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Revisiting the Load Capacity Curve for Sustainable Development: The Roles of Plastic Waste Trade, Digital Trade, and BioTrade in OECD Countries

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ABSTRACT

This study examines the validity of the Load Capacity Curve (LCC) hypothesis and assesses the environmental implications of emerging trade structures, focusing on BioTrade, digital trade, and plastic waste trade. Using a balanced panel of 36 OECD countries from 2011 to 2023, the analysis investigates how income dynamics and trade composition jointly influence the load capacity factor (LCF). Methodologically, the study employs the regularized Common Correlated Effects (rCCE) estimator and the Bias-Corrected Method of Moments (BCMM) approach. The empirical findings provide robust evidence supporting the LCC hypothesis, revealing a U-shaped relationship between income and LCF in OECD economies. Digital trade and BioTrade significantly enhance ecological capacity, reflecting the roles of technological diffusion, efficiency gains, and biodiversity-oriented economic activities. In contrast, plastic waste trade has a detrimental effect on LCF, highlighting the environmental risks associated with waste-driven trade flows. Based on these results, the study recommends that OECD countries strengthen digital and biodiversity-based trade channels while tightening regulations on plastic waste trade. Leveraging the LCC mechanism through sustainability-oriented trade policies can enable advanced economies to convert economic growth into long-term ecological resilience.

1 | Introduction

Organisation for Economic Co-operation and Development (OECD) countries, due to their high-income levels, intensive production and consumption patterns, and advanced industrial and service sectors, are responsible for a significant share of global environmental pressures. As a result, they are central to discussions on environmental sustainability (ES) (Dixit et al. 2026). In these countries, economic prosperity has historically increased alongside natural resource use, energy consumption, and waste

generation. This has resulted in the transgression of environmental boundaries and the exceeding of ecosystems' carrying capacities (Ulucak and Ozcan 2020). In this context, ES is both an ecological imperative and a strategic objective for OECD countries in terms of long-term economic stability, social welfare, and fulfillment of global responsibilities. Within the framework of the United Nations Sustainable Development Goals (SDGs), OECD countries are particularly committed to contributing directly to the goals of "Responsible Consumption and Production" (SDG 12), "Climate Action" (SDG 13), "Life Below Water" (SDG 14),

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and “Life on Land” (SDG 15). These specific SDGs are especially relevant for OECD countries due to the structural characteristics of their economies and their disproportionate impact on global environmental outcomes. Unlike many developing economies, OECD countries have high per capita consumption, resource-intensive lifestyles, and complex global value chains, which extend their environmental footprint beyond their own borders. In this context, SDG 12 is critical because it directly addresses unsustainable consumption and production patterns that are most evident in advanced economies. SDG 13 is equally important, given the historical responsibility of OECD countries for a large share of cumulative emissions and their leadership in climate policy and green innovation. Additionally, SDGs 14 and 15 are closely connected to OECD countries through international trade dynamics, including marine pollution, biodiversity loss, and transboundary environmental pressures resulting from activities such as resource extraction and waste trade. Therefore, these goals are not only relevant but also structurally embedded in the sustainability challenges and policy responsibilities of OECD countries, making them the most appropriate framework for analyzing environmental sustainability in this context. SDGs aim to prevent countries from exceeding their environmental carrying capacities through sustainable natural resource management (Xing et al. 2025), waste reduction and recovery (Xu and Işık 2025), climate change mitigation (Torney and Gueye 2009), and ecosystem conservation (Habib et al. 2025). Therefore, ES in OECD countries is closely linked to the responsibility of taking a leading role in implementing the global sustainable development agenda.

In the literature, commonly used indicators to empirically measure ES include carbon emissions, greenhouse gas emissions, ecological footprints (Dam et al. 2024), air and water pollution indicators (Parris 2014), and green growth indices (Mehmood and Kaewsaeng-on 2026). These indicators make specific dimensions of environmental pressures visible. However, they mostly address environmental degradation in a unidirectional manner and do not account for the regenerative capacity of ecosystems. For example, while carbon emissions or pollution indicators reflect the demand side of the environment, they often exclude ecological supply factors such as biocapacity. This complicates the holistic assessment of countries’ long-term ES performance, that is, the balance between environmental demand and ecological supply (Caglar et al. 2026). Therefore, traditional and classical indicators used in the literature are limited in fully capturing the structural and biophysical dimensions of ES.

At this point, the Load Capacity Factor (LCF) emerges as a more comprehensive and suitable indicator for assessing ES. LCF directly measures the relationship between a country’s biocapacity and ecological footprint, representing the performance of ecosystem carrying capacity in relation to economic and commercial activities. An LCF greater than 1 indicates that ecological supply meets environmental demand, signaling a sustainable structure, whereas an LCF less than 1 reflects environmental overshoot and increased ecological pressure (Pata 2021). The LCF is calculated as the ratio of a country’s biocapacity to its ecological footprint, reflecting the balance between ecological supply and environmental demand (Siche et al. 2010). Formally, for country i at time t , it is defined as: $LCF_{it} = \text{Biocapacity } (BC_{it}) / \text{Ecological Footprint } (EF_{it})$, where BC refers to the capacity of ecosystems to

generate renewable biological resources and absorb waste, particularly carbon emissions, given existing technology and management practices, while EF represents the total demand placed by human activities on these ecosystems, including resource consumption and waste generation. In other words, BC reflects the regenerative and absorptive capacity of nature, whereas EF captures the pressure exerted by economic and consumption activities (Monfreda et al. 2004). This structure makes LCF a biophysical and integrative indicator, as it directly measures whether a country operates within its ecological limits. Specifically, values greater than one ($LCF > 1$) indicate that ecological capacity exceeds environmental demand, implying ecological sustainability, whereas values below one ($LCF < 1$) reflect ecological deficit or environmental overshoot, where human pressure surpasses nature’s regenerative ability. LCF incorporates both the supply and demand sides of the environment, offering a more comprehensive assessment of long-term ecological balance.

The LCF values for OECD countries shown in Figure 1 indicate significant heterogeneity across countries. For example, in Canada, Finland, Colombia, New Zealand, and Sweden, most LCF values exceed 1 ($LCF > 1$), suggesting these countries have relatively high biocapacity. In contrast, in highly industrialized and densely populated countries such as Germany, Belgium, Japan, Italy, and the United Kingdom, LCF values below 1 ($LCF < 1$) indicate that environmental demand exceeds ecological supply, increasing sustainability risks. These differences suggest that ES in OECD countries cannot be explained solely by economic development; factors such as trade structures, production technologies, and environmental policies also play a crucial role.

The determinants of countries’ ecological balance performance are not limited to domestic production and consumption patterns but are closely linked to cross-border flows of goods and waste. International trade, in particular, can redistribute environmental pressures among countries, reducing stress on biocapacity in some nations while increasing it in others. Therefore, analyzing the observed differences in LCF values among OECD countries requires careful consideration of the environmental aspects of trade, especially specific flows such as plastic waste trade. The literature on plastic waste trade offers substantial insight into the structural dynamics of global waste flows, their geographical redistribution, and policy outcomes. Developed countries are often found to export plastic waste to developing countries, transferring environmental burdens across borders, creating “pollution havens,” and placing significant pressure on local ecosystems (Browning et al. 2021). However, most studies focus on environmental outcomes such as emissions, waste volumes, or local pollution indicators, while largely neglecting measures that directly assess the balance between countries’ biocapacity and ecological footprint. Yet, plastic waste trade is significant not only for local environmental quality but also for shaping countries’ long-term ecological carrying capacities.

