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TWO ROADS TO A BIOECONOMY: CLUSTERING THE WORLD'S LEADING BIOFUEL PRODUCERS

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ABSTRACT

The global shift towards decarbonization has made biofuels an important transitional energy resource. However, existing assessments often focus on production volume while overlooking differences in national sustainable development strategies. To address this gap, this study examines whether the global biofuel market follows distinct sustainable development pathways. Analysing 22 countries that account for over 90% of global biofuel supply, the study uses time-series forecasting to impute missing data and K-means clustering to group countries based on economic innovation, environmental performance, social dependence, and production scale. The findings identify two main models: an "Agriculture-Driven" model characterized by high labour intensity and an "Innovation-Led" model marked by higher R&D expenditure. Although the two models differ in their socio-economic characteristics, they show no significant differences in production output or transport decarbonization potential. This suggests that high-tech industrialization is not the only requirement for a high-performing bioeconomy. The study therefore emphasizes the need for policies that account for these different development pathways rather than applying a one-size-fits-all approach.

KEYWORDS: *Biofuel Production; Sustainable Development Pathways; K-means Clustering; Agricultural Employment; R&D Innovation.*

1. INTRODUCTION

As the global energy sector moves towards decarbonization, biofuels have become an important transitional resource, particularly in sectors that are difficult to electrify, such as aviation and heavy shipping (International Energy Agency, 2023; International Renewable Energy Agency, 2024). However, treating the global biofuel sector as a uniform industry driven by a single idea of sustainability is an oversimplification. Although reducing carbon emissions is a global objective, the political and economic factors shaping biofuel production differ across countries (Hodbod and Tomei, 2013). Some countries view biofuels as a high-tech strategy for energy independence and transport modernization, while others, particularly in the Global South, use them to promote rural development, reduce poverty, and create agricultural employment (Arshad et al., 2018; Mathews, 2007). These differences suggest that the global market consists of distinct sustainable development pathways, shaped by varying combinations of economic innovation, social dependence, and environmental impact.

Recent studies also describe the global biofuel sector as fragmented into different development pathways shaped by national priorities. The literature identifies two broad approaches: one focused on socio-economic development (SDG 1: No Poverty; SDG 2: Zero Hunger) and another focused on energy industrialization and climate mitigation (SDG 7: Affordable Energy; SDG 9: Industry; SDG 13: Climate Action). Bastos Lima (2021a) and Rodriguez Morales (2025) argue that these differences create identifiable policy clusters. The "Industrial-Climate" pathway, commonly found in the Global North, including the EU and USA, as well as Brazil, prioritizes large-scale agribusiness and efficiency to support decarbonization. Skogstad and Wilder (2019) and Ziolkowska et al. (2010) describe policies in these regions as "institutional gatekeepers" focused on strict sustainability certification and market stability. However, this approach can produce unintended outcomes, as efforts to achieve SDG 13 may also increase inequality and land concentration (Comineti et al., 2023; Singh and Clough, 2024).

In contrast, the "Socio-Economic" pathway, discussed in studies on India and Eastern Africa by Khan et al. (2025) and Miftah and Mutta (2024), treats biofuels primarily as a tool for rural development. This approach aims to decentralize energy production and involve smallholder farmers. However, Djatmika et al. (2023) caution that weak governance can allow agribusiness interests to dominate, marginalizing the rural communities these policies intend to support. Oladoye et al. (2024) also highlight that regional policy approaches across Africa and the Americas differ in their emphasis on social development and environmental standards, although these differences remain largely qualitative in existing research.

Beyond these policy differences, research shows that biofuel development is also shaped by resource availability and macroeconomic stability. These factors help explain why countries with similar political goals may follow different development pathways. Acharya and Perez-Pena (2020) show that comparative advantages in feedstock production, particularly land and labour availability, may influence policy adoption more strongly than political will alone. Ozturk (2016) similarly identifies a positive relationship between land and labour inputs and production output. Argueyrolles et al. (2025) show through CGE modelling that fiscal subsidies and fossil fuel reforms influence biofuel competitiveness, while Vicente Perin et al. (2025) identify economic freedom and market stability as important conditions for sector growth. Qi et al. (2025) further highlight green finance innovation and economic affluence as factors that help reduce carbon emissions through biofuels. These findings suggest that a country's development pathway depends on the interaction between agricultural employment and its capacity for innovation.

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Technological advances in second-generation (lignocellulosic) and third-generation (algae-based) biofuels also influence these development pathways. Harjanti et al. (2025) and Nath (2024) argue that these technologies could help bridge the gap between the two approaches. By using agricultural residues, advanced biofuels can reduce the conflict between energy production (SDG 7) and food security (SDG 2), potentially allowing countries to pursue industrial development without compromising social welfare (Pramanik et al., 2023; Russo et al., 2025).

However, innovation also faces a "commercialization gap." Datta et al. (2024) and Jha et al. (2024) note that despite their scientific potential, the high costs and infrastructure requirements of advanced biofuels limit their adoption in developing economies. Blay-Roger et al. (2024) and Sani et al. (2024) argue that without targeted R&D expenditure, these technologies may strengthen the advantage of industrialized countries and widen the gap between development pathways. This makes R&D indicators important for distinguishing countries advancing biofuel technology from those relying on traditional feedstocks.

