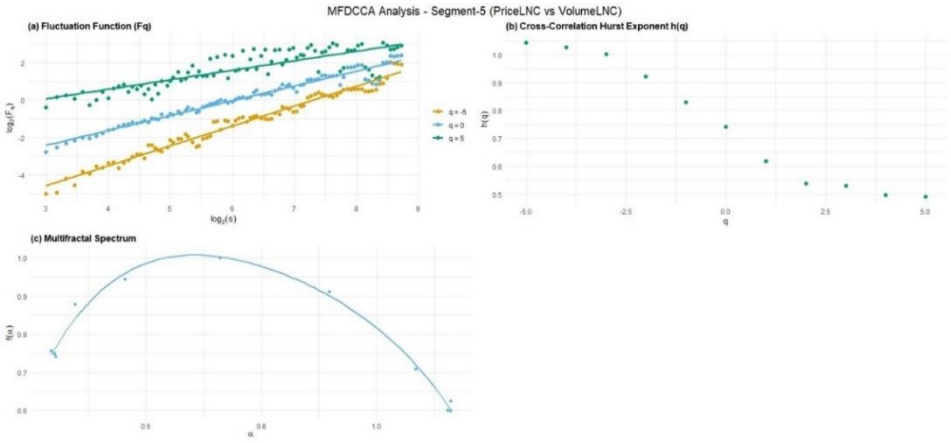
Segment 4 exhibits characteristics of a phase with market conditions consistent with low volatility. During this period, different structures are observed in small and large fluctuations, but no clear sign of extreme changes is evident, implying that pricing behaviour continues to reveal a balanced multifractal structure. Trading volume, meanwhile, remains largely anti-persistent. That is, changes are short-lived, and there is only a weak connection between past behaviour and price. Despite this, price-volume cross-correlations reveal extensive and asymmetric spectra, as shown in Figure no. 8 and summarised in Table no. 3, maintaining multifractal complexity to a non-negligible degree, despite moderate conditions in individual series. Considering all these outputs for this segment, we can state that normal financial market conditions may reduce volatility but do not eliminate non-linear dependence. These findings suggest that the dynamics embedded in the price–volume relationship may contain structurally relevant information even during periods of relative market stability.



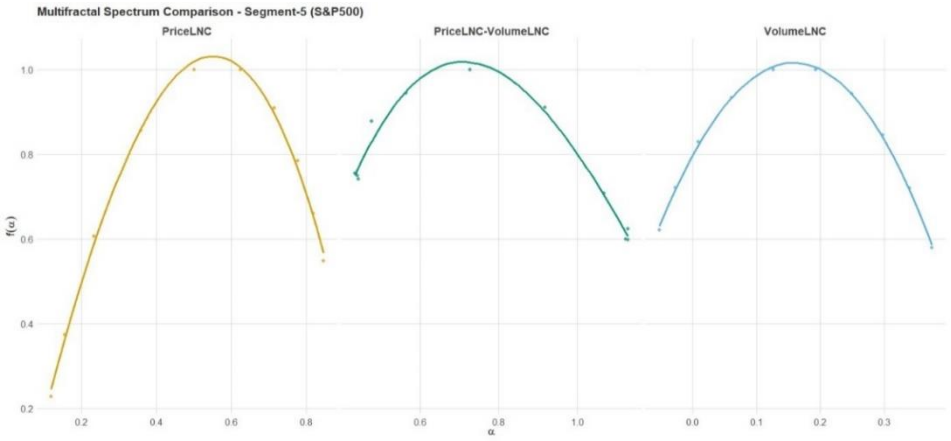
(a) - Price Spectrum



(b) - Volume Spectrum



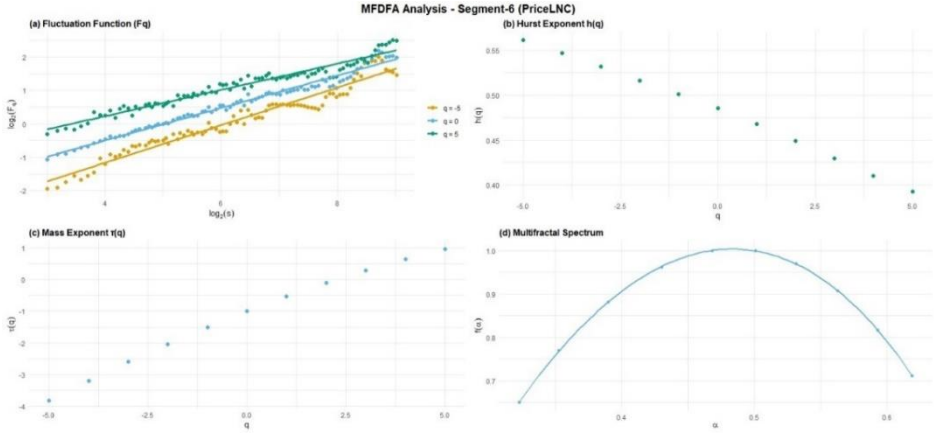
(c) - Price- Volume Cross-Correlation Spectrum



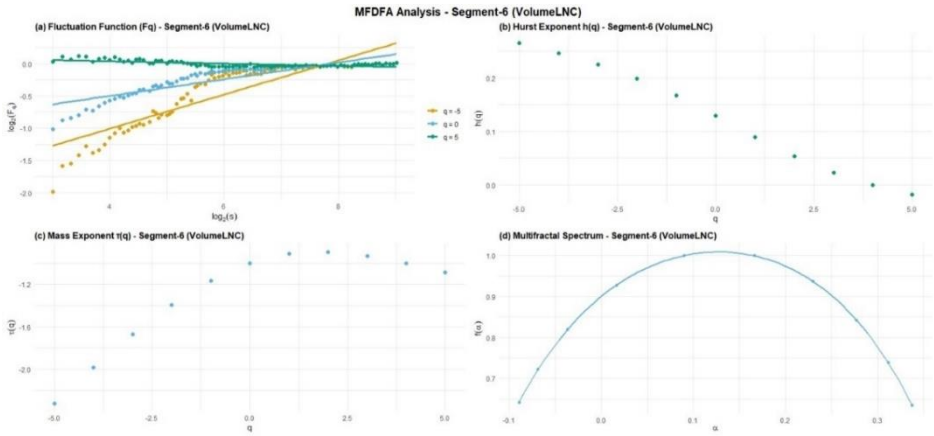
(d) - Spectrum Comparison

Figure no. 9 – Segment 5

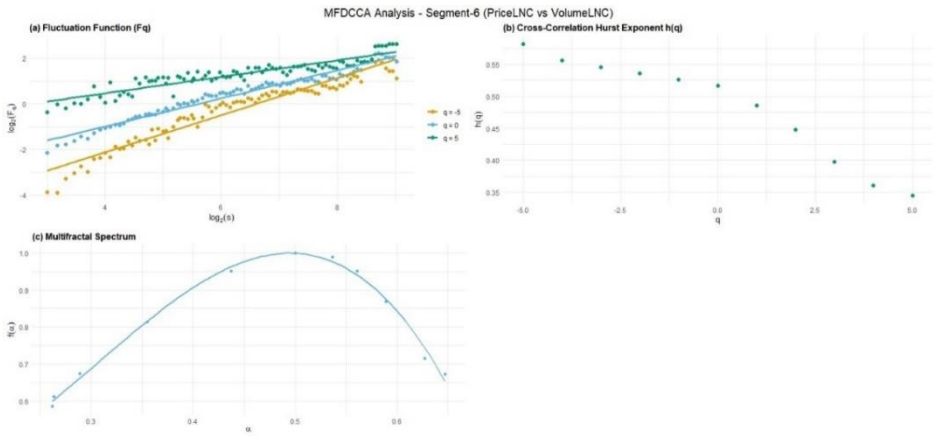
Segment 5 coincides with a period of heightened uncertainty that culminates in the Covid-19 shock and is marked by particularly strong multifractal features across market variables. Price dynamics display a rich and relatively balanced multifractal structure, pointing to the coexistence of persistent and anti-persistent behaviour across different fluctuation scales. Trading volume, by contrast, exhibits a more constrained and asymmetric multifractal profile, indicating that trading activity is largely driven by short-lived and rapidly reversing responses. The most striking feature of this segment is observed in price–volume cross-correlations, which show one of the broadest and asymmetric multifractal spectrum in the sample, as illustrated in Figure no. 9 and summarised in Table no. 3. This marked amplification of joint multifractality suggests intensified nonlinear information coupling under extreme uncertainty and highlights the heightened sensitivity of price–volume interactions to abrupt market shocks.