Plastic waste trade influences the LCF through several identifiable pathways affecting both ecological demand and supply. First, plastic waste imports increase environmental pressure by intensifying local waste accumulation and mismanaged recycling

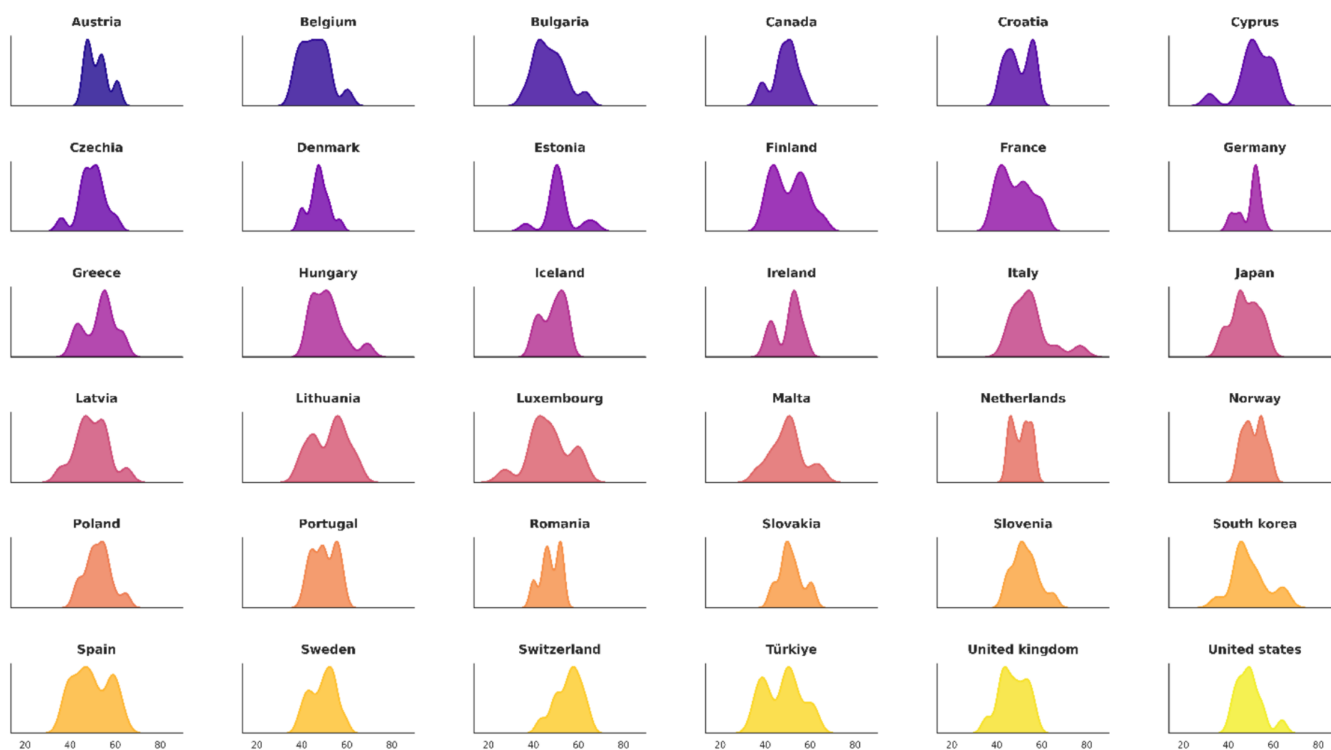


FIGURE 1 | LCF values for OECD countries. *Source:* Global Footprint Network (2025).

processes. This results in a higher EF due to increased pollution and energy use in processing, thereby reducing LCF. Second, imported waste generates negative spillovers on BC by degrading soil quality, contaminating water resources, and harming biodiversity. Third, plastic waste exports do not eliminate global ecological impacts; instead, they shift environmental burdens across borders, often to countries with weaker environmental regulations, consistent with the pollution haven mechanism. This displacement may artificially improve LCF in exporting countries while worsening it in importing ones. Finally, even under regulated conditions, the energy- and resource-intensive nature of plastic recycling and processing contributes to emissions and resource depletion, further increasing EF. Together, these channels show that plastic waste trade affects LCF by increasing ecological demand and, in many cases, eroding ecological supply.

The PWT data presented in Figure 2 show that this trade reaches high volumes in OECD countries and exhibits fluctuating trends over time. In particular, countries such as the United States, Germany, Japan, the United Kingdom, and France display higher levels of PWT, highlighting the potential constraining effects of these activities on LCF, which cannot be overlooked. However, there is a notable gap in the literature regarding studies that assess the ES of PWT using comprehensive biophysical indicators such as LCF. This gap limits understanding of the net effects of PWT on the environmental demand–supply balance.

At this point, focusing only on trade volumes and directions is insufficient for evaluating the environmental impacts of PWT. The nature and type of trade are crucial in determining its ecological pressures. Therefore, analyses of ES in OECD countries benefit from incorporating not only tangible examples such as

PWT but also qualitative forms of trade, including digital trade (DGD) and biotrade (BIOT), which can provide broader insights into the effects on LCF and biocapacity. Although general trade and other trade types have significant potential for ES through economic growth, welfare enhancement, and technology transfer, these effects are often indirect and depend on specific conditions.

Conventional trade indicators do not adequately distinguish the environmental content and quality of trade, as empirical studies using aggregate trade measures often suffer from aggregation bias and fail to capture sectoral and cross-country heterogeneity in environmental impacts (Cole and Elliott 2003; Copeland and Taylor 2004). Most empirical studies rely on aggregate measures such as trade openness or total trade volume, which treat trade as a homogeneous activity and overlook its structural composition (Antweiler et al. 2001). However, the environmental effects of trade are highly heterogeneous and depend on the nature of traded goods, production processes, and regulatory frameworks (Grossman and Krueger 1995). As highlighted in the ecological literature, aggregate trade indicators fail to capture the asymmetric distribution of environmental burdens across countries and sectors (Bai and Givens 2021; Jorgenson and Clark 2012). Recent studies also emphasize that trade-related environmental impacts vary significantly across sectors such as waste trade, DGD, and resource-based trade, which cannot be disentangled using conventional indicators (Shah and Ximei 2024; Qiu and Wan 2023). Therefore, relying solely on aggregate trade measures obscures the underlying mechanisms through which trade affects environmental sustainability.

DGD can reduce environmental pressures by lowering transaction costs, decreasing physical transportation, improving

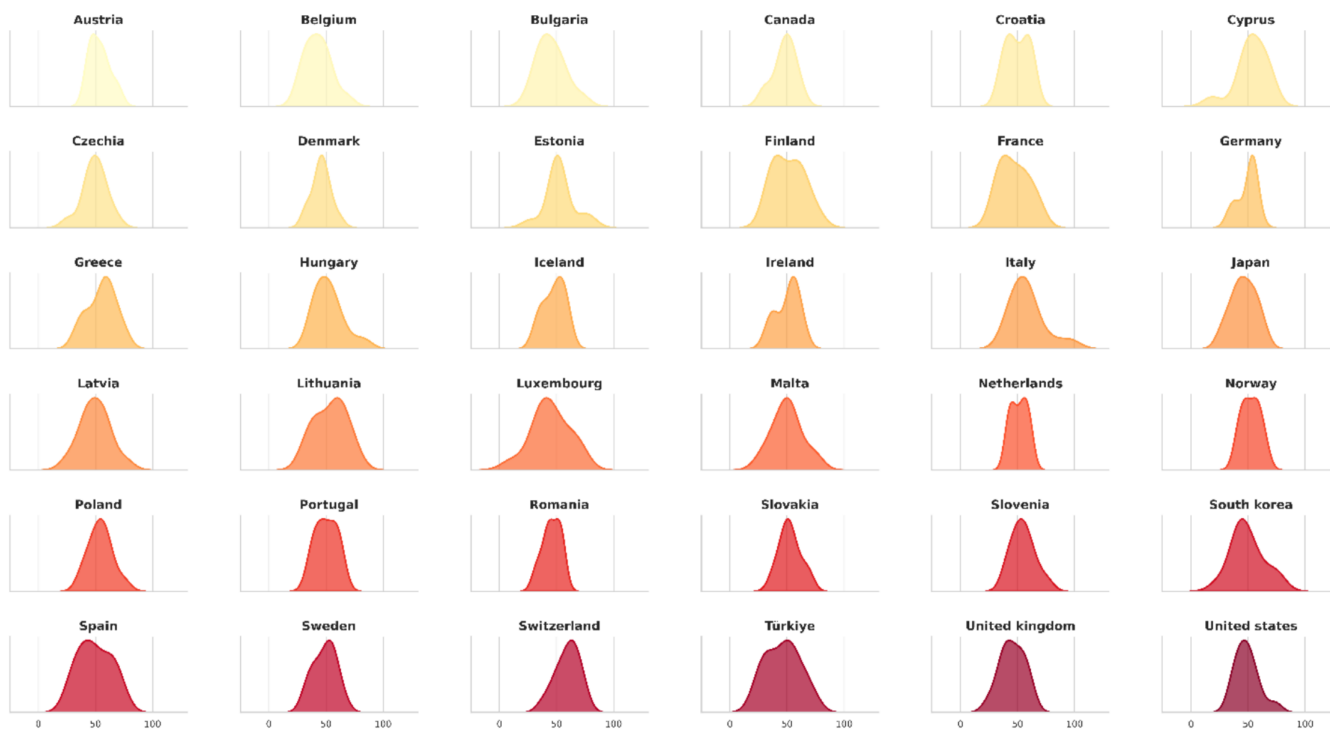


FIGURE 2 | Plastic Waste-Related Trade (PWT) values for OECD countries. *Source:* UNCTAD (2025).

production efficiency, and accelerating the diffusion of knowledge-intensive technologies (Jaller and Pahwa 2020). BIOT, in contrast, promotes the sustainable use of biological resources, ecosystem-based production, and biodiversity conservation, thereby supporting the enhancement of countries' biocapacity (Stamboulakis and Sanderson 2020).