This gap between technological potential and market realities also highlights a limitation in current assessments, including the Statistical Review of World Energy (Energy Institute, 2024a) and REN21 (2024), which mainly evaluate countries based on production volume. Bailis and Baka (2011) note that this focus overlooks the structural differences within the sector, treating countries with different political and economic systems as similar industrial systems. A country achieving high production through labour-intensive, low-efficiency agriculture follows a different path from one relying on capital-intensive, high-R&D refining processes (Ewing and Msangi, 2009; Hettinga et al., 2009). Focusing only on production scale therefore fails to capture the different production archetypes. Understanding these differences is important because policies designed for technology-driven markets may fail or cause unintended social harm when applied to markets dependent on agricultural employment (Dauvergne and Neville, 2010).

This focus on production volume is accompanied by a methodological gap. Despite qualitative evidence of different development pathways and their determinants, few studies have used statistical clustering to test these groupings empirically at the global level. Most recent studies rely on qualitative reviews or descriptive classifications. Acosta-Michlik et al. (2011) proposed a hybrid framework using fuzzy logic to examine trade-offs but did not develop a global country typology. Aguiar et al. (2024) used clustering to study bibliometric trends rather than national performance indicators. Kanzari et al. (2024) used multivariate clustering to identify energy patterns, but their study focused only on Africa. Similarly, Chovancová et al. (2025) applied regression clustering to EU policies, while Whistance et al. (2024) used scenario modelling for the US and Brazil. Neither study covered biofuel-producing countries globally.

Overall, the literature lacks a global typology that combines R&D innovation, production scale, transport decarbonization, and socio-economic factors. This study addresses this gap by using quantitative indicators to identify patterns in the global biofuel sector. It moves beyond the qualitative North-South distinction discussed by Bastos Lima (2021b) and develops a data-based classification of how countries manage the trade-offs between energy security, climate mitigation, and rural development.

Building on this gap, the present study moves beyond production-based rankings to examine the structural characteristics of the world's leading biofuel producers. It focuses on 22 countries accounting for over 90% of global supply and considers four dimensions: innovation, environmental performance, social dependence, and production scale. This approach helps identify the underlying development characteristics of countries that may otherwise appear similar in terms of production output.

The main objective of this study is to determine whether the global biofuel sector can be grouped into distinct development pathways. Rather than assuming a common development model, the study uses unsupervised machine learning to identify natural groupings among countries. It addresses two research questions:

RQ1: Can the global biofuel sector be grouped into distinct sustainable development pathways based on differing national priorities?
RQ2: Which factors primarily distinguish these development pathways?

This study contributes to the existing literature by combining dimensions that have often been examined separately. While previous research has studied the technical efficiency of biofuel production (Hill et al., 2006) and the industry's overall environmental impact (Searchinger et al., 2015), fewer studies have integrated these aspects into a common classification framework. By applying unsupervised clustering to data from 22 leading biofuel-producing countries (Table 1), this study identifies underlying patterns in the global market beyond descriptive statistics. This approach also provides a basis for considering development policies suited to each country's pathway rather than applying the same policies across the Global North and South.

Table 1. Global Biofuels Production by Country

Country	TWh	Country	TWh
United States	452.1	Canada	13.4
Brazil	241.9	Poland	12.4
European Union	180.3	Finland	9.2
Indonesia	108.2	Colombia	8.9
China	44.7	United Kingdom	8.1
Germany	41.3	South Korea	7.9
India	27.6	Belgium	4.8
Argentina	26.6	Austria	4.8
Netherlands	23.0	Portugal	3.7
Thailand	22.4	Australia	1.4
France	21.8	Mexico	0.4
Spain	19.2		

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2. METHODOLOGY

2.1. Data Sources and Variable Selection

This study uses a dataset covering four dimensions of sustainable development in the global biofuel sector: economic innovation, environmental impact, social dependence, and production scale. The analysis covers 22 countries (listed in Table 1) over the period 2019–2022. Together, these countries account for over 90% of global biofuel production, ensuring representation of major production patterns, from established industrial leaders to emerging economies.

The indicators and their respective data sources are as follows:

- **Biofuel Production (Scale):** Measured in Terawatt-hours (TWh), obtained from the Statistical Review of World Energy (Energy Institute, 2024b).
- **R&D Expenditure (Innovation):** Gross domestic expenditure on R&D as a percentage of GDP.
- **Employment in Agriculture (Social):** Agricultural employment as a percentage of total employment.
- **CO_2 Emissions from Transport (Environment):** Transport-sector carbon dioxide emissions (Mt CO_2e).

All socio-economic and environmental indicators were obtained from the World Bank's Development Indicators database (World Bank, 2024).

2.2. Data Pre-processing and Imputation

The biofuel production data were complete for 2019–2022, but some socio-economic indicators had missing values for 2022. These gaps were addressed using predictive imputation. Three time-series models—ETS, ARIMA, and Prophet—were used to forecast the missing values, based on their suitability for short- and medium-term forecasting (Box et al., 2016; Hyndman and Khandakar, 2008; Taylor and Letham, 2018).

The forecasting was performed in R (R Core Team, 2023) using the forecast, prophet, tseries, and lubridate libraries. Model performance was assessed using Mean Absolute Error (MAE), and the model with the lowest error for each indicator was selected to estimate its 2022 values. Thus, the final dataset contains observed values for 2019–2021 and imputed estimates for 2022.

To address differences in variable scales, such as percentages and absolute production values in TWh, all indicators were normalized to a range of [0, 1] using Min-Max normalization.

For indicators where higher values represent positive performance (Biofuel Production, R&D, and Agricultural Employment), the standard formula was applied:

$$X_{norm} = \frac{x - x_{min}}{x_{max} - x_{min}}$$

For CO_2 emissions, where higher values indicate poorer sustainability performance, the normalization was reversed to maintain consistent direction across the dataset:

$$X_{norm} = 1 - \frac{x_{max} - x}{x_{max} - x_{min}}$$

Here, $x$represents the raw value, while x_{min} and x_{max} represent the minimum and maximum values observed in the sample, respectively.

