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Biofuels, green finance, and economic expansion: empirical evidence from the European Union

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Abstract

This study examines the role of biofuel production and consumption, alongside green finance, in driving economic expansion within the European Union (EU). Employing panel data from EU countries spanning 2001–2022, the analysis follows a rigorous econometric approach. The econometric approach includes unit root tests (Im–Pesaran–Shin and ADF), panel cointegration tests (Pedroni and Kao residual tests), cointegrating regressions (FMOLS and DOLS), and robustness tests (fixed effects, random effects, and systems GMM). The findings reveal that both biofuel production and consumption significantly contribute to the EU's economic expansion, reinforcing the circular economy framework. In addition, green finance enhances biofuel consumption, further supporting economic growth. The findings also reveal that biofuel production and green finance have a more significant effect on smaller economies than on larger ones. These insights underscore the need for EU policymakers to prioritize cost-effective biofuel production and implement strategies that stimulate consumption, fostering long-term sustainable development.

Keywords: Green finance, European Union, Biofuel consumption, Biofuel production, Renewable energy, Economic growth

Introduction

As a prominent alternative to fossil fuels and an important contributor to the circular economy, biofuels hold a crucial position within the European Union's renewable energy landscape, offering substantial potential for shaping a low-carbon economy. Several studies have highlighted the significant impact of both biofuel production and consumption on economic growth (Velenturf & Purnell 2021; Hasan et al. 2023). For instance, Hartley et al. (2019) suggest that a strategic shift in the bioethanol industry, focusing on a single product, has the potential to drive economic growth without compromising food safety. Nakamya (2022) shows that biofuels can serve as a novel framework for poverty alleviation and economic growth, especially in economies heavily reliant on agriculture as their primary revenue source. Meyer et al. (2013) find that biofuels are considered as significant economic drivers for the Brazilian economy. Several other studies underscore the significance of both biofuel production and consumption

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as crucial contributors to economic expansion (Arima et al. 2017; Bandyopadhyay et al. 2009; Datta 2022; Demirbas 2009; English et al. 2008; Foran 2001; Foran & Crane 2000; Gehlhar et al. 2012; Moschini et al. 2012). Also, the contribution of renewable energy to economic development relies heavily on substantial financing for renewable energy projects. However, financing for renewable energy projects is still in its nascent stages of development, especially in underdeveloped and developing countries, primarily due to uncertainties about prospects and the cost–benefit framework (Adekoya et al. 2021; Managi et al. 2022; J. Wang et al. 2023). The same circumstances apply to investing in biofuel development. By reducing financial barriers, investing in biofuels can drive innovation across the entire bioenergy sector, leading to broader economic development.

The European Union (EU) presents a unique and policy-driven environment for studying the relationships among biofuel production, consumption, green finance, and economic expansion. The EU prioritizes increasing biofuel production to reduce crude oil dependency and advance food security, climate goals, and climate change mitigation. This commitment is evident in ongoing initiatives, such as the revision of the *Renewable Energy Directive* by the European Parliament. The EU Commission's *RePowerEU* proposal also supports European energy security, sustainable domestic biofuel production, circular economy principles, and carbon neutrality goals. A European Commission report highlights strong public support, with 85% of Europeans favoring reduced reliance on Russian oil and gas, with biofuels as a prominent alternative. In addition, the EU took the roadmap of the *European Advanced Biofuels Flight Path* initiatives to target the 2 million tons of sustainable biofuels used in EU civil aviation. Besides, the EU *Strategic Energy Technology Plan* (SET-Plan) is another key initiative to promote a carbon-neutral economy that is directly related to biofuel development. In addition, biofuels play a growing role in the EU economy, driven by factors such as rural development, energy security, investments, and independence. The past 15 years have seen significant progress, with the current decade expected to be crucial. Notably, not all EU member countries have contributed equally to this development (Hasan & Oláh, 2022). In summary, biofuels play multifaceted roles in fostering overall sustainability (Cadillo-Benalcazar et al. 2021).

While a considerable volume of literature explores the connection between biofuels and economic expansion, most investigations lack empirical substantiation, creating a gap in empirical research concerning how biofuel production and utilization contribute to economic growth within a circular economy framework. Especially within the context of the European Union (EU), there remains a need for literature on the economic significance of biofuels, with limited research on their impact in EU countries. The literature highlights the significance of biofuel production across various dimensions within the EU, particularly its impact on climate change policies, its role as an alternative fuel source, its importance for sustainable transport development, and its contribution to reducing greenhouse gas emissions, among other key areas. Consequently, the absence of empirical research on the relationships between EU biofuel production and consumption and economic growth represents a notable gap in the existing scholarship. Additionally, few studies have comprehensively examined the influence of both biofuel production and consumption on economic growth within a unified framework. The lack of integration of the effects of both biofuel production and consumption on economic

growth in a single platform also constitutes a notable gap in the current research landscape. Additionally, the contribution of green financing, along with biofuel production and consumption, toward economic expansion is still in the initial stage.

The identified research gaps motivate this study to formulate specific research questions. Considering the significance and gaps outlined, this study addresses the following key questions: How do the production and consumption of biofuels, along with green financing, impact economic growth in the EU? Additionally, how does green finance promote the production and consumption of biofuels and economic expansion in the EU? The responses to these research questions are individually explored in the findings section, with the outcomes deliberated upon in the discussion section. The research questions outlined above serve to clarify the purpose of this study. Consequently, this study formulates several research objectives informed by the identified research gaps and questions. The first objective is to empirically assess the impact of biofuel production on economic growth within the EU. The second objective is to investigate the empirical influence of biofuel consumption on economic growth in the EU. The third objective aims to explore the impact of green finance on biofuel production, biofuel consumption, and economic growth in the EU. In alignment with these objectives, this study posits three hypotheses on the basis of the literature. The hypotheses are as follows: (i) biofuel production has a significant positive effect on EU economic growth, (ii) biofuel consumption has a significant positive effect on EU economic growth, and (iii) green finance has a positive effect on economic development and promotes biofuel production and consumption.

This study offers substantial contributions to the literature. First, it provides empirical evidence underscoring the importance of biofuels, both in terms of production and consumption, for driving economic growth within the EU. The study revealed that both production and consumption promote economic growth. This finding extends the literature, specifically that of Apergis and Payne (2010a), who demonstrated the contribution of renewable energy consumption to economic growth from the perspective of OECD countries. They included geothermal, solar, wind, wood, and waste electric power consumption as components of renewable energy, but it is evident that biofuel was not included in their study. Therefore, this research includes biofuel consumption and finds a significant effect on economic growth in the EU region. Besides, finding the effect of biofuel production on economic expansion is a significant contribution and addition. Similarly, several studies, such as Apergis and Payne (2010b), Ocal & Aslan (2013), Ozcan & Ozturk (2019), Rahman & Velayutham (2020), and Yildirim et al. (2012), have also demonstrated the contribution of renewable energy consumption to economic expansion. However, biofuels are missing in these studies. This study extends the literature by identifying the contribution of bioenergy from an economic perspective. Moreover, the integration of green finance with biofuel production and consumption has not been included in other studies. Thus, the findings of this study on the impact of green finance on the economy, as well as on biofuel production and consumption, are novel contributions.

The structure of this research paper is as follows. The introduction (Sect. “[Introduction](#)”) is followed by the literature review and hypothesis development (Sect. “[Literature review & hypothesis development](#)”). The data and methods are presented in Sect. “[Data](#)

and methodology”. Sec. “Findings and analysis” describes the findings and analysis, followed by a discussion and policy implications in Sect. “Discussion and policy implications”. Finally, the conclusion is presented in Sect. “Conclusion”, and the references are presented at the end of the paper.

Literature review & hypothesis development

This study offers a literature review that concentrates on the impact of the production and consumption of biofuels and green finance on economic expansion.

Biofuel production and economic growth

The impact of biofuel production is connected in the literature to economic growth and other related forces. This literature review section discusses previous studies on biofuel production and economic growth. For example, Hasan (2022) demonstrated that biofuel production significantly boosts economic growth in the BRICS (Brazil, Russia, India, China, South Africa) economies, aligning with other energy production variables. There is also a strong connection between biofuel production, agriculture, and the environment, given the competition for land (Meyer et al. 2013). Biofuel energy enhances GDP growth, reduces pollution, and positively impacts agricultural output and prices (Al-Mulali 2015). Qiao et al. (2016) highlighted the substantial influence of biofuel production on real GDP per capita, promoting its use and improving living standards. Income per capita similarly positively affects real GDP per capita by creating job opportunities and increasing biofuel consumption. However, the expansion of economic development can hinder marginal land use, resulting in a negative relationship with real GDP per capita. In this research, the labor force has an insignificant effect, whereas real gross fixed capital formation shows a significant and positive association with GDP per capita.

