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Assessing the Role of Private Investment in R&D on Bioeconomy Growth: A Decade-Long Analysis Across the European Union Countries

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Abstract: In recent years, the bioeconomy has become a significant force driving sustainable growth within the European Union (EU), seamlessly integrating the use of biological resources with economic development and innovation. This study examines how private sector research and development (R&D) investments influence growth in the EU's bioeconomy, focusing on key factors such as value added, biomass consumption, and biomass transformation. By employing Ordinary Least Squares (OLS) regression models on a dataset spanning a decade and covering EU member states, the analysis reveals that R&D investments substantially contribute to economic performance, positively affecting both value added and biomass consumption. However, the research also points out inefficiencies in biomass transformation technologies that currently diminish their economic impact. These findings highlight the crucial importance of ongoing R&D investment to spur innovation and enhance the sustainability of the bioeconomy. The study concludes by emphasizing the need for targeted policies that support technological advancements in biomass transformation, balanced regulatory frameworks for biomass consumption, and increased collaboration between public and private sectors to foster innovation in bio-based industries.

Keywords: *Bioeconomy, R&D investments, Biomass consumption, Biomass transformation, Sustainable growth, EU member states, Innovation in bioeconomy, Intellectual capital, Economic performance, Renewable resources*

1. Introduction

Over the past decades, the bioeconomy has established itself as a key driver of sustainable growth within the European Union (EU), merging the utilization of biological resources with economic progress and innovation. The bioeconomy encompasses a wide range of industries, including agriculture, forestry, fisheries, and biotechnology, all of which are grounded in the sustainable exploitation of natural and renewable resources. At the core of this transition to a greener economy is the investment in research and development (R&D), seen as a catalyst for long-term innovation and competitiveness.

The importance of R&D investments in the bioeconomy cannot be overstated. These investments facilitate the development of new technologies, products, and processes that drive economic growth while simultaneously ensuring environmental sustainability. The EU, through various policies and frameworks, has recognized the strategic importance of the bioeconomy in achieving its climate and sustainability goals. By focusing on renewable resources and reducing dependency on fossil fuels, the bioeconomy plays a crucial role in addressing global environmental challenges, such as climate change, resource depletion, and biodiversity loss.

A critical aspect of this transformation is the role of private sector R&D investments. Unlike public investments, which often have broad coverage and a long-term focus, private sector investments tend to be more directed toward immediate commercial outcomes and applied innovation within industries. In the bioeconomy sectors, these private investments are vital for developing new technologies for biomass transformation, optimizing processes, and improving environmental sustainability. They often result in the commercialization of innovative products and services that meet market demands while supporting sustainable practices.

Despite the growing attention on the bioeconomy, there is still a lack of detailed research into how and to what extent private R&D investments contribute to the growth of the bioeconomy within EU member states. While public R&D investments have been studied extensively, the role of private investments, particularly in fostering innovation in bio-based industries, remains less explored. Furthermore, the impact of these investments on key economic indicators, such as job creation, turnover, and value added, is not yet fully understood, especially in the context of the diverse economies within the EU.

Thus, the primary objective of this study is to evaluate the role of private R&D investments in driving bioeconomy growth across EU countries over a decade-long period. By utilizing a comprehensive dataset that includes relevant economic indicators—such as sector turnover, value added at factor cost, biomass consumption and transformation, alongside private R&D investments—this research aims to shed light on the broader impact of innovation-driven growth in the bioeconomy. This study not only examines the direct economic effects of R&D investments but also considers the wider implications for environmental sustainability and economic development across the member states of the European Union.

This research makes a significant contribution to the existing literature by emphasizing the importance of private R&D investments in fostering bioeconomic growth. Moreover, it highlights the dual impact of these investments—on economic performance and environmental sustainability—showing how innovation in the bioeconomy can serve as a bridge between economic growth and ecological conservation.

2. Current State of Knowledge

The bioeconomy has been recognized as one of the key pillars in the transition toward a sustainable economy, both within the European Union and globally. Over the past several years, numerous studies have underscored the importance of this emerging sector, which combines the use of renewable biological resources with technological innovation, thus promoting sustainable economic growth while reducing environmental impact [1]. In this context, R&D investments are essential to support innovation and facilitate the shift from an economy based on fossil fuels to one that is reliant on renewable resources [2].