2.3. Analytical Strategy

To examine whether the global biofuel sector can be divided into distinct development pathways (RQ1), this study applies an unsupervised clustering approach. The K-means algorithm (MacQueen, 1967) was used to divide countries into \(k\) non-overlapping groups by minimizing the Within-Cluster Sum of Squares (WCSS).

The optimal number of clusters (\(k\)) was determined using the Elbow Method (Thorndike, 1953), which identifies the point where additional reductions in variance become smaller. The result was then validated through Silhouette Analysis (Rousseeuw, 1987), which evaluates the cohesion and separation of the resulting clusters.

To identify the factors distinguishing these pathways (RQ2), the clusters were compared across the four indicators. First, Levene's Test (Levene, 1960) was used to assess the equality of variances. For variables meeting the homogeneity of variance assumption, Independent Samples t-tests (Student, 1908) were used to compare cluster means.

For variables that did not meet this assumption (\(p<0.05\)), the non-parametric Mann-Whitney U test (Mann and Whitney, 1947) was applied to compare rank sums. Cohen's \(d\) effect sizes were also calculated to assess the practical significance of the differences. The results were interpreted using Cohen's (1988) benchmarks: small (0.2), medium (0.5), and large (0.8) effects.

Finally, Spearman's rank-order correlation (Spearman, 1904) was used to examine the relationships between the indicators. This non-parametric method was selected for its robustness to potential outliers. The strength of the correlations was interpreted using significance levels and Cohen's (1988) guidelines.

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3. RESULTS

3.1. Typology of the Global Biofuel Production System

To examine whether the global biofuel sector follows distinct sustainable development pathways, K-means clustering was performed using the normalized indicators. The optimal number of clusters was determined using a Scree plot (Fig. 1), which showed a clear elbow at $k = 2$. Although further reductions in inertia occurred beyond this point, the two-cluster solution provided the best balance between structural clarity and statistical interpretability.

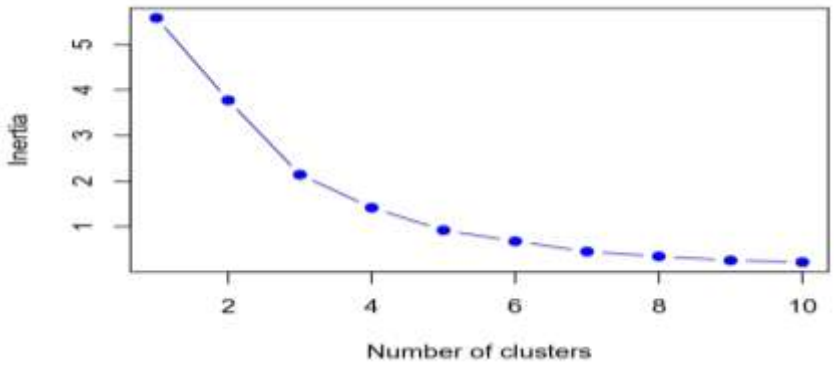


Fig. 1. Determination of the optimal number of clusters using the Scree Plot

The resulting classification divides the 22 countries into two distinct groups (Fig. 2). Cluster 1 ($N = 7$) mainly includes countries from the Global South and transition economies, such as Colombia, Indonesia, and India, characterized by labour-intensive production models. Cluster 2 ($N = 16$) comprises a larger and more diverse group, mainly from the Global North, including the UK, USA, and Germany, along with major emerging producers such as Brazil and China.

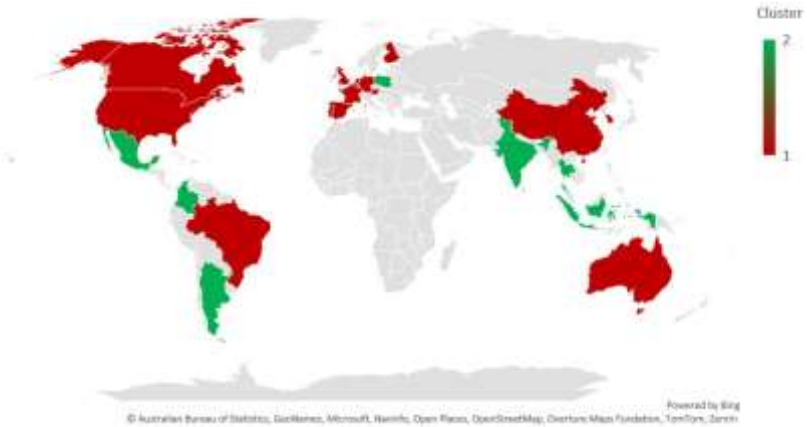


Fig. 2. Geographic distribution of global biofuel archetypes.

Silhouette analysis (Fig. 3) was used to assess the internal cohesion of the clusters, producing an overall average silhouette width of 0.34. Cluster 1 had a higher average silhouette width of 0.41, indicating that the agrarian-transition model is more structurally uniform. In comparison, Cluster 2 had an average silhouette width of 0.32, suggesting greater variation among the industrialized countries. Notably, Brazil and China had negative silhouette widths within Cluster 2. This suggests that although their production scale places them closer to the industrialized group, characteristics such as agricultural dependence also link them to Cluster 1. These countries can therefore be considered hybrid or transitional bio-economies between the two main pathways.