The data presented in Figure 3 indicate that DGD in OECD countries has shown a rapid upward trend, while BIOT has remained relatively stable, reflecting its association with sustainable production practices in many countries. These trends underscore the need for empirical investigation into the potential positive impacts of these trade types on the LCF.

Based on the above explanations, the primary objective of this study is to empirically analyze the relationship between PWT, DGD, BIOT, and LCF for 36 OECD countries. Additionally, to examine the nonlinear effects of economic growth on ES, the study employs GDP and GDP² variables to test the validity of the Load Capacity Curve (LCC) hypothesis proposed by Dogan and Pata (2022). Consequently, the study considers the effects of different trade types and economic growth on the environmental demand–supply balance in OECD countries within a holistic analytical framework. Overall, the study aims to provide a comprehensive framework for understanding ES. The primary research questions are as follows:

- RQ1: Is PWT significant for the LCF of OECD countries?
- RQ2: Do DGD and BIOT contribute to the LCF of OECD countries?
- RQ3: Is the LCC hypothesis valid for OECD countries under GDP and GDP²?

This study makes several distinct and original contributions to the literature. First, although the LCF has been used in previous research, existing studies primarily examine conventional macroeconomic or environmental drivers and do not address the environmental implications of emerging and structurally diverse trade components. In contrast, this study is the first to integrate and disaggregate trade into BioTrade, DGD, and plastic waste trade within the LCF framework, moving beyond aggregate trade measures to capture the varied environmental effects of different trade compositions. Second, no previous study empirically examines how these three distinct forms of trade simultaneously affect ecological carrying capacity, or how their effects differ in direction and magnitude when measured with a biophysically grounded indicator such as the LCF. This disaggregated approach demonstrates that trade is not environmentally neutral but structurally differentiated, offering a fundamentally new perspective on the trade–environment relationship. Third, the study uniquely tests the LCC hypothesis within a framework that explicitly incorporates these differentiated trade channels, providing the first empirical evidence on how modern trade structures interact with nonlinear income dynamics to influence ecological sustainability in OECD countries. Finally, by jointly analyzing economic growth and disaggregated trade effects on environmental carrying capacity, this research addresses a critical gap in the literature and advances a more comprehensive, structurally nuanced, and policy-relevant understanding of sustainability, clearly distinguishing it from previous LCF-based studies.

1.1 | Development of the Theoretical Framework

The theoretical framework of this study is based on Pollution Haven Theory, Ecological Modernization Theory, and the

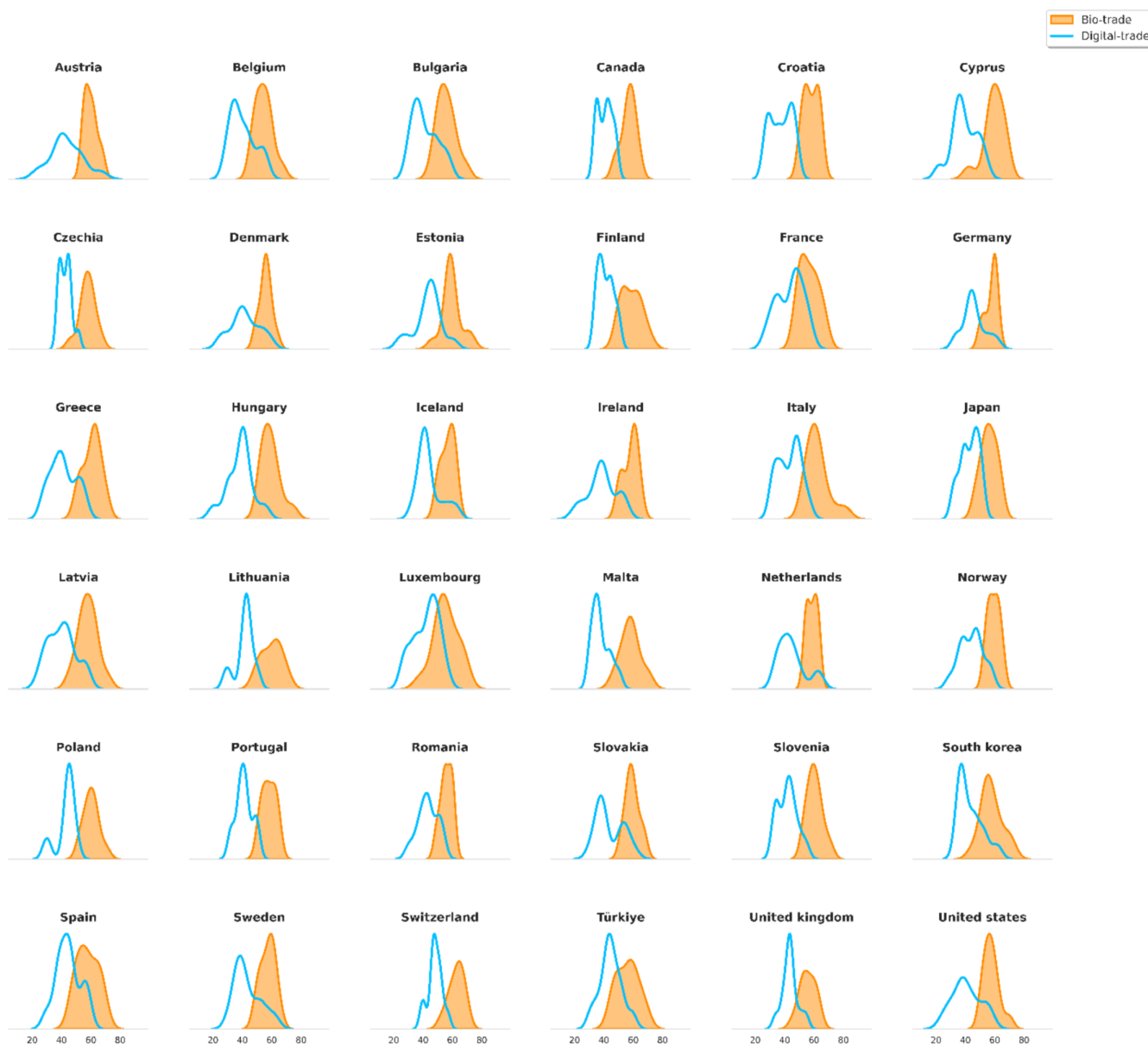


FIGURE 3 | DGD and BIOT values for OECD countries. *Source:* UNCTAD (2025).

LCC hypothesis. The Pollution Haven Theory, introduced by Buchanan (1968), suggests that countries with stricter environmental regulations tend to transfer polluting activities to countries with more lenient regulations. The findings of this study, which show that increases in PWT reduce LCF, support this theory by demonstrating that environmental burdens are redistributed and ecological carrying capacity is weakened through waste trade.

In contrast, Ecological Modernization Theory, as proposed by Mol and Spaargaren (2000), argues that technological innovations, institutional transformation, and environmentally friendly production practices can enable both economic growth and environmental improvement. The observed increases in DGD and BIOT, which elevate LCF, align with the mechanisms suggested by this theory, indicating that efficiency gains and sustainable resource use can support biocapacity.