Sievers & Schaffer (2016) analyze the effects of replacing fossil fuels with biofuels on the German economy. They reported that factors such as a declining population, increased agricultural productivity, and energy plant cultivation in abandoned coal areas increase the production of second-generation biofuels. There is also a strong positive link between biofuel production and employment, indicating economic growth through job creation without impacting crop and food prices in the EU (Makutenas et al. 2018). Hartley et al. (2019) show that the development of the bioethanol value chain in Mozambique positively affects the economy and employment, particularly with respect to effective labor markets. However, involving communal farmers has minimal effects on GDP, employment, and welfare. Additionally, the most significant growth gains are seen with cassava, followed by sugarcane, whereas sweet sorghum has the most negligible impact on real GDP growth.

Ashwath & Kabir (2019) highlight the economic implications of biofuel production, including employment creation, farm revenue, worker income, and local and national economic impact. Malode et al. (2021) noted that biofuels are environmentally friendly but face concerns when food crops are used as raw materials. Subramaniam & Masron (2021) revealed a positive link between economic globalization and biofuel production, whereas Oláh & Popp (2022) emphasized the need for a holistic approach to address economic, environmental, and social challenges. They stress the importance of optimizing economic, social, and environmental aspects for biofuel sustainability. The above

literature and empirical justification support the formulation of Hypothesis 1 in this study as follows:

Hypothesis 1: Biofuel production has a significant positive effect on EU economic growth.

Biofuel consumption and economic growth

A number of previous studies have investigated the impact of biofuel consumption on economic growth and other related forces. This literature review focuses on previous studies on biofuel consumption and economic growth. Ozturk & Bilgili (2015) reported that biomass consumption, openness, and population positively impact economic growth in African nations. Al-Mulali et al. (2016) revealed that biofuel usage, capital stock, urbanization, globalization, and population growth boost Brazil's economy, except for capital and globalization, which have adverse effects. There is also a long-term relationship between militarism, biofuel consumption, economic expansion, and CO₂ emissions, emphasizing the importance of understanding this link for effective policy decisions (Bildirici 2017). Boutabba & Ahmad (2017) highlighted that real income and carbon emissions are key factors influencing biofuel usage, underscoring its growing importance as a renewable energy source. Koengkan (2017) identified bidirectional links between biofuel consumption and economic growth, between oil consumption and economic growth, and between biofuel consumption and oil consumption. Simionescu et al. (2019) show that biodiesel use in EU transportation has a small positive effect on economic growth, with a one-way Granger causality relationship. These findings also highlight the environmental benefits of biodiesel. Simionescu et al. (2019) also reported that only biodiesel-based transport energy positively affects economic development, whereas bioethanol-based energy usage has an adverse effect. Azam (2020) reported that increased energy consumption has a significant positive effect on economic growth in Asian economies. The above literature and empirical justification support the formulation of Hypothesis 2 in this study as follows:

Hypothesis 2: Biofuel consumption has a significant positive effect on EU economic growth.

Green finance, biofuels, and the economy

A number of studies focus on green financing as an influential force of sustainable economic development. For example, Soundarrajan & Vivek (2016) demonstrated the importance of green finance in the development of sustainable economic growth in India. They emphasize that financial institutions should increase investment opportunities in developing a green economy in both direct and indirect ways. Zhang et al. (2021) investigated the relationship between green financing and economic growth on the basis of the Belt and Road Initiative countries' data. They reveal that investing in green energy technologies as well as human resources also promotes green economic development. However, in this case, the acceleration of green economic development varies across countries. They also conducted another study by Zhang et al. (2022), which was based on G-20 countries' data, to investigate the impacts of renewable energy, green financing, and innovation on carbon emissions. They demonstrate that green financing also significantly reduces carbon emissions toward green economic development. Yin

and Xu (2022) analyze the impact of green financing on China's economic development and show that from 2008–2020, both the green financing composite index and the economic growth composite index were promoted; however, not in parallel. The findings suggest that significant development of green financing is essential to promote positive economic growth in China.

Green finance also promotes resource efficiency and boosts green economic growth. In particular, Xu et al. (2023) reported that although green financing does not improve resource efficiency, issuing more green bonds leads to green economic growth through the agricultural industry. Ouyang et al. (2023) also examine the empirical evidence of green financing, natural resources, and economic growth. They find that although green financing has the ability to improve green economic growth, development growth is slow compared with that of other industries and factors.

This study proxies financing to the private sector as green finance; therefore, this study focuses on financing to the private sector as well as the financial development literature to support the concept of biofinancial investment. Saidi (2023) explores the nexus between renewable energy, financial development, particularly domestic credit to the private sector, and economic growth in emerging economies. They reveal a positive impact of renewable energy consumption and investment in the private sector on economic growth. In addition, it identifies a unidirectional relationship between domestic credit to the private sector and renewable energy consumption in these countries. In another study, Wang et al. (2021) investigated the effects of renewable energy consumption on economic expansion and investment in the private sector in China. The results suggest that economic growth promotes the use of renewable energy in China, whereas investment in the private sector has an adverse effect. Eren et al. (2019) examine the influence of financial development and economic growth on renewable energy consumption in India. Research shows that both financial development and economic expansion have positive effects on the consumption of renewable energy. Besides, green investment leads to sustainable economic growth (Ahmed et al. 2023; Batrancea et al. 2021a; Chai et al. 2022; Ioan et al. 2020; Larissa et al. 2020; Zhao et al. 2024). Moreover, previous studies have explored the relationships among green financing, renewable energy development, and economic growth. Alharbi et al. (2023), Bakry et al. (2023), and Rasoulinezhad & Taghizadeh-Hesary (2022) highlighted a significant link between green finance and renewable energy development. On the basis of the literature, Hypothesis 3 is proposed in the following section.

Hypothesis 3: Green finance has a positive effect on economic development and promotes biofuel production and consumption.

Data and methodology

This study begins by exploring biofuel production and consumption data from the EU 27 countries with the aim of collecting the maximum available data. In this context, the first issue is that for most countries, biofuel data were unavailable prior to 2000. This study finds available biofuel data for Austria, Belgium, Germany, Spain, Finland, Italy, France, the Netherlands, Portugal, Poland, and Sweden. Hence, 11 countries were selected as the sample for this study.

Data related to green finance has been limited over the years, and renewable energy finance and investment country data are unavailable for this study area for the specific period in databases such as the World Bank, Private Participation in Infrastructure Project Database, BloombergNEF database, and IRENA public finance data, which were used as proxies in some other literature. However, the following literature (Aslani 2014; Azhgaliyeva et al. 2023; Cárdenas Rodríguez et al. 2015; Fadly 2019; Maulidia et al. 2019; Ragosa & Warren 2019) highlights the contribution of private sector investment to financing renewable energy projects. In particular, Maulidia et al. (2019) mention that there is no dispute that private sector participation is imperative for addressing underinvestment in energy infrastructure. Aslani et al. (2012) suggest that more privatization is needed to promote renewable energy development. Xu et al. (2022) also noted private sector investment as a new force of green finance in terms of the development of renewable energy. In line with the notion of investing in bioenergy projects, this study employs total private sector investment as a proxy for green financing, particularly financing toward the biofuel energy industry. Therefore, this study uses domestic credit to the private sector (% of GDP) as the proxy for financing to the energy sector. In particular, following the statement from the International Energy Agency, this study extracts 60% of the domestic credit to the private sector (% of GDP) as a contribution to clean energy investments.