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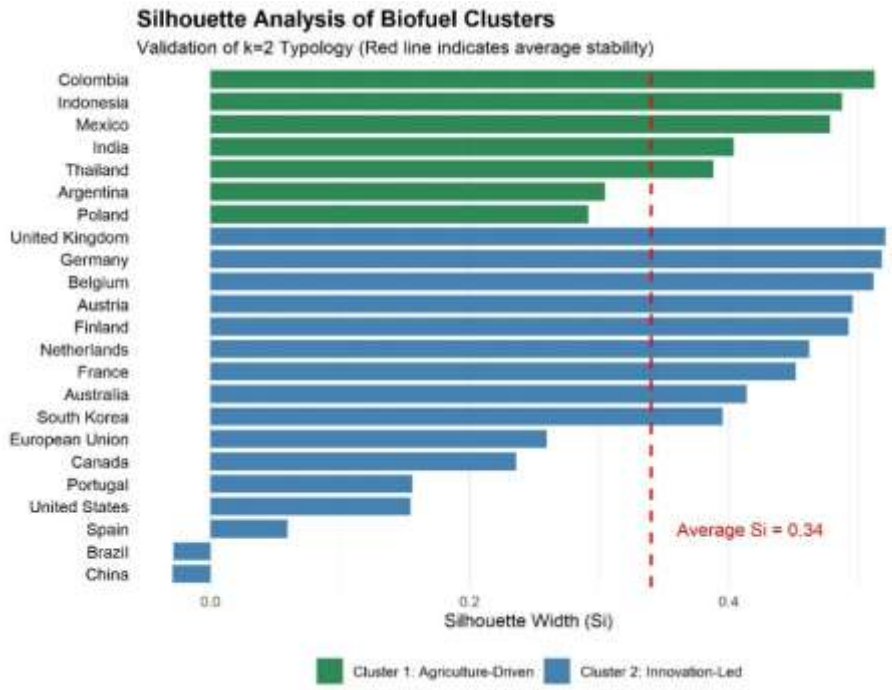


Fig. 3. Silhouette plot validating the k=2 cluster solution.

3.2. Determinants of Sustainable Development Pathways

To identify the factors distinguishing the two pathways (RQ2), Independent Samples t-tests and Mann-Whitney U tests were conducted. The results are presented in Table 2.

Table 2. Independent Samples t-test and Mann-Whitney U test results

Variable	Test	Sta-tistic	df	p	Mean Diff.	SE Diff.	Effect Size	
							Type	Value
R&D Innovation	Student's t	5.602	21.0	< .001	0.4490	0.0802	Cohen's d	2.539
	Mann-Whitney U	2.00	-	< .001	0.4500	-	Rank biserial	-0.964
CO_2 Emissions	Student's t	-0.930	21.0	0.363	-0.0965	0.1038	Cohen's d	-0.421
	Mann-Whitney U	54.00	-	0.920	-0.0099	-	Rank biserial	0.036
Agriculture Employment	Student's t	-4.269[a]	21.0	< .001	-0.3918	0.0918	Cohen's d	-1.934
	Mann-Whitney U	6.00	-	< .001	-0.2768	-	Rank biserial	0.893
Biofuel Production	Student's t	0.782	21.0	0.443	0.0830	0.1062	Cohen's d	0.354
	Mann-Whitney U	53.50	-	0.893	-8.48e-6	-	Rank biserial	0.045

The clusters were compared across four key sustainability dimensions. The results show that the differences between the two groups are mainly associated with socio-economic factors rather than production or environmental indicators.

The main difference is in innovation intensity. Cluster 2 has significantly higher R&D expenditure ($M = 0.53$) than Cluster 1 ($M = 0.08$). This difference was confirmed by an independent samples t-test ($t(21) = 5.60$, $p < 0.001$). The very large effect size (Cohen's $d = 2.54$) indicates that technological investment is the strongest factor distinguishing the two pathways.

In contrast, Cluster 1 has a much higher level of agricultural employment ($M = 0.47$) than Cluster 2 ($M = 0.08$). The Mann-Whitney U test confirmed that this difference is statistically significant ($U = 6.00$, $p < 0.001$), with a large effect size ($d = -1.93$).

However, no statistically significant differences were found between the clusters in CO_2 emissions ($p = 0.363$) or biofuel production ($p = 0.443$). This suggests that production scale and environmental performance do not differ significantly according to the socio-economic model adopted by a country. Both agrarian and industrialized models achieve similar production levels and environmental outcomes despite their different structural characteristics.

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3.3. Structural Interdependencies

To further examine the relationships between the indicators, Spearman's rank correlation analysis was conducted. The results are presented in Table 3.

Table 3. Spearman's rank correlation matrix.

Variable	Statistic	R&D Expenditure	CO_2 Emissions	Agriculture Employment	Biofuel Production
R&D Expenditure	Spearman's ρ	—			
	p-value	—			
CO_2 Emissions	Spearman's ρ	-0.215	—		
	p-value	0.325	—		
Agriculture Employment	Spearman's ρ	-0.516*	-0.027	—	
	p-value	0.012	0.902	—	
Biofuel Production	Spearman's ρ	0.106	-0.834**	-0.059	—
	p-value	0.630	< .001	0.791	—

First, a significant negative relationship was found between R&D expenditure and agricultural employment ($\rho = -0.516$, $p = 0.012$). This indicates a trade-off between modernization and agricultural labour dependence, with innovation-led biofuel development associated with lower dependence on agricultural employment.