Finally, the LCC hypothesis, developed by Dogan and Pata (2022), suggests that the relationship between economic growth and ecological carrying capacity may follow an inverted U-shape. In this study, the negative effect of GDP and the positive effect of GDP² on LCF indicate that the LCC hypothesis holds for OECD countries, suggesting that economic growth beyond a certain income level can support environmental capacity. A graphical summary of all theoretical approaches appears in Figure 4.

2 | Literature Review

2.1 | The Relationship Between PWT and the LCF

Although the literature on PWT has expanded rapidly over the past decade, most studies focus on the structural dynamics



FIGURE 4 | Graphical summary of theoretical approaches.

of PWT, its geographical redistribution, environmental consequences, and policy impacts, rather than directly addressing ES through a holistic biophysical indicator such as the LCF. Specifically, the evolution of global PWT networks, the redirection of trade flows following China's import ban, and the environmental effects of this process have been extensively analyzed. Studies by Liu et al. (2023), Wang et al. (2020), Shi et al. (2021), and Liu et al. (2022), using social network analysis and complex network approaches, have highlighted the center–periphery structure of PWT, emerging trade hubs, and key determinants of trade patterns. These studies emphasize that while PWT brings economic benefits, it also entails significant environmental risks; however, these risks are not linked to integrated sustainability indicators such as ecological footprint, biocapacity, or LCF.

In the literature on the environmental consequences of PWT, ecological footprint, greenhouse gas emissions, and pollution indicators are predominant. Seker et al. (2025) show that plastic waste imports increase ecological footprints and greenhouse gas emissions, while the Environmental Kuznets Curve (EKC) hypothesis may apply depending on income levels. Similarly, Liu et al. (2021) and Li, Ward, et al. (2024) offer more nuanced perspectives by demonstrating that, under certain conditions, PWT can reduce global greenhouse gas emissions within a life cycle assessment framework. However, these studies do not use the LCF concept, which directly measures the balance between environmental pressure and biocapacity, and therefore cannot

reveal the net effect of PWT on countries' ecological carrying capacity.

The LCF literature, by contrast, primarily examines factors such as economic growth, industrialization, energy consumption, and waste generation. Pata et al. (2024) and Karlılar Pata and Pata (2025) find that waste generation reduces LCF in OECD and EU countries, while recycling enhances environmental capacity; however, these studies do not consider international waste trade. Similarly, Çağlar et al. (2024) and Bergougui (2025) confirm the LCC hypothesis within competitive industrial structures, circular economy frameworks, and income growth, but do not account for cross-border environmental burden transfers such as PWT in their models. This gap between the PWT literature and the LCF/LCC literature shows that the two fields have not yet been systematically integrated.

Current studies primarily examine PWT in the context of pollution havens, trade policies, and global governance, while LCF is mainly used as an indicator of the environmental outcomes of domestic production–consumption processes. However, no study has empirically investigated the relationship between PWT and LCF using panel data. In particular, how PWT affects the balance between biocapacity and ecological footprint in OECD countries, and how this interacts with economic growth and the LCC hypothesis, remains an important gap in the literature. This gap highlights the need to evaluate PWT not only in terms of pollution and emissions but also regarding its long-term effects on countries' environmental carrying capacity.

2.2 | The Relationship Between DGD and the LCF

The literature on DGD has expanded rapidly in recent years, with particular focus on its effects on ES, carbon emissions, ecological footprint, and green growth. Most studies indicate that DGD can reduce environmental pressures by optimizing production processes, promoting technological innovation, and enhancing human capital. Cai (2025), for example, shows that DGD significantly reduces carbon emissions in European Union countries, with stronger effects in countries with robust digital infrastructure and high innovation capacity. Similarly, Ji et al. (2023) demonstrate that in China, DGD reduces carbon emissions through industrial structure transformation and green technological innovation. These findings confirm the potential positive role of DGD in improving environmental quality. Since carbon emissions make up the main component of the carbon footprint, which is the dominant part of the EF, reducing emissions effectively lowers ecological demand. Therefore, the emission-reducing effects of DGD identified in the literature implicitly indicate its potential to enhance the LCF by reducing pressure on the environmental demand side.

More broadly, the effects of DGD on ecological footprint, green total factor productivity, and ES have been extensively analyzed. Qiu and Wan (2023) show that DGD reduces ecological footprints in BRICS countries, an effect strengthened by green technological innovations. Zhang et al. (2022) and Shah and Ximei (2024) find that DGD lowers ecological footprints in G7 and BRICS-T countries, with evidence supporting the Environmental Kuznets Curve (EKC) hypothesis. Studies by Xiong and Luo (2023) and Zhang and Choi (2025) further highlight that the impact of DGD on green productivity is nonlinear, with environmental benefits becoming more pronounced beyond certain threshold levels. Multinational studies, including Li, Hu, et al. (2024) and Cai (2025), indicate that the carbon-reducing effects of DGD vary according to countries' development levels, innovation capacities, and digital infrastructure.

In the DGD literature, environmental impacts are primarily assessed using carbon emissions, ecological footprint, material footprint, or green growth indicators. The LCF, which represents the balance between biocapacity and ecological footprint as a comprehensive measure of ecosystem services, has not yet been studied in relation to DGD. Research on LCF and the LCC hypothesis has mainly focused on economic growth, energy consumption, industrialization, waste generation, and the circular economy. No empirical studies currently examine the direct impact of DGD on LCF. This suggests that the environmental effects of DGD are typically measured using single-dimension pressure indicators, and a framework reflecting the balance between ecological demand and supply is largely lacking.

Therefore, the relationship between DGD and LCF represents a clear gap in the literature. Specifically, for OECD countries, it remains unexamined whether DGD supports biocapacity, how its mitigating effects on ecological footprint are reflected in LCF, and whether the LCC hypothesis holds under both linear and nonlinear effects of economic growth. Although existing studies

provide strong evidence that DGD improves environmental quality, whether these improvements enhance countries' long-term environmental carrying capacity remains unanswered. In this context, analyzing DGD within the LCF and LCC framework offers potential for both conceptual and empirical contributions to the literature.

2.3 | The Relationship Between BIOT and the LCF

The literature on BIOT primarily addresses biodiversity conservation, local development, ethical supply chains, and SDGs. Institutional frameworks such as the United Nations Convention on Biological Diversity (CBD), the Nagoya Protocol, and the Union for Ethical BioTrade (UEBT) seek to regulate the trade of biological resources to minimize pressures on ecosystems. Reid (1996) and Görg and Brand (2000) emphasize that the commercialization of genetic resources can align with biodiversity conservation only under appropriate regulations and property rights. Although these studies suggest that BIOT can theoretically support biocapacity, they do not establish a direct connection with quantitative indicators of ES. BIOT influences the LCF through its direct effects on both ecological supply (biocapacity) and ecological demand (EF). On the supply side, BIOT promotes sustainable use of biological resources, biodiversity conservation, and ecosystem-based production systems, which help maintain or enhance biocapacity by preserving ecosystem regeneration capacity. Activities such as certified biodiversity trade, sustainable harvesting, and ecosystem-friendly value chains reduce pressure on natural systems. On the demand side, BIOT can lower the EF by encouraging environmentally responsible production methods, reducing resource depletion, and limiting environmentally harmful extraction practices.

Applied studies on BIOT typically focus on local communities and micro-level sustainability outcomes. Elias et al. (2022) show that BIOT activities in the Amazon basin contribute simultaneously to environmental, social, and economic sustainability. Similarly, Castro and Stork (2015) and Welford and Breton (2008) argue that the trade of biological products can create income mechanisms that promote natural resource conservation. Motiekaitytė (2007) and Oliva (2015) demonstrate that the sustainable harvesting of biological products, such as medicinal and aromatic plants, can reduce ecosystem pressures. However, these studies largely rely on qualitative assessments or local environmental indicators and do not use comprehensive metrics, such as the LCF, which reflect the balance between a country's total ecological demand and biocapacity.