This study mainly follows panel data analysis. In experimental modeling, this study employs the augmented neoclassical framework provided by Al-Mulali et al. (2016), Apergis & Payne (2010a), Apergis & Payne (2010b), Munir et al. (2020), Ozturk et al. (2010), Streimikiene & Kasperowicz (2016), Smolović et al. (2020), and Kasperowicz et al. (2020) to evaluate the link between energy production and consumption with GDP growth. The aggregated production function is given in the following section.

$$GDP_{it} = f(\text{Capital}_{it}, \text{Labour}_{it}, \text{Green Finance}_{it}, \text{Biofuel Production/Consumption}_{it}) \tag{1}$$

Later, on the basis of the above concept, this study transforms the model into a logarithmic structure, which is mentioned in the following section.

$$\ln GDP_{it} = \beta_0 + \beta_1 \ln CAP_{it} + \beta_2 \ln LAB_{it} + \beta_3 \ln GF_{it} + \beta_4 \ln PRO_{it} + \epsilon_{it} \tag{2}$$

$$\ln GDP_{it} = \beta_0 + \beta_1 \ln CAP_{it} + \beta_2 \ln LAB_{it} + \beta_3 \ln GF_{it} + \beta_4 \ln CON_{it} + \epsilon_{it} \tag{3}$$

Here, *i* refers 1–11 for each country, and *t* refers to the time from 2001–2022. where $\ln GDP_{it}$ represents the natural logarithm of gross domestic product, $\ln CAP_{it}$ represents the natural logarithm of gross capital formation, $\ln LAB_{it}$ represents the natural logarithm of the total labor force, $\ln GF_{it}$ represents the natural logarithm of green finance, $\ln PRO_{it}$ represents the natural logarithm of biofuel production, encompassing both bioethanol and biodiesel production, and $\ln CON_{it}$ represents the natural logarithm of biofuel consumption, encompassing both bioethanol and biodiesel consumption. To show the impact of green finance on biofuel production and consumption, as well as economic growth, this study also performs experiments with the following regressions.

$$\ln GDP_{it} = \beta_0 + \beta_1 \ln CAP_{it} + \beta_2 \ln LAB_{it} + \beta_3 \ln GF_{it} + \epsilon_{it} \tag{4}$$

$$\ln\text{PRO}_{it} = \beta_0 + \beta_1 \ln\text{GDP}_{it} + \beta_2 \ln\text{CAP}_{it} + \beta_3 \ln\text{LAB}_{it} + \beta_4 \ln\text{GF}_{it} + \epsilon_{it} \tag{5}$$

$$\ln\text{CON}_{it} = \beta_0 + \beta_1 \ln\text{GDP}_{it} + \beta_2 \ln\text{CAP}_{it} + \beta_3 \ln\text{LAB}_{it} + \beta_4 \ln\text{GF}_{it} + \epsilon_{it} \tag{6}$$

The details of the variables, measures, and sources are mentioned in Table 1.

This study conducts the Pesaran (2004) cross-sectional dependence (CD) test following the concept of Munir et al. (2020), followed by panel unit root tests for all the variables. The concept of unit root tests for this study has been taken from the studies by Munir et al. (2020) and Apergis & Payne (2010a, 2010b), which include both the Im, Pesaran, and Shin (IPS) tests conducted by Im et al. (2003) and the ADF unit root test conducted by Dickey & Fuller (1979). In the unit root tests, this study assumes the null hypothesis that there is a unit root and the alternative hypothesis that the data are stationary.

After conducting the static data test, this study proceeded with the panel cointegration test to determine whether the variables were cointegrated. Two types of panel cointegration tests were employed. The first is the Pedroni residual cointegration test (Pedroni 2000, 2004). Pedroni developed seven test statistics to examine the null hypothesis that no cointegration occurs in nonstationary panels. These seven statistical tests account for panel heterogeneity, considering both short-run dynamics and long-run slope and intercept coefficients (Neal 2014).

The second cointegration test conducted here is the Kao residual cointegration test (Kao 1999). Here, for both tests, I assume the ‘Null Hypothesis: No cointegration’ and ‘Alternative Hypothesis: There is a cointegrated relationship.’

This study considers both the unit root test outputs and the panel cointegration test outputs. Considering the output of the panel cointegration test, this study conducts a cointegrated panel regression experiment, particularly Panel Fully Modified Least Squares (FMOLS), and later compares the results with those of another panel cointegrated model, the Panel Dynamic Least Squares (DOLS) model (Pedroni 2000, 2004). These models are also appropriate when the number of observations is less than the number of observations. Many previous studies have also used these two models in

Table 1 Variable measurement

Variables	Measure	Sources
lnGDP (Gross Domestic Product)	Constant 2015 US\$	The World Bank Database, 2024
lnCAP (Gross Capital Formation)	Constant 2015 US\$	The World Bank Database, 2024
lnLAB (Labor Force)	Total labor force (Constant 2015 US\$)	The World Bank Database, 2024
lnGF (Green Finance)	Investment to the private sector (60% of Domestic credit to private sector, % of GDP)	The World Bank Database, 2024
lnGB (Green Bond)	Green Bond Issuances (Billion US Dollars)	The International Monetary Fund, 2025
lnPRO (Biofuel Production)	Biofuels Production—Mb/d—Total	Energy Information Administration, 2024
lnCON (Biofuel Consumption)	Biofuels Consumption—Mb/d—Total	Energy Information Administration, 2024

Source: Author’s explanation

similar circumstances (Al-Mulali 2015; Apergis & Payne 2010b; Kayhan & Özdemir 2021; Khan et al. 2019b; Singh et al. 2019). Finally, this study used two software programs, EViews and STATA, to test the estimated regressions and conduct other analyses.

Findings and analysis

Descriptive statistics, unit root, & panel cointegration

The descriptive statistics, correlations, and variance inflation factor analysis of this study are presented in Table 2 below. This study provides the mean, median, maximum (Max), minimum (Min), standard deviation (Std. Dev.), skewness, kurtosis, Jarque–Bera, probability, and number of observations. The values of the descriptive statistics are based on the natural logarithm of the corresponding variables.

Before conducting the unit root test, this study first performs a cross-sectional dependence (CD) test, specifically the Pesaran (2004) CD test. The results (see Appendix 2) indicate that the variables are significant, confirming the presence of cross-sectional dependence. Munir et al. (2020) outlined the detection of cross-sectional dependence necessitates the use of second-generation unit root tests. However, due to the short time span of the panel and to maintain consistency with the existing literature, first-generation unit root tests (IPS and ADF–Fisher) are employed, with cross-sectional dependence being accounted for in the subsequent panel cointegration and long-run estimation procedures.. Table 3 presents the results of the unit root test. This study experiments with the unit root at a level I (0) and the first difference I (1) for both IPS and ADF–Fisher chi-square. This study revealed mixed results of

Table 2 Descriptive statistics and correlations

Statistics	Descriptive statistics					
	lnGDP	lnCAP	lnLAB	lnGF	lnPRO	lnCON
Mean	13.459	11.925	2.353	12.847	2.401	2.522
Median	13.167	11.726	2.193	12.774	2.362	2.564
Maximum	15.106	13.576	3.794	14.481	4.324	4.355
Minimum	12.177	10.264	0.958	10.018	− 2.996	− 3.912
Std. Dev	0.903	0.904	0.901	1.004	1.261	1.304
Skewness	0.331	0.252	0.081	− 0.059	− 1.069	− 1.679
Kurtosis	1.788	1.910	1.512	2.106	5.542	8.963
Jarque–Bera	19.242	14.549	22.605	8.205	95.613	398.168
Probability	0.000	0.001	0.000	0.017	0.000	0.000
Sum	3257.026	2885.826	569.361	3108.988	499.432	514.546
Sum Sq. Dev	196.314	197.116	195.615	242.956	329.306	345.332
<i>Correlation analysis</i>						
lnGDP	1	–	–	–	–	–
lnCAP	0.991	1	–	–	–	–
lnLAB	0.897	0.858	1	–	–	–
lnGF	0.933	0.932	0.771	1	–	–
lnPRO	0.684	0.671	0.649	0.655	1	–
lnCON	0.701	0.695	0.645	0.693	0.873	1
VIF Tolerance	–	0.10	0.12	0.21	0.23	0.25
Observations	242	242	242	242	208	204

Source: Author experiment. Notes: VIF refers to variance inflation factor tolerance

Table 3 Unit root test

Variables	IPS	ADF—Fisher Chi-square
lnGDP	2.148	9.219
ΔlnGDP	−4.796***	65.540***
lnCAP	0.732	13.034
ΔlnCAP	−9.522***	123.420***
lnLAB	2.268	11.913
ΔlnLAB	−5.510***	71.159***
lnGF	−3.312***	50.136***
ΔlnGF	−2.515***	38.775**
lnPRO	−5.729***	76.913***
ΔlnPRO	−5.239***	63.560***
lnCON	−2.429***	58.231***
ΔlnCON	−4.351**	58.090***

Source: Author experiment (Note: Δ refers to the first difference unit root test). ***, **, and * refer to the 99%, 95%, and 90 significance levels, respectively

Table 4 Pedroni residual cointegration test

Tests	Production	Consumption
<i>Alternative hypothesis: common AR coeffs. (within-dimension)</i>		
Panel v-Statistic	−0.407	−0.590
Panel rho-Statistic	0.732	0.793
Panel PP-Statistic	−2.820***	−2.897***
Panel ADF-Statistic	−2.637***	−2.368***
<i>Alternative hypothesis: common AR coeffs. (Weighted Statistics)</i>		
Panel v-Statistic	0.326	−0.726
Panel rho-Statistic	0.471	0.200
Panel PP-Statistic	−4.016***	−4.646***
Panel ADF-Statistic	−2.831***	−2.382***
<i>Alternative hypothesis: individual AR coeffs. (between-dimension)</i>		
Group rho-Statistic	1.813	2.020
Group PP-Statistic	−4.764***	−7.510***
Group ADF-Statistic	−2.443***	−3.072***

Source: Author experiment. ***, **, and * refer to 99%, 95%, and 90 significance levels, respectively

overall unit root findings. The dependent variable GDP, as well as key forces of the augmented neoclassical framework, contains a unit root, indicating nonstationarity in I (0); however, green finance, biofuel production, and consumption are significant at both I (0) and I (1). This significant output indicates that biofuel production is stationary at both levels and in the first difference. Considering the above circumstances, this study moves forward with the cointegration test to decide on further experimental modeling.