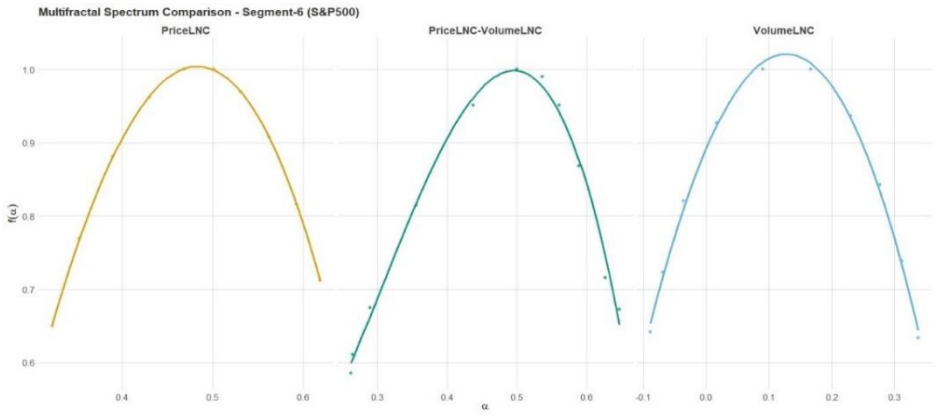
(a) - Price Spectrum



(b) - Volume Spectrum



(c) - Price- Volume Cross-Correlation Spectrum



(d) - Spectrum Comparison

Figure no. 10 – Segment 6

Segment 6 captures the post-pandemic adjustment phase and points to a moderation in multifractal intensity, albeit without a full return to linear market dynamics. Price movements continue to exhibit a clear scale-dependent structure, with different responses across small and large fluctuations and a persistent degree of heterogeneity across time scales. Trading volume, by contrast, remains largely anti-persistent, suggesting that trading activity is only weakly linked to its own past and retains a predominantly short-lived character. Price–volume cross-correlations display a multifractal structure of intermediate breadth and symmetry, more closely aligned with the price spectrum than with volume dynamics, as illustrated in Figure no. 10 and summarised in Table no. 3. Taken together, these patterns suggest that although conditions appear more consistent with market efficiency in the post-pandemic period, nonlinear joint dynamics and the structural imprint of earlier disruptions continue to influence price formation.

Table no. 3 – Multifractal spectrum characteristics by segment

Segment	Series	α_min	α_max	Δα (Width)	f(α)_max	Spectrum Shape/ Slope
1	PriceLNC	≈ 0.25	≈ 0.70	≈ 0.45	≈ 1.00	Symmetric
1	VolumeLNC	≈ -0.15	≈ 0.20	≈ 0.35	≈ 0.95	Left-skewed (anti-persistent)
1	Price-Volume	≈ 0.20	≈ 0.80	≈ 0.60	≈ 1.00	Asymmetric/ Broad
2	PriceLNC	≈ 0.20	≈ 0.70	≈ 0.50	≈ 1.00	Symmetric
2	VolumeLNC	≈ -0.10	≈ 0.25	≈ 0.35	≈ 0.95	Left-skewed
2	Price-Volume	≈ 0.15	≈ 0.85	≈ 0.70	≈ 1.00	Asymmetric/ Broad
3	PriceLNC	≈ 0.20	≈ 0.65	≈ 0.45	≈ 1.00	Symmetric
3	VolumeLNC	≈ -0.10	≈ 0.25	≈ 0.35	≈ 0.95	Left-skewed
3	Price-Volume	≈ 0.15	≈ 0.85	≈ 0.70	≈ 1.00	Asymmetric
4	PriceLNC	≈ 0.20	≈ 0.70	≈ 0.50	≈ 1.00	Symmetric
4	VolumeLNC	≈ -0.05	≈ 0.30	≈ 0.35	≈ 1.00	Slightly left-skewed
4	Price-Volume	≈ 0.20	≈ 0.95	≈ 0.75	≈ 1.00	Asymmetric/ Right-skewed
5	PriceLNC	≈ 0.15	≈ 0.85	≈ 0.70	≈ 1.00	Symmetric
5	VolumeLNC	≈ -0.05	≈ 0.35	≈ 0.40	≈ 1.00	Left-skewed
5	Price-Volume	≈ 0.10	≈ 1.00	≈ 0.90	≈ 1.00	Broad/ Asymmetric
6	PriceLNC	≈ 0.20	≈ 0.70	≈ 0.50	≈ 1.00	Symmetric
6	VolumeLNC	≈ 0.00	≈ 0.30	≈ 0.30	≈ 1.00	Left-skewed
6	Price-Volume	≈ 0.20	≈ 0.80	≈ 0.60	≈ 1.00	Symmetric/ Broad

This table summarises the multifractal spectrum characteristics of normalised log-price (PriceLNC), log-volume (VolumeLNC) and their cross-correlations (Price-Volume) over six structurally segmented periods.

5.5. Cross-segment synthesis of multifractal results

Across the six structurally identified segments, several recurring patterns emerge from the joint interpretation of the MFDFA and MFDCCA results. Price dynamics exhibit clear scale dependence throughout the sample, with persistent behaviour tending to dominate small fluctuations and anti-persistent behaviour becoming more pronounced for large fluctuations. While this scale-dependent structure is observed in every segment, the intensity and symmetry of multifractality change over time, pointing to segment-specific differences in the way prices are formed.

Trading volume follows a notably different pattern. Across all segments, volume remains largely anti-persistent and is associated with relatively narrow and left-skewed multifractal spectra. This behaviour suggests that volume dynamics are mainly driven by short-lived and small-scale trading activity, with limited long-range dependence, less directly linked to broader market conditions. Although volume series display multifractality, their structural complexity remains consistently lower than that observed for prices.

By contrast, price–volume cross-correlations stand out as the most structurally complex component of the system. In every segment, the multifractal spectra of cross-correlations are wider and more asymmetric than those of the individual price or volume series, indicating stronger nonlinear dependence and greater heterogeneity in joint dynamics. Periods of heightened uncertainty, particularly the global financial crisis and the Covid-19 shock, are associated with a marked amplification of multifractal cross-correlations, reflecting more intense interaction between prices and trading activity across scales.

The evolution of multifractal intensity also varies systematically across segments. The pre-crisis period establishes a baseline level of multifractality, while crisis and high-uncertainty phases are characterised by a pronounced strengthening of nonlinear joint dynamics. In subsequent recovery and post-crisis periods, multifractal intensity moderates but does not disappear, indicating that market behaviour does not fully revert to a homogeneous or purely random structure. This persistence of complex cross-dynamics, even under relatively stable conditions, suggests that market efficiency adjusts over time rather than remaining fixed.

Overall, the cross-segment evidence indicates that analyses focusing on prices or trading volume in isolation provide only a partial view of market dynamics. A joint multifractal perspective on price–volume interactions captures segment-specific patterns of information transmission more effectively and highlights the time-varying nature of market efficiency across different scales, consistent with the Adaptive Market Hypothesis and the Fractal Market Hypothesis.

Taken together, the empirical findings offer coherent answers to the research questions outlined in the Introduction. Both price and trading volume series exhibit multifractal and scale-dependent behaviour across all segments identified by endogenous structural breaks, addressing the first research question. Price–volume cross-correlations, in turn, differ systematically from individual series by displaying stronger nonlinearity and higher structural heterogeneity, which speaks directly to the second research question. Finally, the segment-specific evolution of multifractal properties points to time-varying departures from weak-

form market efficiency rather than a permanent breakdown, lending empirical support to the Adaptive Market Hypothesis and the Fractal Market Hypothesis.