The connection between BIOT and the SDGs is also emphasized in the literature. Cabrera and Cuenca (2024) highlight BIOT as a tool aligned with the SDGs, where appropriate institutional arrangements enhance environmental awareness and resource protection. Wynberg et al. (2015) and Stamboulakis and Sanderson (2020) caution that, under weak governance or excessive regulation, BIOT can produce unintended negative environmental and social outcomes, indicating that this form of trade does not automatically increase environmental capacity. Thus, the literature suggests that the environmental impacts of BIOT

are context-dependent and sensitive to governance quality, yet macro-level empirical analyses remain limited.

A review of the literature on LCF and LCC shows that most studies focus on energy consumption, economic growth, industrialization, waste generation, and the circular economy. No studies have directly examined the effects of BIOT or biological resource trade on LCF. Although existing BIOT research suggests indirect contributions to the preservation of biocapacity, the net impact on the balance between ecological footprint and biocapacity remains unmeasured. Thus, the relationship between BIOT and LCF has not been empirically analyzed, representing a notable gap in the literature.

This gap is especially significant for OECD countries. In developed economies, BIOT may contribute to the conservation of biological resources but, due to increasing demand, may also increase ecological pressures. This dual effect makes the direction of BIOT's impact on LCF ambiguous, requiring its assessment alongside economic growth within the LCC framework. Therefore, analyzing BIOT through the LCF-LCC perspective in OECD countries would address a significant gap by systematically evaluating its contribution to macro-level environmental carrying capacity.

2.4 | Literature Gap

Although the literature on PWT, DGD, and BIOT has grown considerably, a common limitation across these areas is the reliance on single-dimensional environmental indicators such as carbon emissions, ecological footprint, or pollution measures. More importantly, existing studies typically examine these trade types in isolation and do not incorporate a comprehensive biophysical framework that captures the balance between ecological supply and demand. As a result, the literature lacks an integrated approach that simultaneously evaluates the environmental impacts of these diverse trade structures within the LCF and LCC frameworks. This gap obscures the comparative and joint effects of different trade compositions on ecological carrying capacity. Therefore, this study contributes to the literature by providing the first unified empirical analysis that links PWT, DGD, and BIOT to LCF while also testing the LCC hypothesis.

3 | Data and Methodology

3.1 | Data and Variables

This study aims to empirically examine the validity of the LCC hypothesis for 36 OECD member countries during the period

2011–2023, considering the environmental impacts of biotrade, DGD, and plastic waste trade. Table 1 presents information on the variables.

$$\ln LCF_{it} = \vartheta_0 + \vartheta_1 \ln GDP_{it} + \vartheta_2 \ln GDP^2_{it} + \vartheta_3 \ln BIOT_{it} + \vartheta_4 \ln DGT_{it} + \vartheta_5 \ln PWT_{it} + u_{it} \quad (1)$$

where ϑ_0 is the constant term, ϑ_1 to ϑ_5 are the long-term coefficients. ϑ_1 and ϑ_2 are related to the LCC hypothesis of Dogan and Pata (2022), which posits a U-shaped relationship between income and environmental quality (LCF). LCF combines biocapacity and ecological footprint. At early development stages, rising income reduces LCF due to industrialization and resource depletion. Beyond a critical turning point, higher income enables investments in clean technologies, renewable energy, and governance reforms, improving ecological resilience (Wang et al. 2025). Empirical evidence supports this in many contexts: Wang et al. (2025) confirmed a rebound in LCF after approximately \$27,000 per capita GDP, while Pata et al. (2024) and Pata and Pata (2025) found similar patterns in India and 10 European countries, respectively. Deng et al. (2024) also validated the LCC for nine major emitters, emphasizing the role of energy security and green innovation. For LCC to be valid, ϑ_1 must be negative, ϑ_2 must be positive, and both must be statistically significant. The LCC hypothesis is visually shown in Figure 5.

ϑ_3 , ϑ_4 , and ϑ_5 are coefficients related to the environmental interaction of trade. Trade influences the load capacity factor (LCF) by affecting both the ecological supply and demand sides. It can enhance LCF by promoting the transfer of renewable energy technologies, encouraging cleaner production, and supporting sustainable economic growth. However, trade can also increase environmental pressure through higher resource consumption and pollution if not managed with effective environmental policies (Pata et al. 2023). Empirical evidence shows that in Latin American and Caribbean countries, trade openness positively stimulates LCF in the long run, indicating improved environmental quality through trade (Pata and Ertugrul 2023). Conversely, in countries like Türkiye and South Korea, trade openness has been found to negatively impact LCF, likely due to increased energy use and insufficient environmental regulation (Akhayere et al. 2022; Agila et al. 2022). The effect of trade openness on LCF is thus context-dependent, influenced by factors such as natural resource rents, corruption control, and the adoption of sustainable technologies (Wang et al. 2024; Qin et al. 2025). The heterogeneous effects of trade on LCF across countries can be attributed to structural, institutional, and technological differences, especially within OECD economies. Trade affects LCF by influencing both ecological demand (through

TABLE 1 | Data information.

Symbol	Variable	Definition	Source
LCF	Load capacity factor	Index, bio	Global Footprint Network (2025)
GDP	Gross domestic product	Per capita, constant 2015 USD	World Bank (2025)
BIOT	BioTrade	Biotrade's % share of total trades.	UNCTAD (2025)
DGT	Economic complexity	Digital trade's % share of total trades.	
PWT	Plastic waste trade	Plastic waste trade's % share of total trades.	

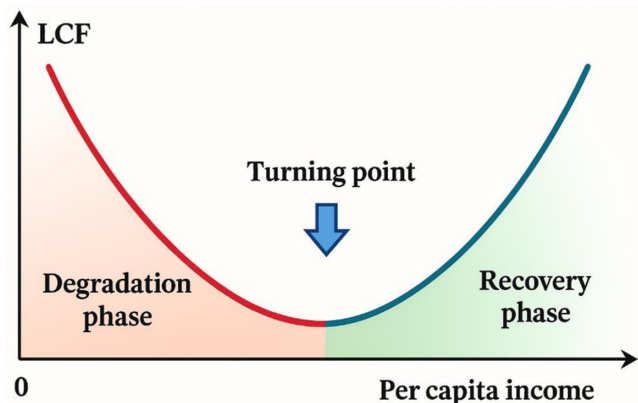


FIGURE 5 | LCC hypothesis. *Source:* Created by the authors based on Dogan and Pata (2022).

resource use and emissions) and ecological supply (through technology transfer and efficiency gains). In countries with advanced technological capacity, trade generally has positive effects by promoting the diffusion of clean technologies and supporting sustainable resource management. This is consistent with ecological modernization theory, which suggests that economic integration fosters greener production systems. Conversely, in countries with resource-intensive production structures or less effective environmental policy enforcement, trade can increase ecological pressure by driving higher energy consumption and pollution-intensive activities. Even within OECD countries, variations in energy mix, industrial composition, digital infrastructure, and regulatory quality result in asymmetric outcomes, with some countries achieving improvements in LCF while others experience ecological degradation.

Trade in specialized segments such as BioTrade, DGD, and plastic waste trade exerts markedly different influences on environmental quality. When effectively regulated, BioTrade promotes biodiversity-based commerce that supports ecosystem conservation, alleviates ecological stress, and fosters sustainable livelihoods. Evidence from Amazonian and Latin American contexts demonstrates that biodiversity trade can advance environmental, social, and economic sustainability simultaneously (Elias et al. 2022; Cordova-Buiza et al. 2022). In contrast, DGD has a nuanced and often nonlinear impact. Initial phases may increase emissions due to economic expansion; however, as digital infrastructure matures and green innovation accelerates, digital trade tends to reduce carbon intensity and ecological footprints by enhancing energy efficiency and enabling cleaner production and logistics (Ashraf et al. 2024; Zhou and Guo 2025; Li et al. 2025). Conversely, plastic waste trade poses significant environmental risks. Unregulated flows of plastic waste are linked to higher ecological footprints, greenhouse gas emissions, and marine pollution, particularly in countries with inadequate waste management systems (Li et al. 2021; Wen et al. 2021; Li, Ward, et al. 2024). These adverse outcomes underscore the urgency of implementing stringent global regulations to curb plastic waste trade (Seker et al. 2025). Based on these explanations, θ_3 and θ_4 are expected to be positive, while θ_5 is expected to be negative.