Second, a strong negative correlation was observed between biofuel production and transport-related CO_2 emissions ($\rho = -0.834$, $p < 0.001$). This indicates that higher biofuel production is associated with lower transport-related CO_2 emissions, regardless of whether a country follows an agrarian or industrialized development pathway.

4. DISCUSSION

4.1. The Structural Divide: Agriculture-Driven vs. Innovation-Led Models

The clustering results reveal two distinct structural patterns in the global biofuel economy, with countries differing not only geographically but also in their socio-economic production models.

Cluster 1, which includes countries such as India, Indonesia, and Colombia, represents an agriculture-driven model characterized by high labour intensity. This is consistent with Domac et al. (2005), who observed that while developed countries focus on technology-intensive bioenergy systems, developing economies often depend on traditional, labour-intensive approaches to generate employment. This difference is supported by the strong negative correlation between R&D expenditure and agricultural employment found in this study. It suggests that as a country's bioeconomy becomes more technologically advanced, its dependence on agricultural labour decreases. This supports Mac Clay and Sellare (2025), who argued that advanced bioeconomy activities requiring high research capabilities have less potential for large-scale job creation than biomass-intensive processes. Therefore, Cluster 1 countries should not be viewed as lagging but as using the bioeconomy to support social inclusion and rural employment, as emphasized in ASEAN bioeconomy programmes (Wang et al., 2022).

In contrast, Cluster 2, which includes countries from the Global North, such as the USA and Germany, along with major emerging economies, follows an innovation-led pathway. Its defining feature is higher R&D intensity, which Gatto et al. (2021) identify as an important indicator of the technological dimension of the bioeconomy. The dominance of this model in Western Europe and North America is expected, given their historical focus on the biochemical and pharmaceutical applications of biomass (Bracco et al., 2018). However, the inclusion of Brazil and China in this cluster rather than the agriculture-driven Cluster 1 challenges the traditional North-South distinction and requires further examination.

4.2. Hybrid Cases: Why Brazil and China Differ from the Typical Global South Pattern

The classification of Brazil and China in the technology-intensive Cluster 2, despite their status as developing countries with large agricultural outputs, reflects state-led modernization rather than a statistical anomaly.

In Brazil, the biofuel sector has shifted considerably from manual to mechanized production. Deininger (2013) notes that although mechanization represents a technological advancement driven by R&D, it also reduces labour intensity. This explains why Brazil does not fit the Cluster 1 profile. Its sugarcane industry is no longer primarily a source of low-skilled agricultural employment but has developed into a technology-intensive energy sector. This transition is supported by a strong sectoral innovation system, including the BIOEN programme and extensive genomic research (Hotta et al., 2010). These developments have enabled Brazil to improve productivity through incremental innovation rather than relying only on its geographical advantages (Dos Santos E Silva et al., 2019; Furtado et al., 2011).

Similarly, China's position in the innovation-led cluster reflects strong state intervention. Its bioeconomy is being shaped by top-down policies rather than developing organically. The 14th Five-Year Plan, for example, prioritizes biological manufacturing and security alongside traditional agriculture (Zhang et al., 2022). F. Zhang et al. (2011) describe this as a "hybrid innovation model", in which state-supported R&D programmes increase the technological intensity of the sector, distinguishing China from other Asian countries in Cluster 1. The use of biotechnology to improve production efficiency (Li and Hu, 2025) further reduces the sector's dependence on labour-intensive practices, making China's profile more similar to that of the USA and Germany than to India or Indonesia.

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4.3. Production Volume and Environmental Impact

The statistical analysis found no significant difference in biofuel production volumes between the agriculture-driven Cluster 1 and the innovation-led Cluster 2. This suggests that high technological intensity is not essential for achieving high production levels, as labour-intensive models in the Global South can also contribute substantially to global energy supply. This supports Lima and Gupta (2013), who argue that biofuel production is concentrated in the Global South mainly because of favourable climatic conditions and land availability rather than technological advantages. This creates a complex relationship in which the Global North depends on the South for biofuel supplies, while the South relies on Northern markets to support investment (Mathews, 2007).

The study also found a strong negative correlation between biofuel production and transport-related CO_2 emissions, indicating that higher production is associated with lower emissions. This finding supports recent research identifying liquid biofuels as an important means of reducing transport-sector emissions (Solaymani, 2023; Tao et al., 2023). However, studies such as DeCicco et al. (2016) warn that process emissions and land-use changes may offset these benefits. The overall findings here are consistent with Bozbay and Güngörmüşler (2022), who observed significant CO_2 reductions in major producers such as Brazil and China. Nevertheless, given the differences in production models identified in this study, the sustainability of these outcomes may depend on the pathway adopted. The mechanized, high-yield model of Cluster 2 may offer greater efficiency, while the labour-intensive model of Cluster 1 supports socio-economic stability. A sustainable global biofuel strategy should therefore accommodate both pathways rather than impose a single technology-focused standard.

5. CONCLUSION

The main findings of this study can be summarized in three points. First, the global biofuel market is not uniform but consists of two distinct sustainable development pathways: an "Agriculture-Driven" model characterized by high labour intensity and an "Innovation-Led" model marked by higher R&D expenditure. This distinction challenges the traditional North-South divide and shows that state-led mechanization can reduce dependence on agricultural labour.

Second, a trade-off exists between modernization and agricultural employment. The strong negative relationship between R&D expenditure and agricultural employment indicates that greater technological investment is associated with lower dependence on agricultural labour. Thus, while the Innovation-Led model emphasizes technological development, the Agriculture-Driven model offers greater potential for rural employment.