6. CONCLUSION

This study offers a comprehensive examination of the multifractal behaviour of prices, trading volume, and their cross-correlations in the S&P 500 index by jointly applying MFDFA and MFDCCA within a structural break framework. By considering both the full sample and six endogenously identified segments, the analysis shows that market dynamics are scale-dependent, multifractal, and subject to change over time. Rather than pointing to a permanent breakdown of market efficiency, the findings indicate segment-specific departures from weak-form efficiency, reflected in persistent and heterogeneous multifractal structures. These patterns are consistent with the Adaptive Market Hypothesis and the Fractal Market Hypothesis, suggesting that market efficiency adjusts in response to evolving economic conditions, investor behaviour, and information flows. Consistent with the cross-segment synthesis, the evidence further shows that multifractality and scale-dependent behaviour persist across all segments, although with varying intensity. While price and trading volume display distinct structural features, their joint dynamics consistently exhibit greater heterogeneity and stronger nonlinear dependence, particularly during periods of elevated uncertainty.

The analyses indicate that both price and volume series exhibit a multifractal structure. The Hurst exponent $h(q)$, the nonlinear mass function $\tau(q)$ and the expanding multifractal spectrum $f(\alpha)$, which varies with the degree of moment q, show that the series do not have a fixed fractal structure and exhibit multifractal properties. In particular, the fluctuation functions corresponding to low and high q values show that small and large-scale fluctuations exhibit different behaviours at different time scales; this situation reveals the presence of multifractal behaviour of statistical properties in the series.

Segment-based analyses show that the S&P 500 time series exhibits a time-varying multifractal structure. Each segment has different spectrum widths, slopes and maximum points. This is thought to indicate that time-varying dynamics in the market, differences in investor behaviour and reactions to external shocks affect the structure of the series. The asymmetric structure observed in the spectral profiles of the volume series and the fluctuations in the spectrum width suggest that these series may exhibit diffuse multifractal features depending on time.

MFDCCA analyses have been very useful in examining the common multifractal behaviour between price and volume series. The wider and more asymmetrically distributed cross-spectra suggest that price-volume interactions have stronger and more spectrally distinct multifractal features compared to individual series. These results suggest that volume is not a passive indicator but an important component of price formation, especially in market structure studies.

In the full-sample MFDFA analysis, raw log-return and log-volume change series (PriceLNC and VolumeLNC) were used without normalization to preserve the natural multifractal structure. However, all cross-correlation (MFDCCA) and segment-wise MFDFA/MFDCCA analyses were conducted using normalized series to ensure consistency and comparability across scales. In the calculation of fluctuation functions, the squaring approach commonly used in the literature was adopted. This method, while providing

theoretical continuity, also allowed for a more stable calculation of $\tau(q)$, $h(q)$, α and $f(\alpha)$ functions.

As a result, the S&P 500 index exhibits a scale-dependent, multifractal and time-varying structure in terms of both price and volume. This structure does not suggest a permanent violation of the weak-form Efficient Market Hypothesis. Instead, it calls into question the strict random walk assumption at certain market segments and time scales, pointing to segment-dependent persistence, memory effects, and heterogeneous behaviour. The patterns observed across segments further indicate that market efficiency evolves over time and varies across scales, rather than remaining uniform throughout the sample period. The detection of such complex structures once again reveals the importance of multifractal approaches in financial modeling, forecasting, and risk management processes.

The present findings are consistent with the conclusions of some prior studies, particularly those by Kantelhardt *et al.* (2002) and Zhou (2008), which suggest that financial time series have multifractal properties. The apparent multifractality in price series is similarly found by Miloş *et al.* (2020) and Carbone *et al.* (2004). Our results showing that volume series also exhibit multifractal structures are in line with the approaches emphasised in studies such as Jizba *et al.* (2012) and Wątorek *et al.* (2021) that market volume is a reflection of information flow and investor reactions. Moreover, the existence of cross-multifractal relations between price and volume in the context of MFDCCA results is also revealed in studies such as Oświęcimka *et al.* (2006) and Wang *et al.* (2013). However, the asymmetric structure of the spectrum, especially in the volume series, differs from some related findings in the literature, such as Rak *et al.* (2015), as well as earlier studies on financial correlation structures (Drożdż *et al.*, 2001). In conclusion, this study is consistent with the existing literature in terms of both its methodological approach and the results obtained, and it is thought that this study will contribute to the literature by presenting original findings in some aspects.

6.1. Limitations and Future Research

Despite the robustness of the empirical findings, several limitations should be acknowledged. First, the analysis focuses on a single benchmark index, which may limit the generalisability of the results to other markets or asset classes. Second, although the sample period is relatively long, multifractal outcomes can be sensitive to the choice of scale ranges and segment lengths inherent in the methodology. Third, methodological constraints associated with MFDCCA – such as the emergence of negative fluctuation functions for certain moments – necessitated the use of a second-moment-based approach, which may restrict the interpretation of higher-order dynamics. In addition, during the implementation of MFDFA, occasional negative values of the fluctuation function $F_q(s)$ for certain moment orders required the adoption of a moment-restricted formulation, which, while ensuring numerical stability, may lead to a less sharp representation of the underlying multifractal structure.

From a scientific perspective, this study contributes to the literature by highlighting the importance of jointly analysing prices, trading volume, and their multifractal cross-correlations within a regime-dependent framework. By showing that nonlinear price–volume interactions exhibit stronger and more heterogeneous multifractal properties than individual series, the results provide new insights into the mechanisms of information transmission and the time-varying nature of market efficiency.

From a practical standpoint, the results carry several important implications. For regulators, the pronounced strengthening of price–volume cross-dynamics during turbulent periods suggests that monitoring joint multifractal indicators may help identify early signals of market stress and instability. For investors and portfolio managers, the scale-dependent and segment-specific nature of market efficiency implies that risk–return characteristics vary across time horizons, underscoring the potential value of adaptive and regime-aware investment strategies. For risk managers, the broader and more asymmetric multifractal spectra observed in price–volume cross-correlations highlight the importance of accounting for nonlinear dependence structures that extend beyond standard linear correlation measures, particularly in periods of heightened uncertainty. In this context, understanding the nature of the market allows the use of volatility clustering as a tool to measure and forecast risk, incorporating long-term price dependence and the tendency of adverse shocks to cluster. Once market characteristics are properly identified, risk forecasting models can be enhanced (Kobeissi, 2013).

Researchers who will conduct future studies that will contribute to the literature may be advised to use MFDFA and MFDCCA analyses together in order to identify the multifractal structure and to take volume series into account. In addition to this study with the S&P 500 index, which reflects a significant economic size, similar studies for the indices of other major stock exchanges and indices representing relatively smaller economies can increase the depth and diversity of the literature. Thus, the change in efficiency over time and the possible different structures of self-similarity and long memory characteristics can be revealed. A technical recommendation for future researchers on the subject is to choose the values such as series size and scale range carefully when running these analyses. Especially in the MFDCCA method, it would be useful to make a meticulous study on the method to be preferred to avoid negative *F(q)* values. Future research could build on the present framework by exploring alternative multifractal approaches, such as cross-multifractal spectrum methods, to further examine the robustness of price–volume interactions across different market segments.

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Does Green Transition Harm EU Public Debt?

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Abstract: This study examines the impact of green transitions on public debt in 27 European Union (EU) countries, employing the dynamic Generalized Method of Moments (GMM) estimation technique. Covering the period from 2019 to 2024, the empirical results confirm that the green transition increases EU public debt levels. In addition, this study analyzes the threshold level of green transition that does not harm public debt using dynamic panel threshold estimation. The panel threshold findings reveal that the green transition has a significantly negative impact on public debt below the threshold and a significantly positive impact above the threshold. This implies that the green transition increases debt after a certain threshold level. Therefore, the results indicate that while a green transition is necessary to meet climate goals, fiscal prudence and private sector participation are needed for sustainable transitions.