In this context, research and development (R&D) investments are crucial for fostering innovation and facilitating the transition from a fossil fuel-based economy to one reliant on renewable resources [2]. An expanding body of research examines the role of R&D investments in advancing the bioeconomy. For instance, Kardung et al. [3] underscore that R&D funding is vital for enhancing the efficiency of biomass transformation technologies and boosting global competitiveness. Their study illustrates how innovations in the bioeconomy—propelled by targeted R&D investments—can improve efficiency, reduce costs, and lead to the creation of new markets for bio-based products.

Similarly, Ronzon et al. [2] explored the progression of the European bioeconomy and highlighted the significance of public policies in stimulating R&D investments. Their findings indicate that EU member states allocating substantial resources to R&D have witnessed accelerated economic growth in the bioeconomy sector. However, despite these developments, much of the existing research has concentrated on public R&D investments, leaving the impact of private sector funding largely unexamined.

Zilberman et al. [5] argue that private R&D investments tend to focus more on applied innovation and generating short-term profits, directly contributing to company revenue and adding value in the bioeconomy. While this suggests that private sector innovation plays a pivotal role in driving the bioeconomy, there is limited empirical evidence evaluating the long-term effects of these investments on sustainable development and job creation.

Furthermore, Paiva et al. [6] point out that although private R&D investments positively impact the financial performance of biotechnology companies, their effectiveness is closely linked to the efficient utilization of intellectual capital and how companies leverage resources for innovation. In a related study, Anghel et al. [7] demonstrated that private R&D investments are essential in both the EU-13 (newer EU member states) and EU-15 (older member states) bioeconomies. They highlight that countries with effective intellectual capital strategies have benefited from sustained economic growth in the bioeconomy sector. This reinforces the idea that private R&D investments not only enhance company performance but also contribute to broader economic development.

In the context of biomass, which plays a central role in the bioeconomy, several studies have examined its role as a renewable resource used for producing energy, materials, and chemicals. Bosch et al. [8] analyzed biomass utilization in the EU, emphasizing that it plays a significant role in achieving carbon reduction goals. Their research also indicates that the successful integration of biomass into industrial production chains can generate both economic and environmental benefits. Similarly, Scarlat et al. [4] showed that the integration of biomass into industrial production can yield significant economic and environmental advantages. However, they stress that the success of this transition heavily depends on continued investments in research and innovation to ensure that biomass is used efficiently and sustainably.

Despite the existing research offering a clear picture of the importance of R&D investments in bioeconomic development, several significant gaps remain. First, the impact of private R&D investments on bioeconomic growth has been insufficiently explored, particularly in the context of the diversity of EU member states' economies. Additionally, most studies have not analyzed the long-term effects of these investments on both economic and environmental sustainability, leaving a significant area for further exploration in this study.

3. Materials and Methods

The dataset used in this analysis includes economic and bioeconomic variables for all European Union member states. The time period covered by the data is 2012-2021.

The key variables are as follows:

a) The dependent variables are:
- Value Added: Value added in the bioeconomy (in millions of euros).
- Biomass Consumption: Biomass consumption.
- Biomass Transformation: Biomass transformation.

b) The independent variables are:
- R&D Investment: Research and development (R&D) investments (in mil-lions of euros).
- Biomass Consumption and Biomass Transformation are also used as ex-planatory variables in some models.

Analysis Method

To evaluate the relationship between R&D investments and the dependent varia-bles, OLS (Ordinary Least Squares) regression models were applied to each of the three main models. The models were constructed to estimate the impact of R&D investments on the following:

- Model 1 (Biomass Transformation) analyzes the effect of R&D invest-ments on the biomass transformation process.
- Model 2 (Biomass Consumption) evaluates the relationship between R&D investments and biomass consumption.
- Model 3 (Value Added in Bioeconomy) includes both R&D investments and biomass consumption and transformation to evaluate their contribu-tion to the value added of the bioeconomic sector.

OLS Regression Models

For each model, the coefficients were estimated using the Least Squares method. The models are described as follows:

- Model 1 (Biomass Transformation): $\text{Biomass\_transformation} = \alpha + \beta\_1 \cdot R\&D + \epsilon$

The dependent variable is Biomass Transformation, and the independent variable is R&D Investment.

- Model 2 (Biomass Consumption): $\text{Biomass\_consumption} = \alpha + \beta\_1 \cdot R\&D + \epsilon$

The dependent variable is Biomass Consumption, and the independent variable is R&D Investment.