Figure 6 presents the expected environmental impacts of trade variables. Researchers have found that DGD reduces material

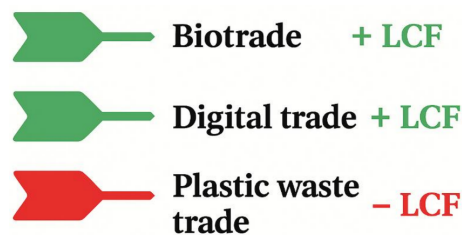


FIGURE 6 | Expected signs of trade related variables.

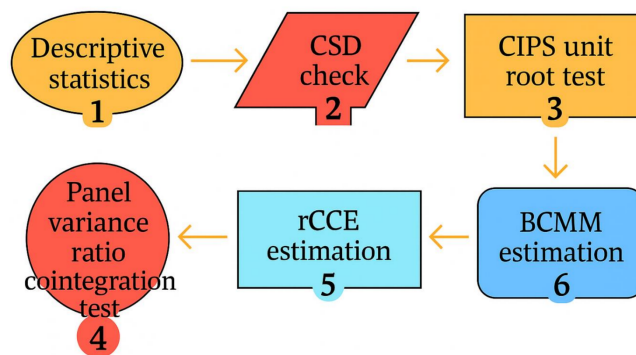


FIGURE 7 | Empirical process.

footprint (Yingchao and Xiang 2024), ecological footprint (Shah and Ximei 2024), and carbon emissions (Tian et al. 2024). However, no study has examined the effects of DGD on LCF. Seker et al. (2025) reported that plastic waste trade increases both CO₂ emissions and ecological footprint. The environmental impacts of biotrade have not yet been empirically studied; only Bakouan and Sawadogo (2024) analyzed its relationship with income inequality using econometric methods. From this perspective, this study aims to add a new dimension to the trade-environment discussion by pioneering the analysis of the effects of biotrade, DGD, and plastic waste trade on LCF.

3.2 | Methodology

The study employs four different panel data approaches that account for cross-sectional dependence (CSD) and visually presents the empirical strategy in Figure 7. In the first stage, it examines the statistics of the variables, such as the mean and standard deviation. In the second stage, the study analyzes the transmission of economic, social, and political shocks between countries using Pesaran's (2015) weak CD test and Fan et al.'s (2015) CDw+ tests. The validity of cross-sectional dependence can be assessed with the statistics from these tests; if the null hypothesis of no CSD is rejected, the use of second-generation panel data methods becomes necessary for effective estimation.

In the next step, Pesaran's (2007) CIPS unit root test is applied to examine the stochastic properties of the variables. CIPS is a second-generation panel unit root procedure designed for panels in which cross-sectional units are correlated through one or more unobserved common factors, such as global shocks. It builds on

the CADF (Cross-sectionally Augmented Dickey–Fuller) regression, which augments each individual ADF regression with cross-sectional averages of the level and first difference of the series to remove the influence of these common factors, as shown in Equation (2).

$$\Delta BIOT_{it} = \beta_i + \delta_i BIOT_{it-1} + \sigma_i \overline{BIOT}_{t-1} + \sum_{l=0}^p \tau_{ij} \Delta \overline{BIOT}_{it-1} + \sum_{l=0}^p \varphi_{ij} BIOT_{it-1} + z_{it} \quad (2)$$

For each unit, a CADF t -statistic is computed, and the CIPS statistic is then calculated as the simple average of these individual statistics, as shown in Equation (3) and is robust to CSD.

$$CIPS = N^{-1} \sum_{i=1}^j t_i(N, T) \quad (3)$$

CIPS tests the null hypothesis of a unit root in all units and allows different autoregressive parameters across units.

In the fourth stage, the study applies Westerlund's (2005) variance ratio cointegration test. This test is designed to determine whether a stable long-run relationship exists among variables in panel data by analyzing the stochastic properties of regression residuals. The test is based on the idea that if variables are cointegrated, the residuals from the estimated long-run equation should exhibit mean-reverting behavior rather than follow a random walk. Unlike methods that rely on common factor assumptions, the Westerlund variance ratio test assesses cointegration by comparing the variability of the cumulative residual process with the contemporaneous residual variance across cross-sectional units. The null hypothesis states that no cointegration exists for any unit in the panel, while the alternative allows for cointegration in at least some units. By aggregating individual variance ratios, the test produces a panel-level statistic with well-defined asymptotic properties.

In the fifth stage, the study applies the regularized Common Correlated Effects (rCCE) approach proposed by Juodis (2022). The CCE method is shown in Equation (4).

$$\ln r_{it} = \alpha_{it} + \beta_i \ln x_{it} + \gamma_i \ln \bar{y}_{it} + \delta_i \ln \bar{x}_{it} + c_i w_t + \varepsilon_{it} \quad (4)$$

Here, r_{it} denotes the parameter coefficient, and w_t represents the unobserved common factor. Building on the logic of the CCE framework, the rCCE estimator can be interpreted as a refinement that explicitly addresses the risk of over-parameterization arising from the inclusion of multiple cross-sectional averages. While the standard CCE approach augments each unit-specific regression with cross-sectional means to proxy unobserved common factors, it treats all such proxies as equally relevant, which may lead to efficiency losses. The rCCE approach extends this idea by embedding a regularization mechanism into the CCE structure.

Specifically, rCCE imposes a penalty on the coefficients associated with the cross-sectional averages, shrinking less informative components toward zero. This penalization allows the estimator to distinguish between dominant and weak common

influences without requiring prior knowledge of the true number of unobserved factors. Moreover, by reducing sensitivity to irrelevant common components, rCCE improves overall inference.

The preference for the rCCE estimator over the standard CCE approach is primarily driven by the need to improve estimation efficiency in the presence of cross-sectional dependence, a defining feature of OECD panel data. While the conventional CCE estimator accounts for unobserved common factors by augmenting regressions with cross-sectional averages, it treats all such factors as equally relevant, which can lead to over-parameterization and efficiency loss, especially when the number of cross-sectional units is large. In contrast, the rCCE approach introduces a regularization mechanism that penalizes less informative cross-sectional components. This is particularly important in the OECD context, where countries are highly interconnected through trade, financial markets, and synchronized policy frameworks. By mitigating the impact of irrelevant or weak factors, rCCE enhances estimation precision, reduces multicollinearity concerns, and provides more reliable long-run coefficients.

As a final stage, the study employs the novel Bias-Corrected Method of Moments (BCMM) estimator developed by Breitung et al. (2022). In dynamic panels with lagged dependent variables, standard estimators are susceptible to Nickell bias, finite-sample distortions, and sensitivity to CSD. BCMM addresses these issues by incorporating an analytical bias correction directly into the moment conditions, rather than relying on external instruments. Equation (5) presents the BCMM approach.

$$y_{it} = \sum_{j=1}^p \partial_j y_{i,t-j} + x_{it} \beta + \underbrace{\alpha_i + \mu_{it}}_{e_{it}} \quad (5)$$

where y_{it} denotes the dependent variable (i.e., the load capacity factor) for country i at time t , while $y_{i,t-j}$ represents its lagged values up to order p , capturing the dynamic structure of the model. The coefficients ∂_j measure the persistence effect of past values of the dependent variable. The term x_{it} is a vector of explanatory variables (including PWT, DGD, BIOT, and control variables), and β is the associated parameter vector reflecting their long-run effects. The component α_i captures unobserved country-specific fixed effects, while μ_{it} represents the idiosyncratic error term. The composite error term is denoted by $e_{it} = \alpha_i + \mu_{it}$.

Based on Equation (5), a bias-corrected moment function ($m_i(\theta)$) can be estimated as in Equation (6)

$$m_i(\theta) = \frac{1}{T} \left[\left(\frac{y_{i,t-1} - \bar{y} - 1}{x_{i,t} - \bar{x}_i} \right) - \left(\frac{T}{T-1} b(\partial_1) (e_{it} - \bar{e}_i) \right) \right] e_{it} \quad (6)$$

In Equation (6), $m_i(\theta)$ denotes the bias-corrected moment function for cross-sectional unit i , where θ is the vector of parameters to be estimated. The terms \bar{y} and \bar{x}_i represent the time averages of the dependent and explanatory variables, respectively, used to eliminate fixed effects. The expression $\frac{T}{T-1} b(\partial_1)$ refers to the analytical bias correction term, where T is the time dimension of the panel and $b(\partial_1)$ captures the magnitude of dynamic bias arising from the inclusion of lagged dependent variables. The term $(e_{it} - \bar{e}_i)$ denotes the deviation of the error term from its

individual mean, ensuring that the moment conditions are centered. Overall, the coefficients and components in Equation (6) are designed to correct for dynamic panel bias (Nickell bias) and to produce consistent parameter estimates.