Keywords: Green Transitions; Public Debt; European Countries; Threshold Level.

JEL classification: O11; O52; H63.

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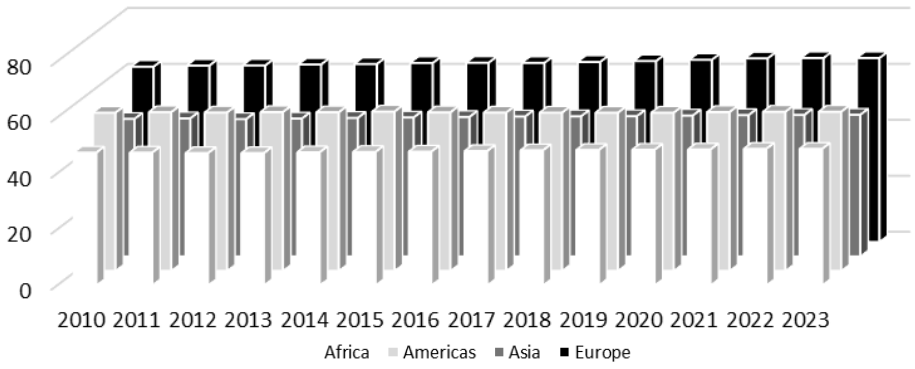
1. INTRODUCTION

The World Economic Forum's (2024) New Nature Economy report highlighted the urgency of accelerating the green transition as a pathway toward a sustainable economy. This transition primarily focuses on reducing greenhouse gas emissions by adopting environmentally sustainable and low-carbon approaches, such as enhancing the adoption of renewable energy, clean technologies, and energy efficiency. The report emphasizes that approximately $44 trillion over half of the global Gross Domestic Product (GDP)significantly relies on natural resources (World Economic Forum, 2024). The depletion and degradation of these resources, driven by climate change, threaten global supply chains, food security, and financial stability, resulting in substantial economic losses (World Economic Forum, 2024). Thus, global leaders are urged to advance the green transition to ensure long-term environmental sustainability and enhance future well-being.

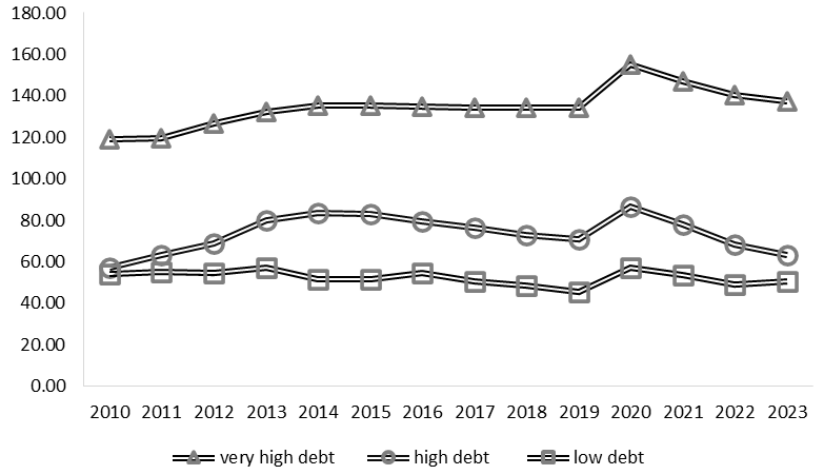
On the effort to accelerate the green transition, European Union (EU) countries are fully committed to being frontrunners in cutting greenhouse gas emissions. The EU aims to achieve carbon neutrality by 2050, along with an interim goal of reducing carbon emissions by 55% by 2030 (Duwe *et al.*, 2023; Meyer-Ohlendorf *et al.*, 2023). To meet this target, the European Green Deal (EGD) has implemented a wide range of initiatives and projects focused on transitioning to a circular economy to minimize waste and maximize resource efficiency, as well as promoting renewable energy and green technologies to restore biodiversity and reduce emissions. For example, as part of its commitment to decarbonizing the transportation sector and improving sustainable mobility, the EU is investing €422 million in 39 projects to expand alternative fuel infrastructure, including 2,500 electric charging stations, nine green port initiatives, and 35 hydrogen refueling stations throughout Europe's transportation hubs and corridors (European Alternative Fuels Observatory, 2025). Additionally, an energy island in the North Sea is being built to provide Denmark and the Netherlands with a minimum of 3GW of power by 2030, contributing to the goal of reducing greenhouse gas emissions by 70% (European Alternative Fuels Observatory, 2025). About $34 billion will be invested in this energy project, making it the largest infrastructure project capable of providing energy to 3 million households in the EU.



Source: Global Green Growth Institute (2025)

Figure no. 1 – The Green Growth Index

These trends have been highlighted in the analysis of the Green Growth Index, which measures a country's progress in achieving sustainability targets by integrating four key dimensions of efficient and sustainable resource use, natural capital protection, green economic opportunities, and social inclusion. Compared to other regions, EU countries have taken the leading position from 2010 to 2023, with the Green Growth Index rising from 62.59 in 2010 to 65.67 in 2023, showing steady progress (see Figure no. 1). Green growth has been actively promoted by the EU, and Europe's 3% increase in Green Growth Index scores from 2010 to 2023 was slightly higher than that of the Americas, whose index ranged from 56.43 to 57.27, indicating moderate success driven by social equity and environmental quality initiatives. Asia and Africa consistently had the lowest scores, with Asia increasing from 48.99 to 50.51 and Africa slightly rising from 47.96 to 49.56, both remaining in the lower-moderate range. With sustained investment and policy refinements in climate, energy, and environmental strategies, the EU is steadily advancing its green transition toward carbon neutrality while setting a benchmark for other regions to follow.

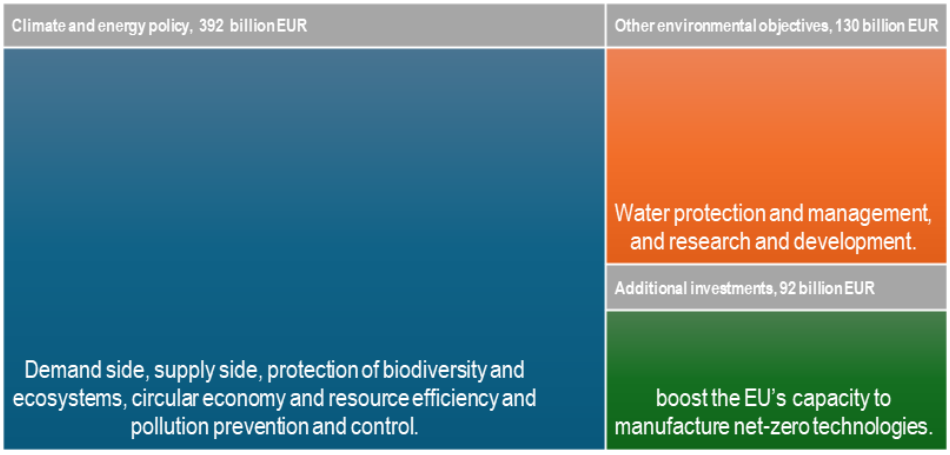


Source: Eurostat (2024)

Figure no. 2 – Public debt across EU

However, concerns over government debt have been rising due to the unprecedented debt levels reached in many EU countries. Figure no. 2 displays public debt across EU countries from 2010 to 2023, specifying that (i) very high debt countries exceed 90% of GDP (Belgium, Greece, Spain, France, Italy, Cyprus, Portugal); (ii) high debt countries range between 60% and 90% of GDP (Germany, Ireland, Croatia, Hungary, Netherlands, Austria, Slovenia, Finland); and (iii) low debt countries have debt below 60% of GDP (Bulgaria, Czech Republic, Denmark, Estonia, Latvia, Lithuania, Luxembourg, Malta, Poland, Romania, Slovakia, Sweden). In parallel, EU countries have committed to green transitions under the EGD through massive investments in renewable energy, infrastructure upgrades, and decarbonization projects. Between 2021 and 2030, the EGD demands a substantial investment of approximately EUR 600 billion per year (see Figure no. 3). Additionally, the EU requires an extra EUR 92 billion to strengthen its capacity to produce net-zero

technologies. These additional investments cannot be covered by the public sector alone, underscoring the fact that the fiscal sustainability of such an aggressive green transition remains a critical concern. While the progress toward transforming the green transition is accelerating sharply, the exhaustion of public debt raises the question of whether green transition efforts are leading to a "debt trap" for EU countries. Therefore, this paper aims to shed light on the impact of the green transition on public debt in EU countries[1]. Moreover, this study explores the threshold levels in the green transition–debt relationship to determine the point at which green transition efforts may hamper or harm public debt in EU countries. The results of this study have significant policy implications, especially when it involves maintaining a balance between goals of sustainability and debt management. Policymakers can develop strategies that optimize the returns on green investments while reducing the financial risks associated with growing public debt by knowing the turning point of the relationship between green transition and debt.