Table 4 presents the Pedroni residual cointegration test results for the biofuel production model. This study tests within-dimensions, weighted statistics (Pedroni 1999, 2000, 2004), and alternative hypotheses: the individual AR coefficient (between-dimensions). Table 4 presents seven test statistics, such as the v statistic, rho statistic,

Table 5 Kao residual cointegration test

Statistics	Production	Consumption
ADF	- 2.287***	- 1.821**

Source: Author experiment. ***, **, and * refer to 99%, 95%, and 90 significance levels, respectively

Table 6 Breusch–Pagan test for heteroscedasticity

Statistics	Value
Chi ²	0.600
P value	0.4371

Source: Author experiment

PP statistic, ADF statistic, group rho statistic, group PP statistic, and group ADF statistic. According to Table 4, six statistics (out of 11) are significant in the production, consumption, and combined models, which indicates that the null hypothesis is rejected and that a cointegrated relationship exists in the estimated equations.

This study also conducts the Kao residual cointegration test to demonstrate the robustness of the output of the panel cointegration test in Table 4. Table 5 presents the output of the Kao residual cointegration test. Here, the null hypothesis is that there is no cointegration. According to the ADF statistics, the t-statistics are significant in all the models, which supports the rejection of the null hypothesis. Therefore, the Kao residual cointegration test supports the output of the panel cointegration tests. Given the evidence of a cointegrated relationship, this study also tests pairwise Granger causality tests (see Appendix 3). This study revealed that there is no causal relationship between biofuel production and economic growth or between biofuel consumption and economic growth. However, green finance and economic growth have a causal relationship.

This study also conducts the Breusch–Pagan test for heteroscedasticity. I assume that the null hypothesis (H0) is homoscedasticity and that the alternative hypothesis (H1) is heteroscedasticity. In the estimated regression, GDP is included as the dependent variable, with capital, labor, green finance, biofuel production, and consumption as the independent variables. The findings show that the p-value is greater than 0.05, indicating the absence of heteroscedasticity. The output of the Breusch–Pagan test for heteroscedasticity is presented in Table 6.

Biofuels and economic growth

After conducting unit root and panel cointegration tests, this study identifies a cointegration relationship in the estimated model. As a result, I employ cointegrated panel regression methods in this section, which are presented in three distinct steps. First, I analyze the impact of biofuel production, including green financing, on economic growth. Second, I examine the impact of biofuel consumption, including green financing, on economic growth. Finally, I explore the combined impact of both production and consumption, including green finance, on the economy in a single model.

Table 7 presents the regression results for the biofuel production model, utilizing both FMOLS and DOLS regression techniques, which are commonly employed for analyzing

Table 7 Cointegrated regression (FMOLS and DOLS)

Variables	Equation (2) (DV: lnGDP)—Production model		Equation (3) (DV: lnGDP)—Consumption model	
	FMOLS	DOLS	FMOLS	DOLS
lnCAP	0.441*** (0.022)	0.404*** (0.045)	0.454*** (0.023)	0.416*** (0.049)
lnLAB	0.260*** (0.090)	0.467*** (0.167)	0.359*** (0.084)	0.569*** (0.150)
lnGF	0.035** (0.020)	0.025 (0.039)	0.011 (0.021)	0.005 (0.042)
lnPRO	0.018*** (0.003)	0.019*** (0.005)	— —	— —
lnCON	— —	— —	0.015*** (0.003)	0.018*** (0.005)
Obs	197	208	192	204

Source: Author experiment. DV refers to the dependent variables. In the FMOLS model: Trend specification: Constant (Level); Additional trends: None; Lag specification: None; Kernel option: Bartlett; Bandwidth method: Newey–West Fixed; Panel method: Pooled; Heterogeneous first-stage long-run coefficients: No; Coefficient covariance matrix: sandwich (heterogeneous variances). In the DOLS model, the trend specification is constant (level), the panel method is pooled, the coefficient covariance matrix is sandwiched (heterogeneous variances), and the scaling method is long-run variance. ***, **, and * refer to the 99%, 95%, and 90 significance levels, respectively

regression in the presence of cointegrated relationships. The findings in Table 7 indicate that biofuel production remains highly significant in the FMOLS models. Specifically, a 1% increase in biofuel production corresponds to a 0.018% increase in GDP growth (FMOLS).

This result aligns with those of previous studies; Al-Mulali (2015) reported that biofuel production has a substantial positive impact on the Czech Republic’s economic growth (0.272), indicating that a 1% rise in biofuel energy production leads to a 0.272% increase in the Czech Republic’s GDP. Qiao et al. (2016) also examined the relationship between biofuel production and economic development, with a specific focus on sustainable development. Their findings indicate a significant and positive impact of biofuel production on economic development, particularly in terms of per capita real GDP, with a 1% increase in economic growth corresponding to a 0.295% increase in per capita real GDP. Similarly, Hasan (2022), who investigated the impact of energy production and consumption on economic growth in BRICS countries, reported that biofuel production significantly contributes to economic expansion in the BRICS economy, with a 1% increase in biofuel production associated with a 0.492% increase in GDP (95% confidence interval).

Furthermore, other studies have explored how renewable energy production influences economic growth. Considering biofuels as a subset of renewable energy, studies such as have revealed a significant impact of renewable energy production on long-term economic growth. Dinç & Akdoğan (2019) also identified a long-term influence on countries’ economic growth. Additionally, Singh et al. (2019) reported that a 1% increase in renewable energy production results in a 0.06% increase in the economy. Given these collective findings, this study provides strong evidence supporting the significant positive impact of biofuel production on economic growth within the panel region of interest.

Biofuel consumption is highly significant, with a 1% increase in biofuel consumption corresponding to a 0.015% increase in GDP. While the significance of biofuel consumption is slightly lower than that of biofuel production, the results remain robust.

This study's findings align with those of Al-Mulali (2015), who also utilized the FMOLS model to investigate the impact of biofuel production and consumption on economic growth, using data spanning from 2000–2010. Al-Mulali (2015) reported that biofuel consumption significantly and positively influences economic growth, with a 1% rise in biofuel energy consumption leading to a 0.667% increase in GDP for the overall panel. When considering individual countries, a 1% increase in biofuel energy consumption results in a 0.027% increase in GDP in Italy, 0.020% in the Netherlands, 0.089% in Poland, 5.817% in Portugal, and 0.072% in Sweden. Al-Mulali et al. (2016) further demonstrated that a 100% increase in bioethanol consumption enhances a country's economic progress by 2.2%, which aligns closely with the findings of this study.

These results also support the broader literature on renewable energy consumption and its positive impact on economic growth. Notably, Apergis & Payne (2010b) establish a significant and positive relationship between renewable energy consumption and economic growth. Similarly, Lin & Moubarak (2014) examine this relationship from China's perspective and find that renewable energy consumption significantly influences economic growth. Therefore, biofuel consumption emerges as a significant driver of economic growth within the panel region.

This study conducts an additional experiment (the DOLS model) for both the production model and the consumption model to assess the influence on EU economic growth via the widely recognized cointegrated regression. In the DOLS model, both the production model and the consumption model also exhibit significant importance and robustness. The outputs of the cointegrated regressions (both FMOLS and DOLS) are presented in Table 7.

Green finance has demonstrated a substantial impact on economic growth in the context of our analysis. In the production model, the coefficient is estimated at 0.035, indicating a robust influence on economic expansion, and this effect is statistically significant at the 95% confidence level. However, in consumption models, green finance is found to have an insignificant effect on economic growth. Therefore, this study does not consider the influence of green finance until further experiments are conducted in the following sections.

