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Research article

# Is public debt ‘curse’ or ‘benediction’ for environmental debt: A panel ARDL approach

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ABSTRACT

This paper studies the effect of public debt on environmental debt by considering the top ten highly indebted countries with annual periods from 1996 to 2022, exploring both the theoretical framework and empirical evidence. For the empirical investigation, the study employs the panel ARDL model, and the robustness of these results is confirmed from the FGLS model. The findings indicate that at the initial level of public debt, it is a “Curse” and at a higher level of public debt, it is a “Benediction” for environmental debt, with the turning point around 99 % of public debt to GDP. It shows there exists a non-linear relationship between public debt and environmental debt. The lower level of public debt increases the environmental debt, and when the debt level increases, the environmental debt falls. Along with this, economic growth, imposing environmental taxes, and the usage of renewable energy help mitigate environmental degradation. However, FDI inflows are positively associated with environmental debt. The study underscores that from the initial level of public debt needs to be managed efficiently by converting its effect from “Curse” to “Benediction” for the ecology.

## 1. Introduction

In recent decades, stemming the rising environmental and public debt has been the two distinguishing characteristics of achieving sustainable development in global prospects. Globally, the pressure of debt burden is increasing in the economy due to economic crises, socio-welfare demand, and unanticipated events such as pandemics and natural disasters. To mitigate this high debt burden, the government exploits ecological biodiversity by using it in revenue-generating activities (Boly et al., 2022). As per the Global Footprint Network (2023) report, the global per capita ecological deficit is 1.17 Gha, and the cumulative sum of this ecological biodiversity deficit is known as environmental debt. However, in the initial stage of public debt, it helps to increase the environmental abatement expenditure but in the long run, it reduces this expenditure due to the high pressure of the debt burden and its inefficient use (Asif et al., 2023). Hence, the environmental consequences of debt-financed decisions have sparked critical debates. Is public debt a benediction in the short run by generating funds for green innovation, sustainable infrastructure, and climate resilience? or can it be a curse in the long run by decreasing environmental abatement expenditure due to increasing the country’s liability for higher debt? This duality lies at the heart of modern economic and environmental policymaking, raising urgent questions about the long-term impacts of fiscal strategies on ecological health on achieving SDG-12.

From the “benediction” perspective, it suggests that in the short run for sustainable growth, the public debt acts as a catalyst (Reinhart and Rogoff, 2015). To promote environmental management, the role of public debt is very crucial through the borrowed funds channelled into green infrastructure, subsidies for renewable energy projects, and incentives to promote climate-adoption programs (Fay, 2012). From the empirical side, Sachs (2015) and Flammer (2021) suggest that countries with well-structured fiscal policies and effective governance leverage public debt to finance environmental innovation and transition to low-carbon economies.

In contrast, the “curse” point of view suggests that, in the long run, high public debt restricts fiscal space, forcing governments to prioritize short-term economic growth over long-term environmental sustainability based on priority (Cohen, 1993). Under such constraints, investment in environmental abatement expenditure is reduced, and the government minimizes the importance of green technology by putting more importance on immediate economic relief and debt servicing (Barro, 1979). This scenario occurs in high-debt countries where both

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environmental and public debt are the central issues of the economy (Frankel and Rose, 2005). Moreover, in the long run, the crowding out effect of high debt limits public spending on the environment for sustainable development (Krugman, 1988).

The existing studies examine the link between fiscal and environmental factors either linearly or within a country-specific analysis. With this background, the present paper fills the research gap by examining the non-linear association between public debt and environmental debt by exploring the theoretical and empirical perspectives in the top ten debt countries. Further, the study guides the central research question: Does public debt serve as a catalyst or a constraint for environmental sustainability, and at what point does its role change from substitutable to complementary concerning environmental debt by constructing a theoretical framework and conducting a comprehensive empirical investigation through an ARDL approach? The trends of public debt and environmental deficit are presented in Fig. 1. Our findings not only contribute to the academic discourse on fiscal and ecological economics but also provide actionable insights for policymakers tasked with balancing fiscal responsibility and environmental sustainability. Along with this, one significant contribution of this paper is to find the threshold point of public debt, where the association between public debt and environmental debt changed from substitutable to complementary nature.

In an era marked by climate change, resource scarcity, and growing environmental risks, understanding the implications of public debt for environmental sustainability is more critical. This research aspires to inform fiscal strategies that harmonize economic development with ecological preservation, addressing the pivotal question: Is public debt a curse or a benediction for environmental debt?

The rest of this paper is structured as follows: Section 2 presents the literature review; Section 3 describes the theoretical framework of this study; Sections 4, 5, and 6 explain the data & methodology, results, and the conclusion section, respectively.