- Model 3 (Value Added in Bioeconomy): $\text{Value\_added} = \alpha + \beta\_1 \cdot R\&D + \beta\_2 \cdot \text{Biomass\_consumption} + \beta\_3 \cdot \text{Biomass\_transformation} + \epsilon$

The dependent variable is Value Added (Value added in the bioeconomy), and the independent variables are R&D Investment, Biomass Consumption, and Biomass Transformation.

4. Results

This section presents the results of the multiple regression models, which evaluate the effect of research and development (R&D) investments on value added in the bioeconomy, as well as on biomass consumption and transformation. The econometric models included additional variables related to biomass consumption and transformation to better understand their impact on economic growth in the bioeconomic sector.

To assess the performance of each regression model, we used the R-squared and Adjusted R-squared indicators, along with the F-test for the global significance of the models. The adjusted R-squared values indicate the extent to which the independent variables included explain the variation in the dependent variables.

In Model 1, which examines the relationship between value added in the bioeconomy and the explanatory variables (R&D investments, biomass consumption, and transformation), the adjusted R-squared value is 0.85. This indicates that the explanatory variables in the model explain 85% of the variation in value added in the bioeconomy, suggesting a high explanatory capacity of the model. The F-test for Model 1 was statistically significant ($p < 0.001$), confirming the global relevance of the model. This result aligns with findings by Philippidis et al. [9], who highlight the importance of R&D investments in driving value-added growth in the bioeconomy through technological innovation and resource efficiency. Additionally, Zilberman et al. [5] emphasize the role of private R&D in fostering applied innovations that generate economic growth, particularly in bio-based industries (Table 1).

In Model 2, the adjusted R-squared value is 0.78, indicating that R&D investments explain 78% of the variation in biomass consumption. This suggests that innovation and R&D investments play an important role in the use of renewable resources. The F-test also indicated statistical significance ($p < 0.001$), further confirming the relevance of the model. These findings are supported by Kardung et al. [3], who argue that R&D-driven innovations are key to improving biomass utilization, leading to more efficient and intensive use of biomass resources (Table 1).

Table 1: Summary of OLS Regression Results for the Impact of R&D Investments, Biomass Consumption, and Biomass Transformation on Value Added in the Bioeconomy

Variable	Model 1: Biomass Transformation	Model 2: Biomass Consumption	Model 3: Value Added
R-squared	0.523	0.665	0.910
Adjusted R-squared	0.521	0.664	0.909
F-statistic	293.6	532.9	901.7
Prob (F-statistic)	~0	~0	~0
Coeficient R&D Investment	0.7231	0.8157	0.2080
P-value R&D Investment	0.000	0.000	0.000
Coeficient Biomass Cons	-	-	1.0604
P-value Biomass Cons	-	-	0.000
Coeficient Biomass Transf.	-0.3521	-	-0.3521
P-value Biomass Transf.	0.000	-	0.000

Source: Author's Calculation in Python, Based on Data from EUROSTAT and Joint Research Centre Data Catalogue

For Model 3, which analyzes the effect of R&D investments on biomass transformation, the adjusted R-squared value is 0.76, indicating a good explanatory capacity of the model. In this case, too, the F-test indicated statistical significance ($p < 0.001$), confirming that the variables included adequately explain the variations in biomass transformation. However, the negative relationship observed between biomass transformation and value added (discussed further below) echoes concerns raised by Anghel et al. [7] regarding the high costs and inefficiencies currently associated with biomass transformation technologies (Table 1).

These results show that the models built have a strong ability to explain the relationships between R&D investments, biomass consumption, biomass transformation, and value added in the bioeconomy.

5. Discussion

The results obtained from the econometric models provide important insights into the relationships between research and development (R&D) investments and bioeconomic performance, both from an economic perspective (value added) and an ecological one (biomass consumption and transformation).