Source: Claeys *et al.* (2023) and Speck *et al.* (2023)

Figure no. 3 – Annual Investment Needs for the EGD (2021–2030)

The remainder of this study is organized as follows. Section 2 presents the literature review. Section 3 describes the data and methodology employed in this study. Section 4 reviews the study's findings, and Section 5 offers conclusions and policy implications.

2. LITERATURE REVIEW

Theoretically, the discussion on existing past studies on the determinants of public debt is presented based on three theories: The Two-Gap Model, Keynesian Economics Theory, and Classical Economic Theory. Chenery and Strout (1966) developed the Two-Gap Model, which highlights the role of the savings gap and trade gap in economic growth. The savings gap indicates the insufficiency of savings in financing investment, while the trade gap reflects low earnings from exports to finance import expenditures. Second, the Keynesian economic theory, as suggested by John Maynard Keynes, supports the fact that deficit expenditure increases public

debt (Elmendorf and Mankiw, 1999). Higher government expenditure and investment not only stimulate economic activity and aggregate output, but they also lead to an increase in public debt. In addition, governmental debt is detrimental, according to classical economic theory, because it raises the burden of interest payments, hinders long-term economic growth, and discourages private investment through excessive borrowing (Salsman, 2017). It relies on the assumption that the economy has self-regulating mechanisms that restore it to its actual output level (Witt, 1997). Thus, the following review of past studies will be presented in three stances, along with the research gap, to highlight the contribution of the study.

According to the Two-Gap theory, inadequate savings and export revenues to cover import expenditures lead to the accumulation of debt to achieve long-term economic growth. This suggests that the trade, and savings are connected to public debt. Drazen (2000), Imbeau (2004), Swaray (2005), Ouhibi *et al.* (2017), Kirui (2017), and Musah (2023) reported that savings, trade and budget deficit influence public debt. The savings gap emphasizes how savings impact the extent of government reliance on debt. The government often borrows funds to close the financing gap since the national savings (internal resources) are insufficient to fund investments in infrastructure, health care, and education for sustained economic growth. This tends to increase the amount of debt, indicating that savings have a negative impact on the public debt (Swamy, 2015; Kirui, 2017; Musah, 2023). For instance, a study by Musah (2023) on public debt in Ghana points out that savings have a significant negative impact on Ghana's public debt in the long run only, and not in the short run. This implies that a higher savings level does not affect public debt immediately, but it eases external debt over time. Similarly, a higher level of savings increases the supply of loanable funds, which becomes available for investment without the need for borrowing (Swaray, 2005). Additionally, Imbeau (2004) for federated states, Swaray (2005) for less developed countries, Kirui (2017) for Kenya, Omrane Belguith and Omrane (2017) for Tunisia, and Musah (2023) for Ghana revealed that trade has a significant impact on public debt. An expansion in trade raises the country's public debt as the growth of imports exceeds exports. This contributes to a trade deficit, and the government resorts to external borrowing, accumulating the debt level for financing. In Kenya, for instance, Kirui's (2017) findings indicate that a rise in trade, alongside slow economic growth, led to public debt accumulation due to overreliance on imports compared to exports. Therefore, this study hypothesizes that savings and trade have a significant negative and positive influence on public debt, respectively.

Moreover, the Keynesian theory elucidates that higher government expenditure is used to boost aggregate demand, but it tends to result in higher debt due to deficit-financed fiscal policy (Brown-Collier and Collier, 1995; Aspromourgos, 2018; Ncanywa *et al.*, 2018). This has been proven by Asiama *et al.* (2014), Frimpong and Oteng-Abayie (2006), Asiama *et al.* (2014), Obeng and Sakyi (2017), and Swamy (2015), who found that government expenditure influences a country's public debt. These studies show that government expenditure raises public debt due to fiscal deficits that cause sustained external and domestic borrowing, thereby leading to debt accumulation. The positive impact of government expenditure on public debt aligns with the Keynesian theory, indicating that excessive government expenditure, particularly in developing countries, often relies on borrowing, raising concerns about debt sustainability (Swamy, 2015; Owusu-Nantwi and Erickson, 2016; Obeng and Sakyi, 2017). Thus, this study hypothesizes that government expenditure has a significant positive impact on public debt.

Classical Economic Theory sees public debt as harmful to economic growth because it discourages foreign investors and private investment (Witt, 1997; Broner *et al.*, 2014; Saungweme and Odhiambo, 2019). This occurs through the interest rate channel, where governments require additional funds to meet their obligations as public debt rises, leading to higher interest rates. High rates make it more expensive for the government to borrow funds and deter private sector investment. Besides that, a rise in interest rates further accelerates the level of debt by increasing borrowing costs (Drazen, 2000; Imbeau, 2004; Swaray, 2005; Mupunga and Roux, 2015; Kirui, 2017; Omrane Belguith and Omrane, 2017). Employing the Vector Error Correction Model (VECM), Omrane Belguith and Omrane (2017) examined the impact of the macroeconomic variable of interest rate on Tunisia's public debt. Omrane Belguith and Omrane's (2017) results indicate that interest rates increase Tunisia's public debt, as higher interest payment costs lead to the growth of public debt. On the other hand, Musah's (2023) findings provide a contractionary view of the impact of interest rates on public debt in Ghana. In the short run, higher interest rates lessen the extent of public debt, while in the long run, they accumulate additional debt. Higher interest rates have the short-term effect of discouraging further borrowing and establishing the opposite relationship between interest rates and debt accumulation. Therefore, this study hypothesizes that interest rates have a significant impact on public debt.

Novelty of the study

An extensive number of studies have been conducted on examining the economic and environmental benefits of the green transition, such as Shah *et al.* (2023), Barua (2022), Adebayo *et al.* (2024), Wei *et al.* (2025), and others. As this study aims to examine the impact of the green transition on debt levels, so far only Mammetti *et al.* (2024) and Taghizadeh-Hesary and Rasoulinezhad (2025) have explored the impact of renewable energy transition on developing countries' and mixed advanced and emerging economies' debt. Taghizadeh-Hesary and Rasoulinezhad (2025) interestingly finds that the energy transition lowers developing countries' debt levels, as it lessens the fiscal burden by reducing energy subsidies and the import costs of fossil fuels. This suggests that governments can more effectively spend resources while promoting sustainable energy transitions through renewable energy. Meanwhile, Mammetti *et al.* (2024) demonstrates that the low-carbon transition can increase sovereign debt due to negative growth consequences using stochastic debt sustainability analysis and climate-transition scenarios. However, fiscal adjustments, green growth, and carbon-tax revenue recycling can lessen these debt pressures. By exploring the existing studies on the green transition and debt, we find that this topic is underexplored among scholars, particularly in the context of EU countries.

Table no. 1 – Studies on green transition on debt

Author's	Country	Results	Research hole
Mammetti *et al.* (2024)	15 countries (mixed advanced and emerging economies)	↑Low carbon transition Sovereign debt ↑	Uses scenario-based projections rather than empirical evidence and does not identify threshold effects in the green transition–debt relationship. The findings are not specific to the EU, as the sample includes a mix of advanced and emerging countries.