## 2. Literature review

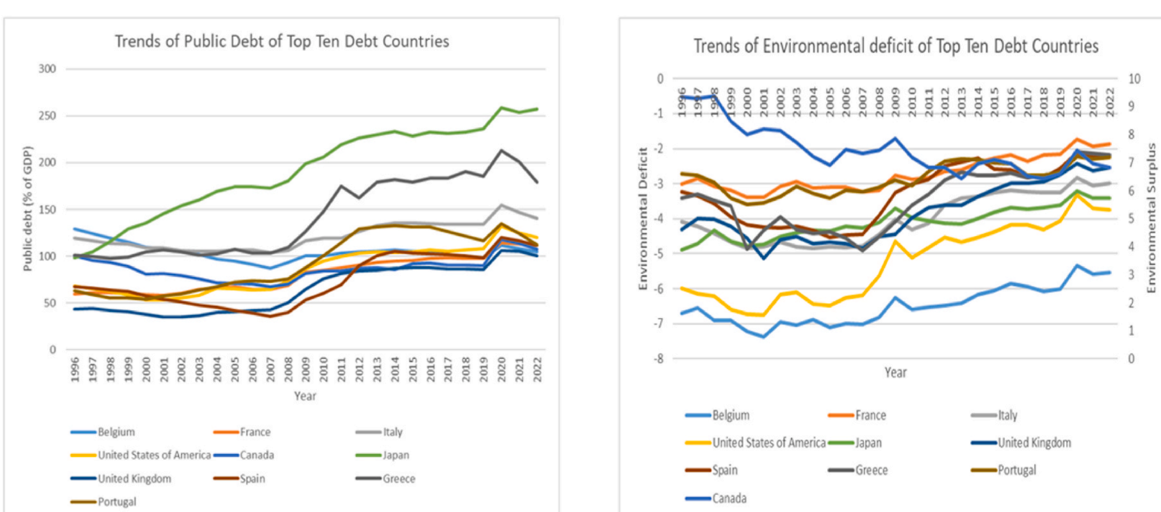
In recent times, public debt and environmental debt have become central concerns for researchers and policymakers striving for financial and environmental sustainability. The review of the study is structured under various headings, examining insights from both theoretical and empirical research on the association between environmental debt and public debt, as well as its connections with renewable energy, environmental taxation, FDI inflows, and economic growth.

### *2.1. Public debt and environmental debt*

From the sustainability development point of view, both public debt and environmental debt are the key concerns in the present world. In terms of this apprehension, Boly et al. (2022) studied the dynamic interplay between public debt and ecological sustainability and found that in the short run, public debt helps to achieve sustainability, but in the long run the effect is negative. In a similar line, Asif et al. (2023) studied the impact of fiscal deficit on environmental quality by employing a battery of distinct ARDL approaches in India. They explored that both in the short- and long-run, public debt and environmental debt are complementary. Similar work has also been done by Baret and Menuet (2024) and Sommer et al. (2020), and they observed a moderate level of public debt supporting green initiatives, while excessive debt exacerbates environmental degradation. In contrast, Aigbedo (2023) studied the effect of external debt on the environmental performance of 180 countries and found no impact of debt burden on environmental performance. However, the association between public and environmental debt depends primarily on the strategic management of debt (Khan et al., 2016; Pearce et al., 1995).

From the point of view of the policy, Halkos and Papageorgiou (2018) discussed the strategic management of pollution, public debt, and taxation through game theory, highlighting the potential for fiscal measures to mitigate environmental degradation while ensuring economic stability. Similarly, Ezenekwe et al. (2023) shift the focus to Nigeria, demonstrating how public debt and agricultural development mitigate environmental pollution despite the challenges posed by increased carbon emissions and economic vulnerabilities. Meanwhile, Qi et al. (2022) provide spatial insight from China, revealing how local government debt catalyzes urban pollution reduction through innovative environmental policies, showcasing the role of fiscal instruments in environmental stewardship.

Furthermore, several studies highlight that the increase in public debt restricts the ability of a country to invest in green technologies and climate adaptation strategies (Barbier, 1998; Daumas, 2023). However, unsustainable fiscal policies often lead to the exploitation of natural resources and exacerbate environmental degradation (Koskela and Schob, 2002). Whereas a significant portion of the literature studied the effect of public debt on economic growth (Yamin et al., 2023; Reinhart and Rogoff, 2015; Krugman, 1988), but its effects on environmental debt are notably scarce. Similarly, fiscal decentralization helps in bringing new ideas and innovations (Chi et al., 2021); however, how fiscal measure by controlling the public debt influences the environment debt




(A) (B)

**Fig. 1.** Trend pattern of public debt and environmental debt of top ten debt countries.

is rarely studied.