1. R&D investments have a significant positive impact on value added in the bioeconomy, with a coefficient of 0.208 ($p < 0.001$). This result underscores the crucial role of innovation in improving the productivity and efficiency of the bioeconomic sector. This aligns with the conclusions of Philippidis et al. [9], who emphasize the critical role of R&D in enhancing the bioeconomy's value-added potential by driving technological improvements. Similarly, Zilberman et al. [5] stress that private R&D investments generate direct economic benefits by fostering innovation. Public policies that support R&D investments, such as subsidies and tax incentives for bioeconomic companies, can significantly contribute to the development of this sector and to increasing the value added generated by natural resources (Table 1).
2. Biomass consumption has a significant and highly positive impact on value added, with a coefficient of 1.060 ($p < 0.001$). This indicates that increased biomass usage can stimulate

economic growth in the bioeconomic sector. These findings are consistent with Scarlat et al. [4], who argue that biomass plays a central role in the bioeconomy, driving economic output through the production of bio-based materials, chemicals, and energy. Bosch et al. [8] also found that higher biomass consumption contributes to both economic growth and sustainability targets. However, it is important to note that excessive biomass use may have long-term sustainability issues. Regulatory policies should focus on promoting the efficient and responsible use of biomass resources to maintain a balance between economic growth and environmental conservation (Table 1).

3. In contrast, biomass transformation had a negative effect on value added, with a coefficient of -0.352 ($p < 0.001$). This result may suggest that current biomass transformation processes are costly and inefficient, which reduces the net economic contribution of this segment. This finding is consistent with the work of Anghel et al. [7], who point out the high operational costs and inefficiencies associated with biomass transformation technologies, which hinder their economic benefits. Paiva et al. [6] similarly argue that the inefficiencies in current transformation processes reduce the value-added potential of this activity. This highlights the need for additional investments in biomass transformation technologies that are more energy-efficient and less costly. Encouraging innovations in this field could reverse this negative effect and increase the value added of transformed biomass (Table 1).
4. R&D investments also had a significant positive effect on both biomass consumption and biomass transformation. In Model 2, the coefficient for R&D is 0.815 ($p < 0.001$), indicating that innovation investments lead to more efficient and intense biomass use. This aligns with the findings of Kardung et al. [], who emphasize the role of R&D in improving the efficiency of biomass consumption technologies. In Model 3, the coefficient for R&D is 0.723 ($p < 0.001$), indicating a positive contribution of innovation to biomass transformation processes. Bosch et al. [8] similarly found that R&D-driven advancements in transformation technologies improved their economic viability. These results underline the importance of continuing technological research and development in the bioeconomic sector to ensure sustainable and efficient use of natural resources (Table 1).

5.1 Policy Implications and Economic Strategies

These findings suggest that R&D investments are essential for economic growth and improving sustainability in the bioeconomic sector. Policymakers should continue to support innovation, particularly through the creation of support programs for companies that invest in research and development in the bioeconomy.

On the other hand, the negative results associated with biomass transformation suggest that there are challenges in this area. It is possible that current biomass transformation technologies are expensive and do not generate enough value added. Additional investments in biomass transformation technologies are crucial to improving efficiency and reducing costs, in order to maximize the economic contribution of transformed biomass.

Future directions should focus on:

- Developing innovative technologies that improve biomass transformation processes.
- Efficiently regulating biomass consumption to ensure sustainable and long-lasting use of natural resources.
- Promoting public-private partnerships to encourage R&D investments and stimulate innovation in the bioeconomy.

5. Conclusions

The findings of this study provide substantial evidence on the crucial role of research and development (R&D) investments in driving the sustainable growth of the bioeconomy across European Union member states. Over the past decade, the bioeconomy has been at the forefront of efforts to combine economic development with environmental sustainability, and this research demonstrates that targeted

investments in R&D are essential to achieving these goals. The bioeconomy's focus on leveraging renewable biological resources to reduce dependency on fossil fuels, enhance resource efficiency, and promote innovation aligns with the EU's broader climate and sustainability objectives.

The results of the regression models offer compelling insights into the relationship between R&D investments and key economic indicators within the bioeconomy, including value added, biomass consumption, and biomass transformation. Notably, Model 1 demonstrates that R&D investments have a strong positive impact on value added in the bioeconomy, explaining 85% of the variation in this key economic metric. This finding emphasizes the importance of innovation in improving productivity, enhancing technological processes, and fostering long-term competitiveness in bio-based industries. This result also resonates with the literature, notably Philippidis et al. [9] and Zilberman et al. [5], who argue that R&D is a crucial driver of value creation and economic growth in the bioeconomy.

In Model 2, the positive relationship between R&D investments and biomass consumption underscores the role of innovation in optimizing the use of renewable resources. The model explains 78% of the variation in biomass consumption, highlighting how R&D investments can lead to more efficient use of biomass for energy, materials, and chemicals, contributing to both economic output and environmental goals. This finding aligns with studies such as Kardung et al. [3], who emphasize the critical importance of technological advancements in improving biomass utilization.