Capital formation has a positive and statistically significant relationship with GDP, underscoring its role in promoting economic growth in the selected European countries. This finding aligns with the literature, which has consistently highlighted the substantial impact of capital formation on economic growth. For instance, Singh et al. (2019) conducted a multivariate study encompassing both developed and developing countries, examining the nexus between renewable energy production and economic growth. Their results indicated that gross capital formation significantly fosters economic growth, with a 1% increase in capital formation corresponding to a 0.44–0.45% surge in GDP.

This study's findings are consistent with the outcomes of prior research that delves into the relationship between energy consumption and economic growth. For example, Al-Mulali et al. (2016) explored the long-term and short-term effects of bioethanol consumption and capital formation on economic performance in Brazil, revealing

a favorable relationship between capital formation and ethanol consumption and economic growth. Specifically, their findings suggest that a 100% increase in capital formation leads to a notable 13.9% improvement in the country’s economic progress.

The labor force also exerts a positive effect on the economy, corroborating the findings of previous studies. Singh et al. (2019) revealed a significant and positive relationship between the labor force and economic growth, with a 1% increase in the labor force contributing to a 0.27% GDP increase for all countries, 0.31% for developed countries, and 0.23% for developing countries. In the context of both labor force and gross capital formation, Apergis & Payne (2010b) reported that both variables have a significant and positive effect on both short- and long-term economic growth.

Regional economic heterogeneity

This study also tests the impact of biofuel production and consumption, as well as green financing, on the basis of economic heterogeneity. This study divides the 11 countries into two groups on the basis of their economic size. Compared with the other countries, Group 1 comprises five countries with larger GDPs (2021), with each of these countries having a GDP exceeding 1 trillion. These countries include Germany (GDP of 4.260 trillion), France (GDP of 2.958 trillion), Italy (GDP of 2.108 trillion), Spain (GDP of 1.427 trillion), and the Netherlands (GDP of 1.013 trillion). The remaining six countries are included in the second group: Poland (GDP 679.4 billion), Sweden (GDP 635.7 billion), Belgium (GDP 594.1 billion), Austria (GDP 480.4 billion), Finland (GDP 297.3 billion), and Portugal (GDP 253.7 billion).

First, the results regarding the impact of biofuel production on EU economic growth for both Group 1 and Group 2 are presented in Table 8, which demonstrates that biofuel production is significantly positive in Group 2 countries. The output indicates that, compared with larger economies (measured in terms of GDP), biofuel production influences

Table 8 Cointegrated regression – regional economic heterogeneity (FMOLS)

Variables	Production (Group 1) Equation (2) (DV: lnGDP)	Consumption (Group 1) Equation (3) (DV: lnGDP)	Production (Group 2) Equation (2) (DV: lnGDP)	Consumption (Group 2) Equation (3) (DV: lnGDP)
lnCAP	0.323*** (0.016)	0.329*** (0.015)	0.499*** (0.030)	0.481*** (0.027)
lnLAB	1.206*** (0.085)	1.120*** (0.083)	− 0.302*** (0.122)	− 0.242** (0.112)
lnGF	− 0.066*** (0.014)	− 0.077*** (0.013)	0.110*** (0.028)	0.133*** (0.027)
lnPRO	0.002 (0.003)	–	0.016*** (0.004)	–
lnCON	–	0.010 (0.004)	–	0.000 (0.003)
Obs	96	91	101	101

Source: Author experiment. In the FMOLS model: Trend specification: Constant (Level); Additional trends: None; Lag specification: None; Kernel option: Bartlett; Bandwidth method: Newey–West Fixed; Panel method: Pooled; Heterogeneous first-stage long-run coefficients: No; Coefficient covariance matrix: sandwich (heterogeneous variances). In the DOLS model, the trend specification is constant (level), the panel method is pooled, the coefficient covariance matrix is sandwiched (heterogeneous variances), and the scaling method is long-run variance. ***, **, and * refer to the 99%, 95%, and 90 significance levels, respectively

economic growth in smaller economies (measured in GDP). Green finance also positively promotes economic growth in Group 2, indicating a consistent pattern of positive associations between green finance and economic growth and the development of the biofuel sector.

Green finance, economic growth, and biofuels

In previous analyses, this study focused solely on assessing the impact of economic proxies (capital and labor), green finance, biofuel production, and consumption on economic expansion. However, in this section, the study broadens its scope to examine the particular impact of green finance on economic growth, as well as biofuel production and consumption.

Table 9 presents the impact of green finance on economic growth, as well as biofuel production and consumption. The first finding of this experiment is that green finance significantly promotes economic growth. The coefficient is not very high; however, it is still significant at the 99% confidence interval, with a coefficient of 0.089. This output indicates that green finance, particularly private sector investment, promotes economic growth by boosting productive capacity, improving productivity and innovation, promoting energy investment and development, and enhancing overall private sector efficiency.

Green finance has a significantly positive effect on biofuel consumption. This result indicates that financing for the private sector promotes the consumption of biofuels. There are several ways that green finance, which entails financial instruments and investments that prioritize environmental sustainability, can encourage the use of biofuels. It helps expand markets, encourages sustainable farming methods, funds the infrastructure needed to produce biofuels, supports research and development, offers subsidies and incentives, and makes it easier to create networks for distributing eco-friendly biofuels. Green finance can also attract investors who care about the environment through green bonds and sustainable investment portfolios, ultimately helping to increase the use of biofuels as a more sustainable energy source. This result aligns with the findings of Wang et al. (2021) regarding the positive relationship between financial development

Table 9 Green finance, economic growth, biofuel production, and consumption

Variables	Equation (4) (DV: lnGDP)	Equation (5) (DV: lnPRO)	Equation (6) (DV: lnCON)
lnGDP	–	8.299***	7.445***
	–	(1.119)	(1.130)
lnCAP	0.392***	– 3.745***	– 4.533***
	(0.031)	(0.624)	(0.601)
lnLAB	0.466***	6.713***	2.477
	(0.101)	(2.029)	(1.716)
lnGF	0.089***	0.592*	2.213***
	(0.020)	(0.345)	(0.346)
Obs	231	207	204

Source: Author’s explanation. DV refers to the dependent variable. In the FMOLS model: Trend specification: Constant (Level); Additional trends: None; Lag specification: None; Kernel option: Bartlett; Bandwidth method: Newey–West Fixed; Panel method: Pooled; Heterogeneous first-stage long-run coefficients: No; Coefficient covariance matrix: sandwich (heterogeneous variances). ***, **, and * refer to the 99%, 95%, and 90 significance levels, respectively

and renewable energy consumption. Besides, the output is also supported by Eren et al. (2019), who highlight how financial development significantly encourages the consumption of renewable energy. Usman et al. (2023b) also demonstrate that a 1% increase in investment in the private sector promotes energy consumption in Asian developing countries by 3.07%. Komal & Abbas (2015) also noted that positive and substantial economic growth pathways are significantly influenced by investment in the private sector, which in turn impacts energy consumption. Other studies, such as (Khan et al. 2019a; Kihombo et al. 2021; Mahalik & Mallick 2014; Ouyang & Li 2018; Rafindadi & Ozturk 2016; Shahbaz et al. 2013a, 2013b; Usman et al. 2023a), also outline the impact of investment in the private sector, or in other words, financial development, on economic development as well as energy consumption.

Robustness testing

This study also demonstrates the robustness of the results from Eqs. (2) to (6) in Table 10. To validate the robustness of the estimated equations, the study presents findings via fixed-effect (FE), random-effect (RE), and system GMM models. These models yield results that are consistent with the primary equations.

Discussion and policy implication

This study initially posits three hypotheses to investigate the research questions and objectives. The first hypothesis examines the significant impact of biofuel production on EU economic growth. The findings indicate that biofuel production plays an important role in economic growth, with a 1% increase in biofuel production leading to a notable 0.018% surge in GDP growth (FMOLS) and 0.019% in GDP growth (DOLS) models. These results align seamlessly with Hypothesis 1, which postulates that biofuel production has a significant positive effect on EU economic growth. Consequently, this study affirms Hypothesis 1. The second hypothesis explores the substantial impact of biofuel consumption on EU economic growth. The results demonstrate that biofuel consumption holds great significance in both the FMOLS and DOLS models. Specifically, a 1% increase in biofuel consumption correlates with a 0.015% rise in GDP (FMOLS) and 0.018% (DOLS) models. These findings harmonize with Hypothesis 2, which posits that biofuel consumption has a significant positive effect on EU economic growth. Thus, this study confirms Hypothesis 2.

Concerning Hypothesis 3, which suggests a positive impact of green finance on economic growth and biofuel production and consumption, this study partially affirms the hypothesis, as it is found that green finance is insignificant in terms of biofuel production. The analysis demonstrates that green finance has a positive and significant effect on economic growth. Likewise, green finance positively impacts biofuel consumption. Therefore, Hypothesis 3 is partially confirmed.