Author's	Country	Results	Research hole
Taghizadeh-Hesary and Rasoulinezhad (2025)	Developing countries	↑ Energy transition ↓debt	limited to developing countries and assume a linear debt-reducing effect of energy transition, leaving uncertainty about whether similar effects hold in advanced economies such as the EU.

Source: author's own illustration

Table no. 1 displays existing studies examining the impact of the green transition on debt, with a particular focus on developing countries and mixed samples of advanced and emerging economies. This highlights a gap in the literature, as the findings are largely limited to non-EU countries, creating uncertainty as to whether the results are applicable to EU countries. Moreover, Taghizadeh-Hesary and Rasoulinezhad (2025) and Mammetti *et al.* (2024) investigate only linear relationships between the green transition and debt, without considering potential threshold effects of the green transition on debt in EU countries. This clearly highlights the contribution of this study and the gap it aims to fill by examining the impact of the green transition on EU countries' public debt, as these countries are undertaking large-scale green transition initiatives to achieve carbon neutrality by 2050. EU countries are investing heavily in the green transition to boost green technology and develop sustainable industry and transport, contributing to sustainable economic growth. Yet, the rising public debt levels in EU countries raise concerns about whether aggressive green transition efforts influence the extent of public debt. Hypothetically, this study hypothesizes that the green transition has a significant impact on public debt. Therefore, the contribution of this study lies in two forms: (1) it investigates how the green transition influences public debt in EU countries, and (2) it explores the threshold level of green transition at which the transition may shift from being fiscally beneficial to fiscally burdensome. Overall, this study gives a significant conceptual contribution by demonstrating that the fiscal implications of the green transition are not linear but exhibit non-linear dynamics, even though it does not propose a new conceptual framework. These two key findings of the study offer valuable insights for EU policymakers in understanding the impact of the green transition on public debt and in identifying the benchmark level at which green transition efforts remain beneficial before becoming a fiscal burden. Thus, the findings suggest that achieving the climate goals of EU countries requires not only increasing green investment but also careful consideration of fiscal implications to ensure debt sustainability.

3. DATA AND MODEL

In this study, we employed a balanced sample of 27 European countries, including Belgium, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Italy, Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden, and the United Kingdom. The dependent and independent variables were collected for the period 2019 to 2024 from two main sources: the World Economic Forum (2024) and the International Monetary Fund (2024). Table no. 2 displays the variable, symbol, and source. The dependent variable, public debt, is measured as public debt (% of GDP), while the independent variables of savings, trade, government expenditure, green transition, and interest rate are measured by gross domestic savings (% of GDP), merchandise trade (% of GDP), government spending (% of revenue), green growth index, and interest payments

(% of revenue), respectively. The explanatory and dependent variables are selected based on three theoretical frameworks – the Two-Gap Model, Keynesian economic theory, and Classical economic theory – as illustrated in Figure no. 3.

Table no. 2 – Variables with symbol, description and sources

Variables	Symbol	Description	Sources
Public debt	*PB*	Public debt (% of GDP)	World Economic Forum (2024)
Savings	*SAV*	Gross domestic savings (% of GDP)	
Trade	*TR*	Merchandise trade (% of GDP)	
Government spending	*GE*	Government spending (% of revenue)	
Interest rate	*IR*	Interest payments (% of revenue)	
Green transition	*GT*	Green growth index	International Monetary Fund (2024)

Source: author's own illustration

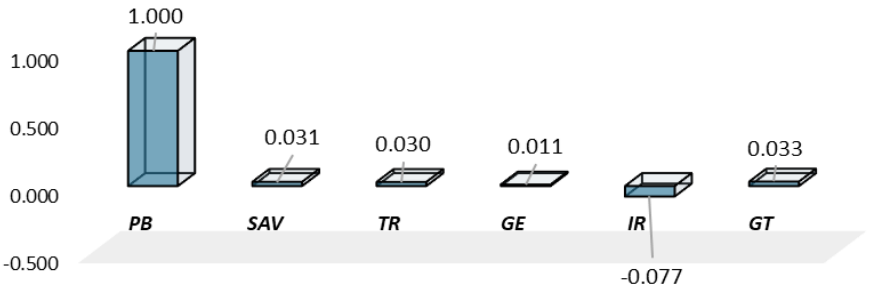
Table no. 3 displays the summary statistics, including the mean, standard deviation, minimum, and maximum values.

Table no. 3 – Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
PB	47.369	1.060	15.700	58.777
SAV	3.405	1.201	1.771	5.323
TR	44.669	0.941	23.026	84.495
GE	2.058	1.088	6.079	15.402
IR	25.917	1.093	16.787	44.158
GT	15.580	0.618	21.333	71.485

Source: author's own illustration

The average value of public debt is 47.369, with minimum and maximum values of 15.700 and 58.777, respectively, for all 27 EU countries. For the green transition, the average value is recorded as 15.580, with the highest and lowest values represented by the United Kingdom and Finland. The highest percentage of interest payments was recorded for Denmark in 2010, whereas the highest percentage of government expenditure is 15.402 in Romania in 1997. Additionally, Figure no. 4 presents the correlation coefficients for the variables. Given the nature of macroeconomic variables, a correlation between government spending, trade openness, and savings is expected. To determine potential multicollinearity, this study first performed a correlation analysis (see Figure no. 4). The correlation matrix indicates a negative correlation between interest rate and savings on public debt, whereas government expenditure, green transition, and trade are positively correlated with public debt. Increases in government expenditure, green transition efforts, and trade are associated with rising public debt.

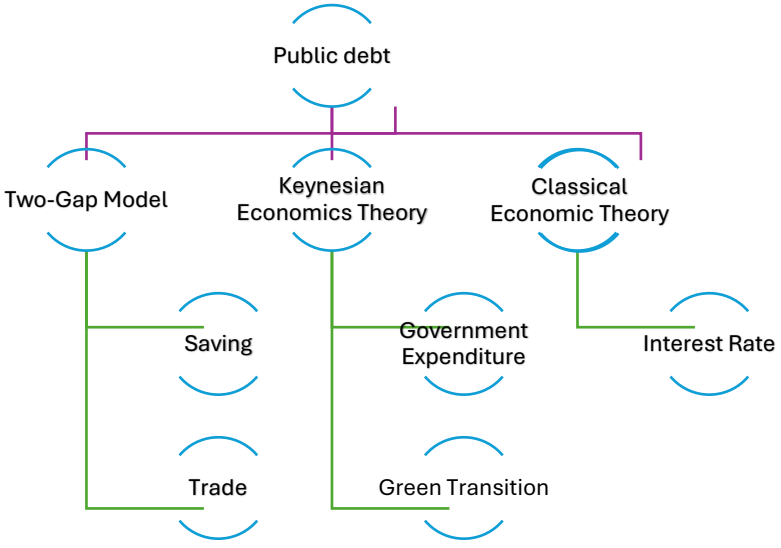


Source: author's own illustration

Figure no. 4 – Correlation analysis

Model

Considering the discussion in the literature review, this study develops a framework based on three theories: the Two-Gap Model, Keynesian Economics Theory, and Classical Economic Theory. As shown in Figure no. 5, the framework illustrates the connection between public debt and the five explanatory variables of savings, trade, government expenditure, interest rate, and, most notably, green transition (Chenery and Strout, 1966; Witt, 1997; Elmendorf and Mankiw, 1999; Salsman, 2017). The Classical Theory highlights that interest rates have a significant impact on the level of debt, while the Two-Gap Model argues that trade and savings contribute to the need for borrowing. Government expenditure and green transition are derived from Keynesian Economics Theory, where an increase in spending and investment in the green transition stimulates economic growth but also influences the level of public debt.