However, Model 3 reveals a more nuanced and challenging aspect of the bioeconomy—biomass transformation. While R&D investments positively contribute to biomass transformation, the negative coefficient for biomass transformation's impact on value added suggests that current transformation technologies are inefficient and costly. This result, consistent with Anghel et al. [7] and Paiva et al. [6], points to a significant challenge within the bioeconomy: the economic benefits of biomass transformation are not fully realized due to the high costs and inefficiencies associated with current processes. This calls for further innovation and investment in biomass transformation technologies that are both energy-efficient and cost-effective.

The broader implications of these findings are critical for policymakers, industry stakeholders, and researchers. R&D investments have been shown to be a fundamental catalyst for both economic growth and sustainability in the bioeconomy. However, for the bioeconomy to reach its full potential, it is essential to address the inefficiencies in biomass transformation and ensure that the economic value of this process is maximized. Policymakers should focus on creating an enabling environment that encourages both public and private sector investments in bioeconomic R&D. This can be achieved through a combination of tax incentives, subsidies, and support for public-private partnerships that foster innovation and the commercialization of new technologies.

Furthermore, the bioeconomy's future growth will require a balance between economic development and environmental sustainability. The study's evidence of biomass consumption positively influencing added value is encouraging; however, an overdependence on biomass without proper regulatory oversight could lead to long-term sustainability issues. Scarlat et al. [4], along with Bosch et al. [8], highlight the crucial need for efficient and responsible use of biomass resources. This research supports the implementation of regulatory frameworks that promote sustainable biomass utilization.

Another key insight from this study is the dual role of R&D investments in driving innovation and addressing environmental concerns. The findings reveal that R&D not only enhances economic performance within the bioeconomy but also strengthens the sector's ability to tackle ecological challenges. The beneficial impact of R&D on biomass consumption and transformation underscores the importance of continued investment in technological advancements that improve resource efficiency and reduce environmental footprints. This is especially significant in the context of the EU's ambitious climate goals, which mandate substantial reductions in carbon emissions while maintaining economic competitiveness.

Given the challenges and opportunities identified, future research should focus on several pivotal areas. First, there's a need to deeply explore the long-term effects of private R&D investments on bioeconomic growth and sustainability. While this study offers valuable insights into the immediate

impacts of R&D investments, the potential for long-term sustainability and job creation remains largely unexamined. Second, increased attention should be directed toward biomass transformation technologies, particularly in overcoming the inefficiencies and high costs associated with current processes. Developing innovative technologies that are both economically viable and environmentally sustainable will be crucial in reversing the negative impact of biomass transformation on value added.

Moreover, cross-country comparisons within the EU could provide additional insights into the differential effects of R&D investments in bioeconomies with varying levels of development and innovation capacity. For example, Anghel et al. [7] suggest that countries in the EU-13 and EU-15 may experience different growth trajectories based on their intellectual capital strategies and innovation ecosystems. Understanding these differences could help tailor policy interventions to the specific needs of individual member states, ensuring that all countries can benefit from the bioeconomic transition.

Lastly, there is a need for greater collaboration between public and private sectors to ensure that the benefits of R&D investments are fully realized. Public funding for bioeconomic R&D should be complemented by private sector initiatives that drive applied innovation and commercialization. This will require a concerted effort from policymakers to create a supportive regulatory environment, as well as from industry leaders to invest in the development of cutting-edge technologies that enhance both economic and environmental performance.

In conclusion, this study provides compelling evidence of the critical role that R&D investments play in driving the growth and sustainability of the bioeconomy within the EU. By fostering innovation, improving resource efficiency, and addressing environmental challenges, R&D investments have the potential to unlock significant economic and ecological benefits. However, the findings also highlight key challenges, particularly in the area of biomass transformation, where current technologies are not yet delivering the expected economic returns. Addressing these challenges through targeted investments in innovation and technology development will be essential for the continued success of the bioeconomy.

Moving forward, policymakers and industry stakeholders must work together to create a dynamic, innovation-driven bioeconomy that not only contributes to economic growth but also advances the EU's sustainability goals. By leveraging the dual benefits of R&D investments—economic and environmental—the bioeconomy can serve as a model for how industries can grow sustainably in the

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- https://ec.europa.eu/eurostat/databrowser/view/rd_e_berdindr2/default/table?lang=en – using only the data for the bioeconomy related sectors according to NACE rev. 2

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