Third, despite these structural differences, the study identifies a strong negative correlation between biofuel production and transport-related CO_2 emissions. This suggests that higher production is associated with lower emissions, irrespective of the development pathway. Therefore, global policies should move beyond a one-size-fits-all approach and recognize labour-intensive production as a distinct and effective pathway towards achieving environmental targets.

REFERENCES

1. *Acharya R.N., Perez-Pena R., 2020, Role of Comparative Advantage in Biofuel Policy Adoption in Latin America., Sustainability, vol.12, no.4, pp.1411;*
2. *Acosta-Michlik L., Lucht W., Bondeau A., Beringer T., 2011, Integrated assessment of sustainability trade-offs and pathways for global bioenergy production: Framing a novel hybrid approach., Renewable and Sustainable Energy Reviews, vol.15, no.6, pp.2791–2809;*
3. *Aguiar W.M.D., Nascimento M.N.D., Vasconcelos R.N., Rocha W.D.J.S.D.F., Jesus T.B.D., Souza D.T.M.D., Pérez T.C., Santana C.O.D., Alves C.T., Oliveira O.B.D., Mania E., Santana M.M.M.D., 2024, Energy transition and bioeconomy: an integrated review of interconnected pathways to sustainable development., Brazilian Applied Science Review, vol.8, no.2, pp.e76219;*
4. *Argueyrolles R., Heimann T., Delzeit R., 2025, Impact of Gasoline and Diesel Subsidy Reforms on Global Biofuel Mandates., GCB Bioenergy, vol.17, no.2, pp.e70019;*
5. *Arshad M., Zia M.A., Shah F.A., Ahmad M., 2018, An Overview of Biofuel., Perspectives on Water Usage for Biofuels Production, Springer International Publishing, pp.1–37;*
6. *Bailis R., Baka J., 2011, Constructing Sustainable Biofuels: Governance of the Emerging Biofuel Economy., Annals of the Association of American Geographers, vol.101, no.4, pp.827–838;*
7. *Bastos Lima M.G., 2021a, International Bioeconomy Governance: Unveiling the Initial Patterns., The Politics of Bioeconomy and Sustainability, Springer International Publishing, pp.67–86;*
8. *Bastos Lima M.G., 2021b, The Contested Sustainability of Biofuels in a North-South Context., The Politics of Bioeconomy and Sustainability, Springer International Publishing, pp.23–47;*
9. *Blay-Roger R., Saif M., Bobadilla L.F., Ramirez-Reina T., Nawaz M.A., Odriozola J.A., 2024, Embracing the sustainable horizons through bioenergy innovations: a path to a sustainable energy future., Frontiers in Chemistry, vol.12, pp.1416102;*
10. *Box G.E.P., Jenkins G.M., Reinsel G.C., Ljung G.M., 2016, Time series analysis: forecasting and control., Wiley;*
11. *Bozbay U., Güngörmüşler M., 2022, Promoting Utilization of Biofuels in The Transportation Sector to Reduce CO2 Emissions: Comparative Analysis., Politeknik Dergisi, vol.25, no.4, pp.1741–1751;*
12. *Bracco S., Calicioglu O., Gomez San Juan M., Flammini A., 2018, Assessing the Contribution of Bioeconomy to the Total Economy: A Review of National Frameworks., Sustainability, vol.10, no.6, pp.1698;*
13. *Chovancová J., Petruška I., Pata U.K., Adamišin P., 2025, Diverse pathways to decarbonization: cluster-specific impacts of energy sources on CO2 emissions in the European Union., Energy Nexus, vol.17, pp.100367;*
14. *Cohen J., 1988, Statistical power analysis for the behavioral sciences., L. Erlbaum Associates;*
15. *Comineti C.D.S.S., Pretel A.F., Schlindwein M.M., 2023, The type of development promoted by Brazilian National Biofuels Policy., Renewable and Sustainable Energy Reviews, vol.182, pp.113368;*

SJIF Impact Factor (2026): 8.863| ISI I.F. Value: 1.241| Journal DOI: 10.36713/epra2016 ISSN: 2455-7838(Online)
EPRA International Journal of Research and Development (IJRD)
Volume: 11 | Issue: 11| November 2026 - Peer Reviewed Journal