Source: author's own illustration

Figure no. 5 – Framework relating public debt and explanatory variables

Accordingly, this study specified the public debt function as follows

$$lnPB_{it} = \alpha_0 + \beta_1 lnSAV_{it} + \beta_2 lnTR_{it} + \beta_3 lnGE_{it} + \beta_4 lnIR_{it} + \beta_5 lnGT_{it} + \varepsilon_{it} \quad (1)$$

where PB is public debt, SAV is savings, and TR is trade, while GE, IR, and GT stand for government expenditure, interest rate, and green transition, respectively. The subscripts i and t represent country and year, respectively; the prefix ln denotes natural logarithms, and ε is the error term.

In this study, we employ a dynamic panel data approach of Generalized Method of Moments (GMM) panel to explore the impact of the green transition on public debt. Eq. (1) is modified into a dynamic panel estimation model in the following form:

$$lnPB_{it} = \alpha_0 + \gamma lnPB_{it-1} + \beta_1 lnSAV_{it} + \beta_2 lnTR_{it} + \beta_3 lnGE_{it} + \beta_4 lnIR_{it} + \beta_5 lnGT_{it} + \varepsilon_{it} \quad (2)$$

The GMM estimation technique is chosen for its capability to address potential endogeneity problems and because it is the most suitable estimation technique for small panel data structures. Arellano and Bover (1995) and Blundell and Bond (1998) explained that the lagged dependent variable of public debt used as a instruments for address endogeneity problem. Initially, first difference GMM (DIFF-GMM) applied to wipe out the country specific effect under the condition that the disturbance term is not serially correlated with the level of explanatory variables (Arellano and Bond, 1991). Unexpectedly, the correlation between the disturbance term and the lagged difference in the dependent variable may lead to endogeneity of the explanatory variables. So, to overcome this issue, DIFF-GMM combined with an estimator in levels to produce a system GMM (SYS-GMM). As a result, we employ System GMM (SYS-GMM) in this study, which was suggested to be more reliable than first-difference GMM by Arellano and Bond in 1991 (Arellano and Bond, 1991; Blundell and Bond, 1998). There are two statistics, including the serial correlation and Sargan tests, used to validate the GMM estimation. In the Hansen test, which is used to verify the instruments, the number of countries should be greater than the number of instruments. The serial correlation test assumes that the errors do not exhibit serial correlation.

Moreover, this study aims to explore the threshold levels of the green transition. Eq. (2) is extended using Kremer *et al.* (2013)'s dynamic panel threshold regression in the following form:

$$\begin{aligned} lnPB_{it} = \alpha_0 + \beta_1 lnSAV_{it} + \beta_2 lnTR_{it} + \beta_3 lnGE_{it} + \beta_4 lnIR_{it} + \beta_5 lnGT_{it} I(lnGT_{it} \le \lambda) \\ + \delta_1 I(lnGT_{it} \le \lambda) + \beta_6 lnGT_{it} I(lnGT_{it} > \lambda) + \varepsilon_{it} \end{aligned} \quad (3)$$

The threshold variable of green transition (GT) is used to split the sample into regimes, where λ is the unknown parameter and I(.) denotes an indicator function. Hence, this threshold regression allows the role of green transition to differ depending on whether GT is below or above the unknown level of λ. According to Caner and Hansen (2004), there are three steps involved in estimating the specific coefficients. First, fitted values are obtained using the ordinary least squares (OLS) technique to estimate a reduced-form regression for the endogenous variables. Second, the threshold parameter is estimated using OLS by substituting the predicted values, and the corresponding sum of squared residuals is computed. Third, the threshold value estimator is chosen as the one that minimizes the sum of squared residuals. The critical values for constructing the 95% confidence interval of the threshold value are provided by Caner and Hansen (2004) as follows: $\Gamma = \lambda: LR(\lambda) \le C\ (\alpha)$, where $C\ (\alpha)$ denotes 95%

percentile of the asymptotic distribution of likelihood ratio statistic $LR(\lambda)$. The number of time periods employed for each cross-section is considered when adjusting the underlying likelihood ratio. Once the threshold value (k) is established, the slope coefficients are estimated using the generalized method of moments (GMM). Following Arellano and Bover (1995) and Kremer *et al.* (2013), lags of the dependent variable are employed as instruments.

4. RESULTS AND DISCUSSION

Prior to evaluating how explanatory variables influence public debt, the GMM model must be validated using the two specification tests of serial correlation and Sargan. The p-value of the Sargan test is 37.75, suggesting that we do not reject the null hypothesis of no over-identifying restrictions (see Table no. 4). The serial correlation test rejects the null hypothesis of no first-order autocorrelation of AR (1) and fails to reject the null hypothesis of no second-order autocorrelation of AR (2). Hence, these two specification tests confirm the validity of the GMM model and indicate that the model specification is reliable. The best estimates between DIFF-GMM and SYS-GMM were chosen using the Difference-Hansen statistic. The discussion that follows will be based on SYS-GMM estimates, as, in light of the Difference-Hansen statistic, they are more accurate and reasonable than DIFF-GMM calculations. Besides that, the lagged dependent variable of public debt is statistically significant at the 5 percent level, meaning that the level of debt in the present period is positively correlated with the level of public debt in the previous year. This implies that the level of debt in the current period increases as the level of debt in the previous year rises.

Table no. 4 – The dynamic GMM panel estimation analysis

	One-Step		Two-Step	
	DIFF-GMM	**SYS-GMM**	**DIFF-GMM**	**SYS-GMM**
lnSAV -	-0.068* (0.090)	-0.021* (0.073)	-0.086** (0.016)	-0.059* (0.094)
lnTR -	-0.076** (0.025)	-0.019** (0.038)	-0.118** (0.011)	-0.026 ** (0.043)
lnGE +	0.052*** (0.005)	0.013** (0.033)	0.016* (0.057)	0.040*** (0.002)
lnIR +	0.094** (0.024)	0.067** (0.024)	0.124** (0.039)	0.011 ** (0.013)
lnGT +	0.041** (0.013)	0.027* (0.072)	0.183* (0.087)	0.089** (0.027)
$lnPB_{t-1}$	0.495*** (0.000)	0.980** (0.031)	0.493*** (0.000)	0.971** (0.036)
	Diagnostic Tests			
No. Observations	162	162	162	162
No. Countries	27	27	27	27
Sargan Test	32.82*** (0.012)	89.34** (0.016)	39.05** (0.015)	37.75** (0.016)
Arellano -Bond test AR (1)	3.46*** (0.001)	4.15 *** (0.000)	2.79*** (0.005)	4.16* (0.000)
Arellano -Bond test AR (2)	1.44 (0.150)	1.13 (0.257)	1.29 (0.195)	1.18 (0.238)
Difference-Hansen			0.909	0.989

Note: Asterisks *, **, and*** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in ( ) stand p-values.

According to Table no. 4, the coefficient of savings is 0.059 and statistically significant at the 10 percent level. The negative value of the savings coefficient implies that a one percent increase in savings is associated with a 0.059 percent reduction in public debt. This suggests that higher savings help reduce reliance on borrowing and enable the government to finance its expenditures with internal funds without the need for external financing. Consequently, lowering the need for external funds reduces the accumulation of debt burdens. The negative impact of savings on debt is aligned with the findings of prior studies by Imbeau (2004), Swaray (2005), Kirui (2017), and Musah (2023).

The statistically significant negative coefficient for trade is -0.026, implying that an increase in trade lessens the extent of debt in EU countries. Statistically, a 1 percent rise in trade is linked with a -0.026 percent reduction in debt levels. The negative impact of trade is contrary to this study's hypothesis and past studies by Swaray (2005) for less developed countries, Kirui (2017) for Kenya, Omrane Belguith and Omrane (2017) for Tunisia, and Musah (2023) for Ghana. The main reason for this negative influence of trade on debt is mainly due to trade surplus, where the EU countries' volume of exports exceeds the volume of imports. This generates more revenue and foreign exchange earnings, strengthening the fiscal position of EU countries and lessening the need for borrowing, thus reducing debt accumulation. As a result, this study signifies that expansion in trade due to export growth reduces debt levels.