This study focuses on the policy implications derived from its hypotheses. First, biofuel production should be prioritized as a key driver of economic growth. In this respect, policy strategies should be aimed at making biofuels more cost-effective to encourage broader usage. Supporting the provision of ethanol policies, which are necessary for global trade and capital development, has become paramount. These measures not only directly impact economic growth but also stimulate it by fostering growth within the

Table 10 Robustness test of Eqs. (2)–(6)

Variables	Equation (2) (DV: lnGDP)			Equation (3) (DV: lnGDP)			Equation (4) (DV: lnGDP)			Equation (5) (DV: lnPRO)			Equation (6) (DV: lnCON)		
	FE	RE	GMM	FE	RE	GMM	FE	RE	GMM	FE	RE	GMM	FE	RE	GMM
lnGDP (L1)	-	-	0.711*** (0.003)	-	-	0.716*** (0.023)	-	-	0.713*** (0.022)	-	-	-	-	-	-
lnPRO (L1)	-	-	-	-	-	-	-	-	-	-	-	0.717*** (0.025)	-	-	-
lnCON(L1)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.670 (0.025)
lnGDP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
lnCAP	0.404*** (0.022)	0.458*** (0.025)	0.211*** (0.014)	0.416*** (0.024)	0.473*** (0.026)	0.210*** (0.014)	0.369*** (0.023)	0.438*** (0.025)	0.208*** (0.013)	7.711*** (1.323)	1.725 (1.085)	0.938** (0.468)	6.593*** (1.300)	0.567 (0.983)	- 0.390 (0.422)
lnLAB	0.467*** (0.097)	0.433*** (0.032)	0.082*** (0.022)	0.569*** (0.095)	0.434*** (0.032)	0.066*** (0.016)	0.617*** (0.070)	0.435*** (0.029)	0.088*** (0.019)	- 3.316*** (0.690)	- 1.298* (0.773)	- 0.557* (0.297)	- 3.639*** (0.684)	- 1.082 (0.728)	0.294 (0.272)
lnGF	0.025 (0.018)	0.053*** (0.019)	0.014 (0.009)	0.005 (0.020)	0.044*** (0.022)	0.019* (0.010)	0.089*** (0.015)	0.102*** (0.016)	0.005 (0.08)	0.662* (0.360)	1.022*** (0.338)	0.002 (0.135)	2.168*** (0.351)	1.579*** (0.301)	0.147 (0.259)
lnPRO	0.019*** (0.003)	0.015*** (0.003)	- 0.001 (0.002)	-	-	-	-	-	-	-	-	-	-	-	-
lnCON	-	-	-	0.018*** (0.004)	0.014*** (0.004)	- 0.003 (0.002)	-	-	-	-	-	-	-	-	-
_CONS	7.189*** (0.254)	6.269*** (0.232)	1.009*** (0.136)	7.064*** (0.258)	6.212*** (0.240)	0.950*** (0.142)	6.469*** (0.200)	5.904 (0.196)	1.095*** (0.138)	- 87.34*** (9.624)	- 17.85*** (5.485)	- 4.522* (2.612)	- 76.76*** (9.424)	- 12.768*** (4.585)	0.145 (2.227)
Obs	208	208	207	204	204	204	242	242	231	208	208	197	204	204	192

Source: Author's explanation. Notes: DV refers to dependent variables, FE refers to fixed effects, and RE refers to random effects. ***, **, and * refer to the 99%, 95%, and 90 significance levels, respectively. L1 refers to the lagged value of 1. Discussion and policy implications

energy sector. For example, increased capital formation has led to new investments crucial for expanding the nation's existing ethanol distribution network. Second, alongside production, the consumption of biofuels should be emphasized over fossil fuels as a key factor in promoting sustainable and environmentally friendly economic development, given the significant impact of economic growth on environmental sustainability. Third, this study highlights the importance of enhancing green financing, particularly in supporting biofuel and other renewable energy projects. In this context, EU countries can incentivize green financing through secure private investment initiatives. Furthermore, this study underscores the importance of government support for advanced biofuels derived from lignocellulosic feedstocks, nonfood crops, or industrial waste and residue streams that have minimal land-use impact. Maintaining tax policies that incentivize the high-tech biofuel industry is essential. National governments can further promote biofuel energy adoption by offering tax breaks to companies engaged in biofuel production and utilization.

Furthermore, green financing has a greater impact on promoting biofuel consumption than on promoting biofuel production. This finding suggests that production requires substantial structural development and technological adoption, which may not be fully supported by private financing alone. Government interventions and public funding may be necessary to complement these efforts. Additionally, production systems tend to respond more slowly to financial incentives, whereas consumption reacts more quickly to various financing initiatives. Moreover, production faces significant barriers, including regulatory constraints, infrastructure requirements, and resource availability, whereas consumption encounters fewer obstacles. Unlike production, which requires strong multifaceted support—including regulatory measures and policy-driven incentives—consumption can be influenced more easily by financial incentives alone.

In conclusion, this research emphasizes the need for concerted efforts by relevant authorities to achieve sustainable economic development. It calls upon policymakers to implement supportive energy policies that foster both economic growth and sustainability.

Conclusion

This study investigates the impact of both bioethanol and biodiesel production and consumption on economic growth, initially focusing on the European Union as the research area. I subsequently narrowed the scope to 11 countries due to data availability constraints. The countries included in this study are Austria, Belgium, Germany, Spain, Finland, Italy, France, the Netherlands, Portugal, Poland, and Sweden. To explore these relationships, I employ nonstationary panel data modeling techniques, including panel unit root tests, panel cointegration tests, fully modified ordinary least squares, and dynamic ordinary least squares, using data spanning from 2001–2022. My analysis, with the economic growth of EU countries as the dependent variable, reveals that both the production and consumption of biofuels have a significant impact on economic growth. However, it is worth noting that biofuel production has a greater impact than biofuel consumption, with production having a approximately 20% larger effect on the European Union economy. Additionally, the regional economic heterogeneity experiment revealed that both biofuel production and consumption are insignificant in the Group

1 regression. However, biofuel production and green finance have a positive and significant effect on economic growth in Group 2.

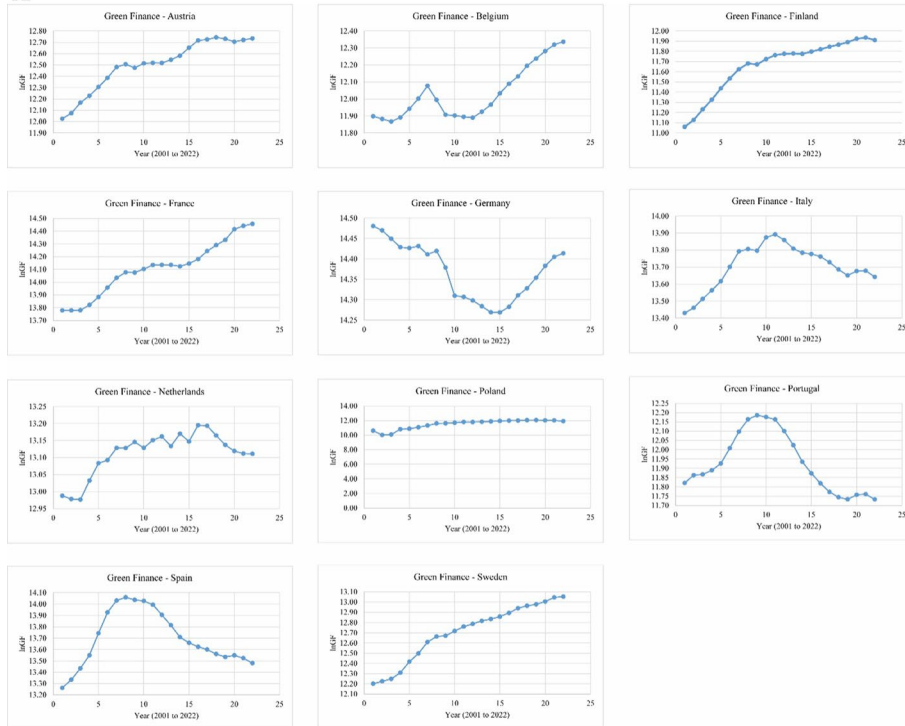
In conclusion, the bioeconomy plays a noteworthy role in the economic aspects of the European Union. Additionally, investment in the private sector is found to have a significant effect on economic expansion. This study offers significant contributions to the literature. First, it highlights the importance of biofuels, both in terms of production and consumption, for fostering economic growth in the European Union. Additionally, our research underscores the notion that prioritizing the development of biofuels is essential for effective biofuel consumption. The consumption of biofuels can yield significant benefits only when paired with robust biofuel production. Moreover, our study contributes to emphasizing the importance of biofuel production and consumption for other growing European Union countries. Ultimately, this research not only enriches the EU economics literature but also enhances our understanding of global biofuel research.