16. *Datta D., Biswas S., Barman D., Mandal E., Das B., 2024, Evolution, Challenges and Benefits of Biofuel Production and Its Potential Role in Meeting Global Energy Demands., Emerging Sustainable Technologies for Biofuel Production, Springer Nature Switzerland, pp.595–632;*
17. *Dauvergne P., Neville K.J., 2010, Forests, food, and fuel in the tropics: the uneven social and ecological consequences of the emerging political economy of biofuels., The Journal of Peasant Studies, vol.37, no.4, pp.631–660;*
18. *DeCicco J.M., Liu D.Y., Heo J., Krishnan R., Kurthen A., Wang L., 2016, Carbon balance effects of U.S. biofuel production and use., Climatic Change, vol.138, no.3–4, pp.667–680;*
19. *Deininger K., 2013, Global land investments in the bio-economy: evidence and policy implications., Agricultural Economics, vol.44, no.s1, pp.115–127;*
20. *Djatmika P., Listiningrum P., Sumarno T.B., Mahira D.F., Sianipar C.P.M., 2023, Just Transition in Biofuel Development towards Low-Carbon Economy: Multi-Actor Perspectives on Policies and Practices in Indonesia., Energies, vol.17, no.1, pp.141;*
21. *Domac J., Richards K., Risovic S., 2005, Socio-economic drivers in implementing bioenergy projects., Biomass and Bioenergy, vol.28, no.2, pp.97–106;*
22. *Dos Santos E Silva D.F., Bomtempo J.V., Alves F.C., 2019, Innovation opportunities in the Brazilian sugar-energy sector., Journal of Cleaner Production, vol.218, pp.871–879;*
23. *Energy Institute, 2024a, Statistical Review of World Energy., Energy Institute;*
24. *Energy Institute, 2024b, Biofuels Production – Statistical Review of World Energy.;*
25. *Ewing M., Msangi S., 2009, Biofuels production in developing countries: assessing tradeoffs in welfare and food security., Environmental Science & Policy, vol.12, no.4, pp.520–528;*
26. *Furtado A.T., Scandiffio M.I.G., Cortez L.A.B., 2011, The Brazilian sugarcane innovation system., Energy Policy, vol.39, no.1, pp.156–166;*
27. *Gatto F., Daniotti S., Re I., 2021, Driving Green Investments by Measuring Innovation Impacts. Multi-Criteria Decision Analysis for Regional Bioeconomy Growth., Sustainability, vol.13, no.21, pp.11709;*
28. *Harjanti S., Prabowo H., Rahim R.K., 2025, Unlocking circular economy and green innovation pathways for sustainable biofuel: a global bibliometric analysis with insights from Indonesia's B40 transition., Frontiers in Sustainability, vol.6, pp.1668947;*
29. *Hettinga W.G., Junginger H.M., Dekker S.C., Hoogwijk M., McAloon A.J., Hicks K.B., 2009, Understanding the reductions in US corn ethanol production costs: An experience curve approach., Energy Policy, vol.37, no.1, pp.190–203;*
30. *Hill J., Nelson E., Tilman D., Polasky S., Tiffany D., 2006, Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels., Proceedings of the National Academy of Sciences, vol.103, no.30, pp.11206–11210;*
31. *Hodbod J., Tomei J., 2013, Demystifying the Social Impacts of Biofuels at Local Levels: Where is the Evidence?, Geography Compass, vol.7, no.7, pp.478–488;*
32. *Hotta C.T., Lembke C.G., Domingues D.S., Ochoa E.A., Cruz G.M.Q., Melotto-Passarin D.M., Marconi T.G., Santos M.O., Mollinari M., Margarido G.R.A., Crivellari A.C., Dos Santos W.D., De Souza A.P., Hoshino A.A., Carrer H., Souza A.P., Garcia A.A.F., Buckeridge M.S., Menossi M., Van Sluys M.-A., Souza G.M., 2010, The Biotechnology Roadmap for Sugarcane Improvement., Tropical Plant Biology, vol.3, no.2, pp.75–87;*
33. *Hyndman R.J., Khandakar Y., 2008, Automatic Time Series Forecasting: The forecast package for R., Journal of Statistical Software, vol.27, no.3;*
34. *International Energy Agency, 2023, Renewables 2023: Analysis and forecast to 2028., International Energy Agency;*
35. *International Renewable Energy Agency, 2024, Accelerating decarbonisation using bioenergy with carbon capture, utilisation and storage., International Renewable Energy Agency;*
36. *Jha S., Nanda S., Acharya B., Dalai A.K., 2024, Introduction to sustainability science in addressing energy security and achieving sustainable development goals., Biomass to Bioenergy, Elsevier, pp.1–14;*
37. *Kanzari E., Fazio G., Fricano S., 2024, The Energy Transition of African Countries: A Cluster Analysis., SSRN;*
38. *Khan M.S., Khan A.A., Dilawar H., 2025, Biofuels and Sustainable Development in India: Evaluating Socio-Economic and Environmental Potential., Journal of Informatics Education and Research, vol.5, no.3;*
39. *Levene H., 1960, Robust tests for equality of variances., Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling, Stanford University Press, pp.278–292;*
40. *Li X., Hu Y., 2025, Deconstruction of China's agricultural bioeconomy policies in the context of sustainable systems transition - Based on policy texts analysis., Agricultural Economics (Zemědělská ekonomika), vol.71, no.12, pp.664–679;*
41. *Lima M.G.B., Gupta J., 2013, The Policy Context of Biofuels: A Case of Non-Governance at the Global Level?, Global Environmental Politics, vol.13, no.2, pp.46–64;*
42. *Mac Clay P., Sellare J., 2025, The Nexus Between Innovation, Value Chains, and Social Sustainability in the Context of a Bioeconomy Upgrading., Business Strategy & Development, vol.8, no.1, pp.e70087;*
43. *MacQueen J., 1967, Some methods for classification and analysis of multivariate observations.;*
44. *Mann H.B., Whitney D.R., 1947, On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other., The Annals of Mathematical Statistics, vol.18, no.1, pp.50–60;*
45. *Mathews J.A., 2007, Biofuels: What a Biopact between North and South could achieve., Energy Policy, vol.35, no.7, pp.3550–3570;*
46. *Miftah F.K., Mutta D., 2024, Potential markets and policies for sustainable liquid biofuel production with emphasis to Eastern Africa countries: a review., Energy, Sustainability and Society, vol.14, no.1, pp.1;*
47. *Nath S., 2024, Biotechnology and biofuels: paving the way towards a sustainable and equitable energy for the future., Discover Energy, vol.4, no.1, pp.8;*
48. *Oladoye P.O., Omotola E.O., Alli Y.A., Oladipo M.E., Ejeromedoghene O., Bamisaye A., 2024, The politics and policies of bioenergy advancement: a global perspective., Microbial Biotechnology for Bioenergy, Elsevier, pp.299–324;*