The main innovation of BCMM is its explicit adjustment for dynamic bias resulting from the correlation between lagged dependent variables and unobserved individual effects. Compared with conventional GMM-based estimators, the BCMM approach offers several practical advantages that are particularly relevant for the empirical structure of this study. Standard GMM techniques often depend on a large set of internal instruments, which may lead to instrument proliferation and weaken the reliability of the estimates. In addition, the validity of these instruments can become questionable in the presence of CSD and heterogeneous dynamics. The BCMM estimator addresses these concerns by embedding bias correction directly into the estimation procedure rather than relying on external instruments. This not only mitigates finite-sample bias but also improves the stability of the estimated coefficients.

4 | Empirical Results

Table 2 presents an initial statistical overview. The descriptive statistics show substantial cross-country and temporal variation in load capacity factor, income, and trade-related variables across OECD economies. The mean value of the LCF is negative, indicating that ecological pressure exceeds biocapacity for most observations. GDP shows relatively low variability, suggesting economic homogeneity among OECD countries, while DGD displays substantial dispersion, reflecting uneven technological integration. The standard deviation of GDP (0.289) is notably smaller than that of DGD (0.699) and the load capacity factor (0.393), indicating that income levels across OECD countries are more homogeneous than trade structures and environmental capacity indicators. In contrast, variables such as DGD and BioTrade show greater dispersion, reflecting differences in technological adoption, trade specialization, and policy orientation among countries. Even plastic waste trade, despite its narrower range, displays consistent variation relative to its mean, highlighting its differentiated role across economies. This pattern aligns with the OECD context, where member countries tend to converge in income levels but diverge in structural characteristics such as DGD intensity, environmental performance, and trade composition. Therefore, the lower variability of GDP does not imply uniformity in economic-environmental dynamics; rather, it underscores that cross-country differences in ecological outcomes are driven more by structural and policy-related factors than by income disparities alone. The minimum and maximum values of BioTrade and plastic waste trade highlight their marginal but environmentally significant roles. The relatively wide dispersion of lnLCF suggests heterogeneous levels of ecological resilience, while the variability in BioTrade, DGD, and plastic waste trade shares indicates structurally different trade compositions.

As shown in Table 3, the results of the CD and CDw + tests unequivocally confirm the presence of strong CSD across all variables. This result reflects the interconnectedness of OECD countries, where global shocks, synchronized business cycles,

TABLE 2 | Descriptive statistics.

Variable	Obs	Mean	Std. dev.	Min	Max
lnLCF	468	-0.304	0.3937	-1.368	0.353
lnGDP	468	4.478	0.2890	3.741	5.044
lnBIOT	468	0.104	0.111	-0.458	0.281
lnDGT	468	4.329	0.699	2.791	5.836
lnPWT	468	0.652	0.062	0.477	0.781

TABLE 3 | CSD results.

Variables	CD test statistic	p	CDw + test	p
lnLCF	22.17*	0.000	774.58*	0.000
lnGDP	75.02*	0.000	1879.90*	0.000
lnBIOT	22.95*	0.000	1005.94*	0.000
lnDGT	81.07*	0.000	2037.19*	0.000
lnPWT	27.36*	0.000	870.03*	0.000

Note: * denotes 5% and 1% level of significance, respectively.

TABLE 4 | CIPS unit root test results.

Variables	Level I(0)	First difference I(1)	Decision
lnLCF	-1.909	-4.238*	I(1)
lnGDP	-1.817	-2.762*	I(1)
lnBIOT	-1.922	-3.350*	I(1)
lnDGT	-1.494	-2.923*	I(1)
lnPWT	-1.822	-3.304*	I(1)

Note: * denotes 1% level of significance.

and common environmental policies transmit effects across borders. Ignoring this dependence would lead to biased and inconsistent estimates, reinforcing the necessity of second-generation panel methods such as CIPS, rCCE, and BCMM in the empirical strategy.

Table 4 presents the results of the CIPS unit root test, which reveals that all variables are non-stationary at levels but become stationary after first difference. The consistency of these results across variables such as GDP, BioTrade, and DGD supports the use of cointegration techniques in subsequent analysis.

Table 5 tests whether a stable long-run relationship exists among the modeled variables. The variance ratio cointegration results reject the null hypothesis of no cointegration under both alternative specifications. This indicates that income, trade components, and ecological capacity evolve together over time. The presence of cointegration further supports the use of long-run estimators such as rCCE and BCMM in the empirical framework.

Table 6 presents the long-run coefficients from the rCCE estimator, which accounts for unobserved common factors. The negative coefficient on income and the positive coefficient on its squared term confirm a U-shaped relationship between economic growth and LCF, supporting the LCC hypothesis. DGD

TABLE 5 | Variance ratio cointegration results.

Alternative hypothesis	Test statistic	<i>p</i>
H_a : Some panels are cointegrated	2.411*	0.007
H_a : All panels are cointegrated	2.202**	0.013

Note: * and ** denote the rejection of no-cointegration at 1% and 5% levels, respectively.

TABLE 6 | r-CCE results.

Variables	Coefficient	Standard error	<i>t</i> -statistic	<i>p</i>
lnGDP	-118.812***	66.012	-1.80	0.072
lnGDP ₂	12.595***	6.951	1.81	0.070
lnPWT	-0.414*	0.160	-2.59	0.010
lnDGT	0.152*	0.037	4.02	0.000
lnBIOT	0.575**	0.252	2.28	0.023

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

TABLE 7 | BCMM findings.

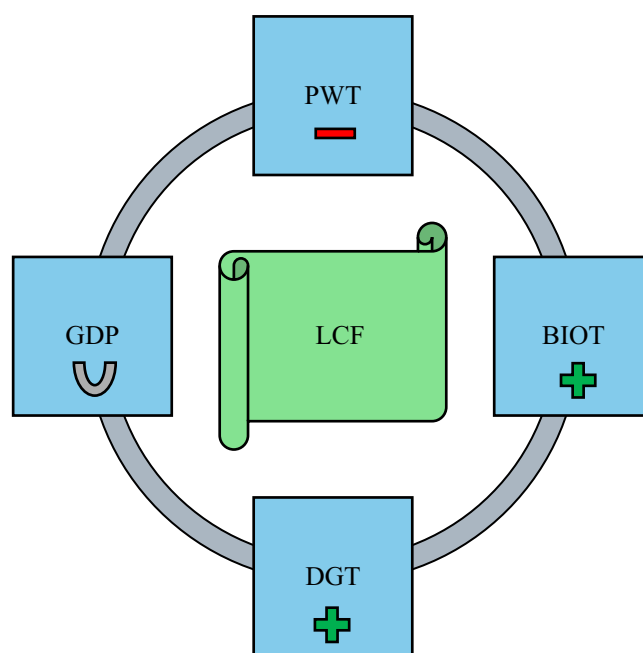
Variables	Coefficient	Standard error	<i>t</i> -statistic	<i>p</i>
lnLCF _{<i>t</i>-1}	0.576*	0.125	4.60	0.000
lnGDP	-1.959*	0.605	-3.23	0.001
lnGDP ₂	0.193*	0.064	2.99	0.003
lnPWT	-0.157**	0.078	-2.02	0.043
lnDGT	0.048**	0.019	2.45	0.014
lnBIOT	0.070***	0.040	1.74	0.081
Constant	4.642*	1.363	3.40	0.001

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

and BioTrade have positive effects on ecological capacity, indicating that technology-intensive and biodiversity-oriented trade channels enhance environmental resilience. In contrast, plastic waste trade significantly reduces load capacity, highlighting the ecological burden associated with waste-driven trade flows.