Moreover, government expenditure is statistically significant at the 1 percent level and is positively connected with public debt in EU countries. The coefficient for government expenditure is 0.040, meaning that a 1 percent rise in government expenditure significantly increases the debt level by 0.040 percent. Although government expenditure stimulates economic growth, it also contributes to higher accumulation of debt due to reliance on borrowing to finance these expenditures when revenues are insufficient. The positive influence of government expenditure on debt is also supported by Asiama *et al.* (2014), Frimpong and Oteng-Abayie (2006), Owusu-Nantwi and Erickson (2016), Obeng and Sakyi (2017), and Swamy (2015).

Regarding the impact of interest rates, the results show a positive coefficient of 0.011, which is statistically significant at the 5 percent level. This denotes that a 1 percent increase in the interest rate leads to a 0.011 percent increase in debt levels. Similarly, this positive influence on debt has been identified by Omrane Belguith and Omrane (2017), Kirui (2017), Mupunga and Roux (2015), signifying that rising interest costs can quickly escalate fiscal vulnerability and accumulate debt levels. The cost of governments repaying their current debt increases when interest rates rise. This affects the budget and reduces funds available for other necessary expenditures, thereby possibly forcing governments to borrow even more to pay off their debt and cover spending. In turn, public debt levels further rise.

Predominantly, the core variable of green transition is statistically significant and has a positive impact on the EU's debt levels. This implies that a one percent increase in green transition leads to a 0.089 percent increase in debt. Despite the fact that the green transition helps the EU progress toward climate neutrality by 2050, it requires significant upfront investment for climate adaptation measures, including upgrades to energy efficiency, renewable energy infrastructure, and sustainable transportation. As a result, public debt levels rise. The positive effects of the green transition contradict the findings of Taghizadeh-Hesary and Rasoulinezhad (2025), who discovered that green investment reduces debt in developing countries. This is because developing countries tend to rely on smaller, less capital-intensive

green initiatives, unlike the large-scale, highly capital-intensive green projects undertaken in EU countries. Hence, the green transition increases the public debt levels of EU countries.

Even though the green transition has resulted in increased public debt, this does not mean that EU nations must abandon their green transition initiatives. EU countries must accelerate their green transition efforts to meet the 2050 carbon neutrality target and set an example for other countries. Thus, this study conducted a threshold analysis to determine the green transition threshold, identifying the level at which the green transition shifts from being beneficial to burdensome. Table no. 5 shows the dynamic panel threshold findings, revealing that the threshold value is 5.552 indicates the turning point in the impact of green transition on public debt. Below 5.522, the impact of the green transition is significantly negative, while the impact turns positive above the threshold of 5.552. This provides empirical evidence that a higher green transition above the threshold value contributes to fiscal pressures and higher debt burdens in EU countries. Green transition investment is becoming more productive and efficient and exhibits beneficial impacts on economic sustainability, but the high capital intensity and upfront investments made in accordance with EU climate targets continue to increase EU debt levels. As a result, the threshold analysis shows that only green transitions beyond the threshold level continue to increase public debt in EU countries. For the other control variables, the impact of savings, trade, government expenditure, and interest rates is similar to the results obtained from the earlier estimations shown in Table 3. Savings and trade negatively impact debt levels, while interest rates and government expenditure positively impact debt levels in EU countries.

Table no. 5 – Dynamic panel threshold regression analysis

Threshold	**5.552**
Confidence interval	[0 .223-10.882]
Impact of GT	
β_5	-0.064**
	(0.021)
β_6	0.044**
	(0.028)
Impact of covariates	
lnSAV -	-0.183*
	(0.09)
lnTR -	-0.047**
	(0.037)
lnGE +	0.020*
	(0.082)
lnIR +	0.033**
	(0.029)
δ_1	0.276**
	(0.018)
Observation	162

Note: Asterisks *, **, and*** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in ( ) stand p-values.

In this study, an additional robustness check conducted by applied alternative estimation technique of Ordinary Least Squares (OLS) and two-stage least squares (2SLS) to check the sensitivity of the main findings. The results are reported in Table no. 6. Empirically, the results

from these two estimations of OLS and 2SLS like earlier results presented in Table no. 4. This provides significant and sound support to the earlier conclusion that the green transition is associated with a high level of debt in EU countries. Green transitions, including investments in renewable energy, green infrastructure, energy efficiency, and climate adaptation, are capital-intensive, which can increase budget deficits and public debt. Additionally, the other controlled variables yield the same results as discussed above.

Table no. 6 – The dynamic GMM panel estimation analysis

	OLS	2SLS
lnSAV -	-0.045**	-0.029**
	(0.027)	(0.025)
lnTR -	-0.019*	-0.070**
	(0.051)	(0.042)
lnGE +	0.025***	0.014**
	(0.032)	(0.023)
lnIR +	0.033***	0.029**
	(0.019)	(0.033)
lnGT +	0.026*	0.058**
	(0.059)	(0.022)
Model criteria		
No. Observations	162	162
No. Countries	27	27
R^2	0.750	0.838
F-statistics	3.130***	2.180***
	(0.000)	(0.005)

Note: Asterisks *, **, and*** denote the 10%, 5%, and 1% levels of significance, respectively. Figures in ( ) stand p-values.

5. CONCLUSION

This study examines the impact of green transition on public debt in European Union countries over the period 2019–2024 using GMM estimation. The empirical evidence reveal that the green transition is associated with higher public debt levels, reflecting the fiscal burden arising from high upfront investment costs, delayed economic returns, and implementation inefficiencies. More essentially, the threshold analysis based on Kremer *et al.* (2013) reveals a non-linear relationship, showing that green transition begins to exert an adverse effect on public debt once a critical threshold is exceeded. These findings contribute theoretically by extending the green finance and public debt literature beyond linear assumptions, highlighting that the fiscal impact of the green transition depends on its scale and intensity. Empirically, this study offers novel evidence from the EU context, demonstrating that even advanced economies with strong environmental commitments face debt sustainability challenges when green investments expand beyond fiscally manageable levels. These findings underscore the importance of carefully sequencing and financing green transition policies to balance environmental objectives with long-term fiscal sustainability.

EU countries are recommended to undertake sustainable and balanced green transition investments to prevent debt pressure, as the green transition is linked to an increase in public debt above certain thresholds. Governments need to prioritize cost-effective green initiatives, the efficient distribution of green funds, and the expansion of private sector financing through

public-private partnerships to share the investment and lessen the debt burden. For instance, EU governments and policymakers should prioritise funding less costly and small-scale green projects rather than expensive large-scale projects, as these can more effectively reduce operating costs. Meanwhile, expensive large-scale green projects should be postponed or financed through EU grants or private funding. An efficient distribution of green funds should be targeted at specific economic sectors rather than being widely dispersed, and green funding should be limited to productive investments with a defined time period, with funding discontinued if targets are not met. This helps EU countries avoid unnecessary increases in public debt. Moreover, EU policymakers and governments should increase the role of the private sector in financing green infrastructure, such as renewable energy, electric vehicles, and power grids, through public–private partnerships. Additionally, EU authorities need to enhance accountability, transparency, and institutional coordination in implementing green transition projects. This helps ensure that public funds are used efficiently, promotes private sector engagement, and reduces reliance on debt-financed public spending.

This study has some limitations. Firstly, it employs public debt as a percentage of GDP as the sole measure of debt, which may not capture the broader fiscal impact of green transitions. Secondly, the analysis is limited to EU countries, which may constrain the generalizability of the findings, and employs short panel data due to data availability. Future research could explore the effects of the green transition using total debt indicators, extend the scope to include non-EU countries, and use longer time periods to achieve a more comprehensive understanding.

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Notes

[1] Public debt in the European Union is shaped by multiple factors, including macroeconomic conditions, fiscal responses to economic crises, demographic pressures, interest rate movements, and structural public expenditures. Hence, not all public debt can be attributed to green transition initiatives. In this study, we do not assume that the green transition is the sole driver of public debt; rather, we examine whether green transition efforts constitute a significant contributing factor to public debt in the EU. Specifically, the analysis focuses on the marginal and potentially non-linear impact of green transition intensity on public debt, while controlling for other macroeconomic influences.