This research has two specific limitations that should be addressed in future studies. The first limitation is the unavailability of biofuel data prior to 2001, resulting in a limited number of sample European Union countries. However, this limitation is acceptable, as other notable studies have also used restricted datasets in terms of years and countries.¹ The second limitation is related to the proxy for green finance. Country-level panel data on green finance are still in their early stages. Consequently, this study could not use direct green finance data and instead relied on a proxy to represent green finance. Considering these limitations, future research should employ more robust analyses with larger sample sizes and longer time periods. Additionally, experimental comparative studies could highlight the contribution of biofuels in regions beyond the European Union. In addition to the economic impacts, exploring the environmental effects of green financing and biofuel development is crucial. Moreover, this study suggests examining the lagged impact via large datasets, particularly for production. Financing in a given year may influence production outcomes in subsequent years.

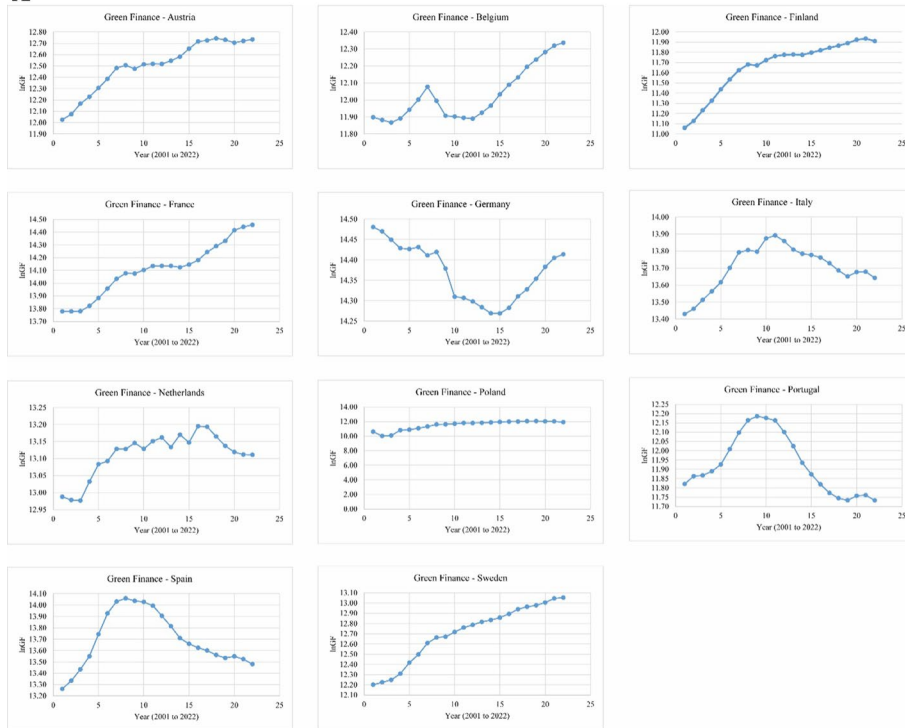
¹ For example, Apergis and Payne (2010b) used data from 13 countries over 15 years, from 1992 to 2007.

Appendix Appendix 1A

A

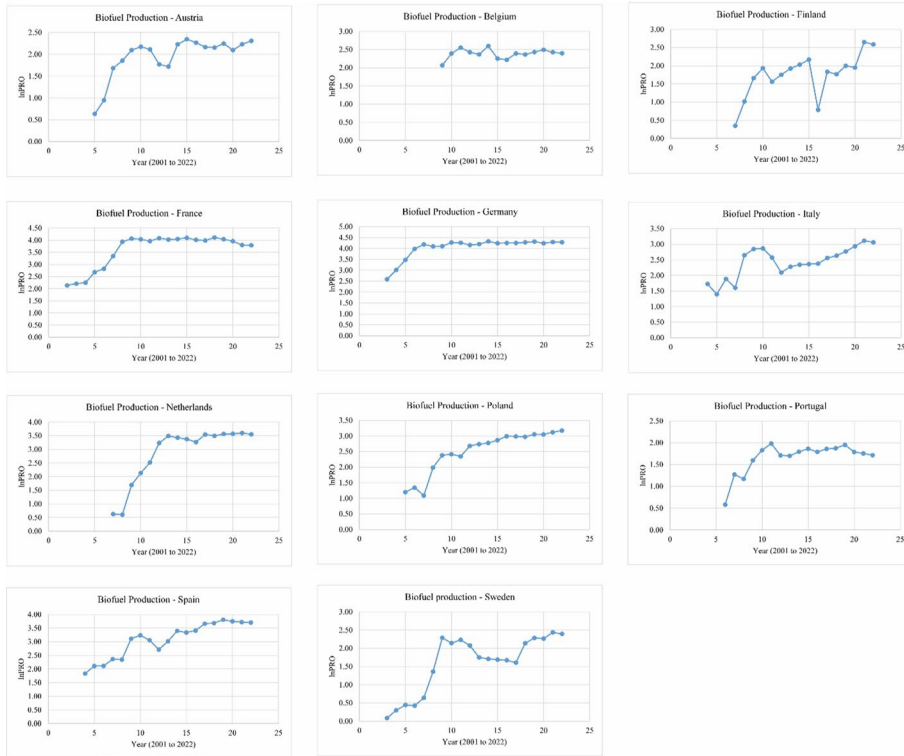


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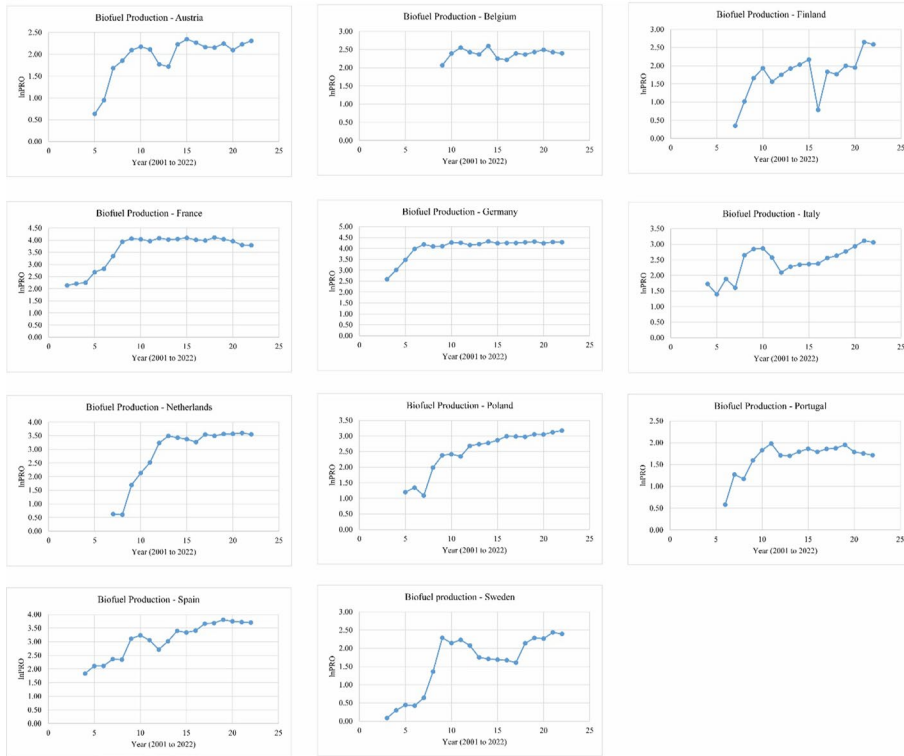