Table 7 presents the results of the BCMM estimator, which confirm the dynamic nature of LCF adjustments. The significant lagged LCF term indicates strong persistence in environmental capacity, while the GDP and GDP² coefficients reaffirm the nonlinear income-environment relationship. The positive contributions of DGD and BioTrade, though with varying significance levels, suggest that innovation-driven and biodiversity-oriented trade can serve as catalysts for ecological improvement. In contrast, the negative effect of plastic waste trade persists, reinforcing the need for stringent international regulations.

Finally, Figure 8 visually summarizes the core empirical findings of the study. From a visual perspective, this evidence highlights the importance of DGD and BioTrade in enhancing LCF, as both channels support efficiency gains, technological diffusion, and biodiversity-oriented value creation that mitigate ecological pressure while sustaining economic activity. More broadly, the figure underscores that OECD countries should actively benefit from

**FIGURE 8** | Visual summary of the results.

the validity of the LCC, since operating beyond the income turning point allows further economic growth when supported by DGD and a sustainability-oriented trade structure.

5 | Discussion

This study provides comprehensive empirical evidence on how economic growth and trade structure jointly influence ecological sustainability in OECD countries, with a particular focus on the LCC framework. The results confirm that the relationship between income and ecological capacity is nonlinear, offering strong support for the LCC hypothesis. At lower income levels, economic expansion is linked to a decline in the load capacity factor, reflecting intensified production, higher material throughput, and increased pressure on natural systems. As income rises further, however, a turning point is reached, and additional growth contributes positively to ecological capacity. This pattern suggests that advanced economies are better able to decouple growth from ecological stress through technological innovation, stronger institutions, and more effective environmental governance. These findings are consistent with earlier LCC-based studies of developed and high-income country groups (Dogan and Pata 2022; Deng et al. 2024; Wang et al. 2025), but they extend the literature by explicitly integrating trade composition into the analysis of ecological capacity rather than focusing solely on emissions or footprint indicators.

One of the most important contributions of this study is its distinction between different forms of trade and their environmental implications. The results show that plastic waste trade has a statistically significant negative effect on the LCF. This finding supports concerns raised in the pollution haven and environmental dumping literature, which argue that environmentally harmful activities are increasingly shifted across borders through trade channels (Bai and Givens 2021). Previous studies have linked

waste trade to higher pollution levels and environmental injustice (Seker et al. 2025), but the present analysis demonstrates that such trade also undermines ecological resilience by eroding the balance between biocapacity and demand. This suggests that the environmental costs of waste trade persist beyond short-term pollution effects and pose structural risks to long-term sustainability.

In contrast, DGD is found to have a positive and significant impact on LCF. This result is consistent with ecological modernization theory, which highlights the role of information technologies, innovation diffusion, and efficiency gains in improving environmental outcomes. Previous research has shown that digitalization and DGD can reduce carbon emissions and ecological footprints by optimizing production processes and lowering transaction costs (Qiu and Wan 2023; Shah and Ximei 2024). The present study extends this understanding by demonstrating that DGD not only reduces environmental pressure but also enhances ecological supply, as indicated by a higher load capacity factor. This finding underscores the potential of intangible and knowledge-based trade to support sustainable development pathways in advanced economies.

BioTrade also emerges as a key driver of ecological resilience. The positive association between BioTrade and load capacity suggests that biodiversity-based trade can contribute to ecosystem regeneration and sustainable resource use. While much of the existing BioTrade literature focuses on micro-level outcomes, such as community livelihoods, biodiversity conservation, and local value chains (Stamboulakis and Sanderson 2020; Elias et al. 2022), this study provides rare macro-level evidence that BioTrade can improve national ecological capacity. This result underscores the importance of aligning trade policies with biodiversity objectives and supports international initiatives that promote sustainable biological resources as engines of green growth.

Taken together, these findings demonstrate that trade is not environmentally neutral and that its sustainability implications depend critically on composition rather than volume alone. Economies that rely more on waste-related trade experience declining ecological capacity, while those that expand digital and biodiversity-oriented trade are better positioned to translate income growth into ecological resilience. This nuanced evidence complements and extends earlier EKC and LCC studies by showing that structural economic choices determine whether higher income levels lead to environmental recovery or continued degradation.

Overall, the discussion suggests that achieving sustainable development in OECD countries requires not only income growth but also deliberate shifts toward cleaner, knowledge-intensive, and biodiversity-friendly trade structures that strengthen ecological capacity over time.

6 | Conclusion and Policy Recommendations

6.1 | Conclusion

This study examines ecological sustainability in OECD countries using the LCC framework. By focusing on ecological load

capacity instead of conventional pollution indicators, it provides a broader perspective on long-term environmental resilience. The empirical results show a clear nonlinear relationship between economic growth and ecological capacity.

The findings also demonstrate that ecological sustainability is strongly influenced by trade structure. Trade is not environmentally neutral, and its effects vary with its composition. Plastic waste trade reduces LCF, indicating that waste-related trade creates lasting ecological stress rather than temporary environmental pressure. This result highlights the structural risks of relying on environmentally harmful trade activities to support economic growth.

In contrast, DGD contributes positively to LCF. This suggests that knowledge-intensive, low-material economic activities can support sustainability by reducing dependence on physical resources. DGD enhances efficiency and supports ecological resilience at the macro level. This finding underscores the importance of transforming the economy toward less resource-intensive sectors.

BioTrade also serves as a supportive factor for ecological capacity. Biodiversity-based economic activities help maintain the balance between ecological demand and supply. This finding suggests that integrating biodiversity into economic systems can strengthen ecological resilience while supporting economic objectives. It also indicates that sustainability-oriented trade models can play a meaningful role in national environmental performance.

Overall, the results confirm that income growth alone does not guarantee ecological improvement. Sustainable outcomes depend on how growth is achieved and which economic activities are prioritized. Economies that rely on waste-intensive trade face declining ecological capacity, while those that promote digital and biodiversity-based trade are more likely to experience ecological recovery. The study therefore emphasizes the importance of structural economic choices in shaping long-term sustainability.

By combining income dynamics with trade composition, this study provides a more comprehensive understanding of ecological sustainability. It shows that strengthening ecological capacity requires more than reducing environmental pressure. It requires deliberate economic restructuring and long-term policy commitment.

6.2 | Policy Recommendations

The findings of this study provide important policy insights for countries aiming to improve ecological sustainability. First, policymakers should recognize that economic growth does not automatically increase ecological capacity. Although higher income levels can support environmental recovery, this depends on supportive institutional and structural conditions. Governments should therefore adopt proactive strategies to guide economies toward sustainable growth rather than relying solely on income effects.

Second, the negative impact of plastic waste trade highlights the need for stricter waste governance. Countries should reduce their reliance on waste-related trade and strengthen domestic waste management systems. Policies that promote recycling, waste reduction, and circular economy practices can help reduce ecological stress. Preventing the externalization of environmental burdens through trade is essential for protecting long-term ecological capacity.

Third, the positive role of DGD suggests that promoting digital transformation can generate environmental benefits. Governments should invest in digital infrastructure and support the expansion of digital services and innovation-driven sectors. Encouraging low-material and knowledge-based economic activities can reduce pressure on natural systems while supporting economic competitiveness. Digital strategies should therefore be integrated into broader sustainability agendas.

Fourth, the positive impact of BioTrade highlights the importance of biodiversity-centered policies. Governments should support economic activities that depend on the sustainable use of biological resources. This includes promoting certification schemes, supporting local value chains, and encouraging private investment in biodiversity-friendly sectors. Strengthening the connection between biodiversity protection and economic development can enhance ecological resilience.

An integrated policy approach is essential. Environmental policies should not be separated from trade and economic development strategies. Coordinated policies that align economic incentives with ecological objectives can help countries advance sustainable development more effectively. By reshaping trade structures, promoting innovation, and protecting ecological systems, policymakers can strengthen ecological capacity and ensure long-term environmental sustainability. Improving ecological sustainability requires shifting from growth-centered to structure-centered strategies for OECD nations.

Author Contributions

Ugur Korkut Pata: conceptualization, investigation, writing – review and editing, writing – original draft, formal analysis, data curation, methodology, project administration. **Mustafa Naimoglu:** writing – review and editing, writing – original draft, investigation, formal analysis, resources. **Selin Karlilar Pata:** writing – review and editing, writing – original draft, visualization, software, validation.

Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

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