SJIF Impact Factor (2026): 8.863| ISI I.F. Value: 1.241| Journal DOI: 10.36713/epra2016 ISSN: 2455-7838(Online)
EPRA International Journal of Research and Development (IJRD)
Volume: 11 | Issue: 11| November 2026 - Peer Reviewed Journal

49. *Ozturk I., 2016, Biofuel, sustainability, and forest indicators' nexus in the panel generalized method of moments estimation: evidence from 12 developed and developing countries., Biofuels, Bioproducts and Biorefining, vol.10, no.2, pp.150–163;*
50. *Pramanik A., Sinha A., Chaubey K.K., Hariharan S., Dayal D., Bachheti R.K., Bachheti A., Chandel A.K., 2023, Second-Generation Bio-Fuels: Strategies for Employing Degraded Land for Climate Change Mitigation Meeting United Nation-Sustainable Development Goals., Sustainability, vol.15, no.9, pp.7578;*
51. *Qi Y., Ibrahim R.L., Saleh Al-Faryan M.A., 2025, Exploring aggregated and disaggregated environmental impacts of biofuels: Do affluence, green technological innovation and green finance matter for top biofuel-abundant economies?, Energy & Environment, vol.36, no.1, pp.291–322;*
52. *R Core Team, 2023, R: A Language and Environment for Statistical Computing., R Foundation for Statistical Computing;*
53. *REN21, 2024, Renewables 2024 Global Status Report., REN21 Secretariat;*
54. *Rodriguez Morales J.E., 2025, Development Pathways and the Political Economy of Maladaptation: The Case of Bioenergy as a Climate Strategy in Brazil., Studies in Comparative International Development, vol.60, no.3, pp.568–612;*
55. *Rousseeuw P.J., 1987, Silhouettes: A graphical aid to the interpretation and validation of cluster analysis., Journal of Computational and Applied Mathematics, vol.20, pp.53–65;*
56. *Russo C., Cirillo V., Pollaro N., Terribile F., Chiodini A., Maggio A., 2025, The global energy challenge: second-generation feedstocks on marginal lands for a sustainable biofuel production., Chemical and Biological Technologies in Agriculture, vol.12, no.1, pp.10;*
57. *Sani J., Sambo A.S., Garba B., Musa M., 2024, Biorefining Technologies in the Global South., International Journal of Research and Innovation in Applied Science, vol.IX, no.X, pp.229–245;*
58. *Searchinger T., Edwards R., Mulligan D., Heimlich R., Plevin R., 2015, Do biofuel policies seek to cut emissions by cutting food?, Science, vol.347, no.6229, pp.1420–1422;*
59. *Singh J., Clough Y., 2024, Challenges and opportunities to a sustainable bioenergy utilization in climate mitigation: a global perspective., Frontiers in Sustainable Energy Policy, vol.3, pp.1460370;*
60. *Skogstad G., Wilder M., 2019, Strangers at the gate: the role of multidimensional ideas, policy anomalies and institutional gatekeepers in biofuel policy developments in the USA and European Union., Policy Sciences, vol.52, no.3, pp.343–366;*
61. *Solaymani S., 2023, Biodiesel and its potential to mitigate transport-related CO2 emissions., Carbon Research, vol.2, no.1, pp.38;*
62. *Spearman C., 1904, The Proof and Measurement of Association between Two Things., The American Journal of Psychology, vol.15, no.1, pp.72;*
63. *Student, 1908, The Probable Error of a Mean., Biometrika, vol.6, no.1, pp.1;*
64. *Tao J., Chen C., Wang J., Li J., Zhou S., Chen C., Yan B., Guo W., Cheng Z., Chen G., 2023, Liquid biofuel powering the sustainable transport with a low-carbon emission: a review., Progress in Energy, vol.5, no.4, pp.042003;*
65. *Taylor S.J., Letham B., 2018, Forecasting at Scale., The American Statistician, vol.72, no.1, pp.37–45;*
66. *Thorndike R.L., 1953, Who Belongs in the Family?, Psychometrika, vol.18, no.4, pp.267–276;*
67. *Vicente Perin R., Castañeda-Ayarza J., Camata S.D.D.S., 2025, Highlighting the relationship between bioethanol fuel and the institutional and macro-environmental environment in developed and developing countries., Biofuels, vol.16, no.7, pp.653–664;*
68. *Wang T., Yu Z., Ahmad R., Riaz S., Khan K.U., Siyal S., Chaudhry M.A., Zhang T., 2022, Transition of bioeconomy as a key concept for the agriculture and agribusiness development: An extensive review on ASEAN countries., Frontiers in Sustainable Food Systems, vol.6, pp.998594;*
69. *Whistance J., Debnath D., Thompson W., 2024, A biofuels outlook for the U.S. and Brazil and what it might mean for sustainable development goal 7., Frontiers in Chemical Engineering, vol.5, pp.1290763;*
70. *World Bank, 2024, DataBank – World Development Indicators.;*
71. *Zhang F., Cooke P., Wu F., 2011, State-sponsored Research and Development: A Case Study of China's Biotechnology., Regional Studies, vol.45, no.5, pp.575–595;*
72. *Zhang X., Zhao C., Shao M., Chen Y., Liu P., Chen G., 2022, The roadmap of bioeconomy in China., Engineering Biology, vol.6, no.4, pp.71–81;*
73. *Ziolkowska J., Meyers W.H., Meyer S., Binfield J., 2010, Targets and mandates: Lessons learned from EU and US biofuels policy mechanisms., AgBioForum, vol.13, no.4, pp.398–412*