Appendix 1B

B

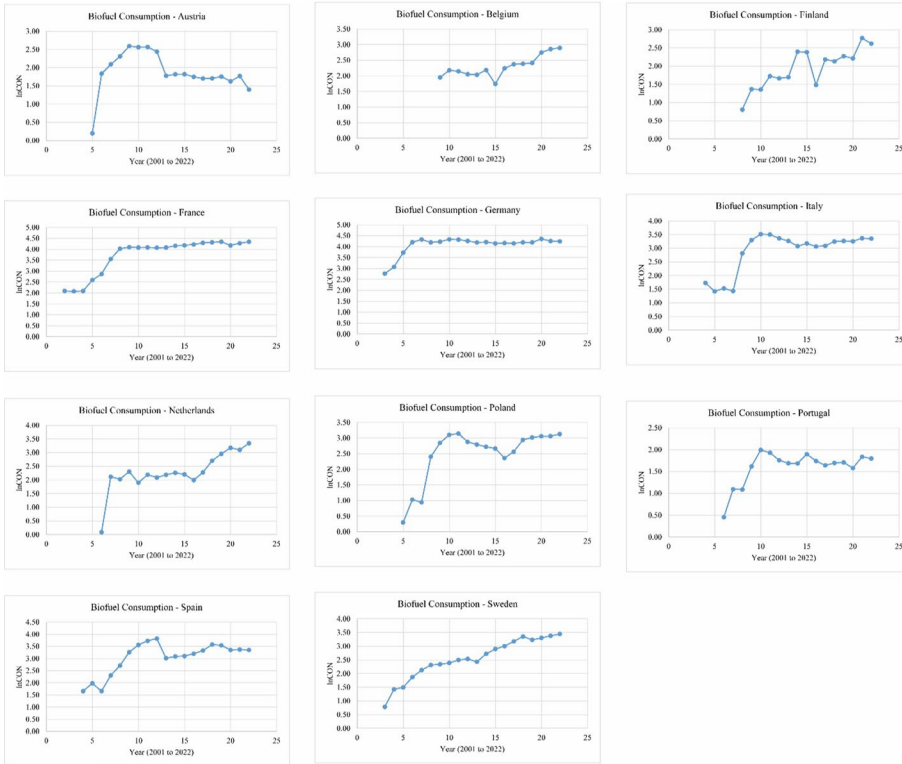


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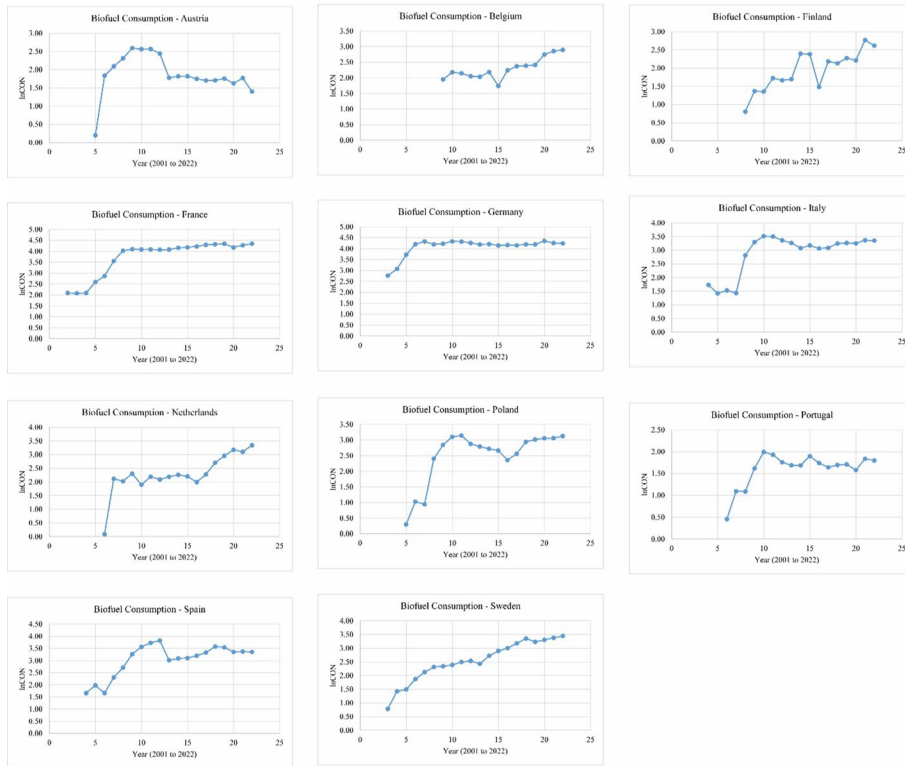


Appendix 1C

C



C



Appendix 2: Cross-sectional dependency

Variable	CD-test
lnGDP	21.79***
lnCAP	17.33***
lnLAB	15.39***
lnGF	2.98***
lnPRO	21.63***
lnCON	18.6***

Author's experiment

Appendix 3: Pairwise granger causality tests

Null Hypothesis	Obs	F-Statistic
lnCAP → lnGDP	220	5.460***
lnGDP → lnCAP	220	5.598***
lnLAB → lnGDP	220	2.892*
lnGDP → lnLAB	220	2.047
lnGF → lnGDP	220	6.387***
lnGDP → lnGF	220	18.348***
lnPRO → lnGDP	186	0.097

Null Hypothesis	Obs	F-Statistic
lnGDP → lnPRO		15.185***
lnCON → lnGDP	180	0.225
lnGDP → lnCON		10.698***
lnLAB → lnCAP	220	2.569
lnCAP → lnLAB		4.459***
lnGF → lnCAP	220	2.529
lnCAP → lnGF		21.739***
lnPRO → lnCAP	186	0.317
lnCAP → lnPRO		15.411***
lnCON → lnCAP	180	1.675
lnCAP → lnCON		11.438***
lnGF → lnLAB	220	7.938***
lnLAB → lnGF		12.119***
lnPRO → lnLAB	186	1.438
lnLAB → lnPRO		12.289***
lnCON → lnLAB	180	0.678
lnLAB → lnCON		8.939***
lnPRO → lnGF	186	1.789
lnGF → lnPRO		12.341***
lnCON → lnGF	180	1.079
lnGF → lnCON		11.111***
lnCON → lnPRO	179	0.544
lnPRO → lnCON		2.256

Author’s experiment. Notes: Sample—2001–2022, Lags—2

Appendix 4: Re-estimation of Table 9 with green bonds (replacement of green finance)

Appendix 4 presents the re-estimation outputs of Eqs. (4)–(6). These equations are also transformed into new equations, Eqs. (7)–(9). The only change in Eqs. (7)–(9) is the replacement of green finance with green bonds. This study analyzes whether green bonds effectively represent green finance. However, owing to data limitations, this study suggests that these findings should not be considered definitive or used as a basis for future research.

$$\ln\text{GDP}_{it} = \beta_0 + \beta_1 \ln\text{CAP}_{it} + \beta_2 \ln\text{LAB}_{it} + \beta_3 \ln\text{GF}_{it} + \epsilon_{it} \tag{7}$$

$$\ln\text{PRO}_{it} = \beta_0 + \beta_1 \ln\text{GDP}_{it} + \beta_2 \ln\text{CAP}_{it} + \beta_3 \ln\text{LAB}_{it} + \beta_4 \ln\text{GB}_{it} + \epsilon_{it} \tag{8}$$

$$\ln\text{CON}_{it} = \beta_0 + \beta_1 \ln\text{GDP}_{it} + \beta_2 \ln\text{CAP}_{it} + \beta_3 \ln\text{LAB}_{it} + \beta_4 \ln\text{GB}_{it} + \epsilon_{it} \tag{9}$$

Variables	Equation (7) (DV—lnGDP)	Equation (8) (DV—lnPRO)	Equation (9) (DV—lnCON)
lnGDP		− 1.473* (0.830)	0.317 (0.929)
lnCAP	0.352*** (0.013)	0.864* (0.500)	0.557 (0.436)

Variables	Equation (7) (DV—lnGDP)	Equation (8) (DV—lnPRO)	Equation (9) (DV—lnCON)
lnLAB	0.850*** (0.067)	4.806*** (1.652)	5.849*** (0.953)
lnGB	− 0.004*** (0.001)	0.050** (0.023)	0.022 (0.015)
Obs	64	64	64
R-sqr	0.998	0.970	0.967

Author's explanation. DV refers to the dependent variable. In the FMOLS model: Trend specification: Constant (Level); Additional trends: None; Lag specification: None; Kernel option: Bartlett; Bandwidth method: Newey–West Fixed; Panel method: Pooled; Heterogeneous first-stage long-run coefficients: No; Coefficient covariance matrix: sandwich (heterogeneous variances). ***, **, and * refer to the 99%, 95%, and 90 significance levels, respectively.

Abbreviation

EU	European Union
RQ	Research questions
BRICS	Brazil, Russia, India, China, South Africa
CO ₂	Carbon dioxide
OECD	Organization for Economic Cooperation and Development
ARDL-PMG	Panel-Pooled mean group-autoregressive distributive lag
FMOLS	Fully modified ordinary least squares
DOLS	Dynamic ordinary least squares

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Author contributions

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Data availability

The data will be available on request.

Declarations

Competing interests

There is no competing interest, because I am the sole author.

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