### 2.2. Renewable energy, environmental tax and environmental debt

To mitigate the environmental debt, the role of renewable energy is like the front wheel of a cycle. The study (Apergis and Payne, 2010) suggests that a country with a strong renewable policy tends to experience a lower ecological footprint and greenhouse gas emissions. However, another strand of literature studies the cost of renewable resources vs the cost of environmental pollution. They declared that in the long run, the cost of environmental pollution is greater than the cost of using renewable resources (Osman et al., 2023). However, increasing the usage of renewable energy not only mitigates the problem of the ecological deficit but also contributes to the security of energy and economic stability of the country (Pao and Tsai, 2011).

Similarly, Environmental taxation is one of the crucial factors that stem from both rising environmental debt and public debt. In the long-term improvement of the environmental condition, the role of carbon tax takes a visible place by adopting cleaner technologies (Nordhaus, 2018). Likewise, Yasmeen et al. (2023) find that in a well-structured "Rule of Law" in the countries, environmental taxes significantly reduce environmental pollution and, on the other hand, increase the revenue of the country. It explains the existence of higher compliance rates in such countries, where legal and institutional frameworks ensure better enforcement and adherence to environmental laws (Li et al., 2021). Along with this, it also reduced inter-generational inequality and public debt (Rausch, 2013). However, the effectiveness of environmental taxation in a country primarily depends on proper implementation and public acceptance (Carattini et al., 2018).

Despite these benefits, some studies highlight the challenges associated with the adoption of renewable energy and environmental taxes due to financial pressure. High initial investment costs and policy uncertainty often hinder the large-scale transition to clean energy (Jaffe et al., 2005).

### 2.3. Economic growth, FDI inflows and environmental debt

The role of economic growth is very substantial in the dynamic nature of environmental sustainability. An inverted U-shape relation exists between these variables, which highlights the "Environmental Kuznets Curve Hypothesis (EKC)". This hypothesis suggests that environmental degradation initially increases with economic growth but decreases after reaching a certain income level (Grossman and Krueger, 1995; Shahbaz et al., 2018). However, recent studies challenge this view, arguing that rapid industrialization often leads to irreversible environmental damage (Dinda, 2004).

Foreign Direct Investment (FDI) has two side effects in shaping environmental debt. On the one hand, FDI brings advanced green technologies and capital, fostering sustainable development (Wei et al., 2022), which helps to improve ecological quality. On the other hand, the "pollution haven hypothesis" suggests that multinational corporations often shift their polluting industries to where there are weaker environmental regulations (Eskeland and Harrison, 2003). Empirical studies provide mixed evidence, with some finding that FDI promotes green growth while others highlight its role in rising ecological degradation (Baek, 2016). From the stance of the policy, stringent environmental regulations and green financing mechanisms mitigate the negative effects of economic growth and FDI on environmental debt (Porter and Linde, 1995).

## 3. Theoretical background and empirical startegy

### 3.1. Environmental debt

The theoretical framework and empirical strategy are conceptualized by following the definition of environmental debt by Boly et al. (2022). Boly et al. (2022) defined the quality of the environment as $Q$, which represents the capacity of nature's biodiversity or the cleanliness of air, soil, water, etc. Further, the pollution is denoted as $P$, which indicates the reduction of environmental quality. The environmental deficit (D) is defined as:

$$D = Q - P \tag{1}$$

The environmental debt (ED) of a country $i$ at year $t$ is:

$$ED_{it} = \sum_{j=q}^{t} D_{ij} \tag{2}$$

where $q$ is the initial time period under study.

To capture the absorptive capacity of the environment, the pollution-generation process is assumed to follow:

$$P = \frac{Z^{\mu}}{G^{\delta}} \tag{3}$$

where $\mu > 0$ and $\delta > 0$ represent the elasticity of emissions of polluting inputs ($Z$) and elasticity of the regeneration process through abatement spending ($G$), respectively. These assumptions are consistent with Boly et al. (2022), and we retain them to preserve theoretical tractability.

Following the framework of Boly et al. (2022), we extend the framework by involving a representative competitive firm and government. While this model does not fully replicate the micro-foundations, particularly household behaviours and portfolio choices, it serves as a conceptual tool to provoke the empirical investigation of the debt–environment relationship within the limitations of this study.

### 3.2. Firm

Here, it is assumed that the firm would produce output $Y$ *by* using three input factors known as labour ($L$), capital ($K$), and polluting inputs ($Z$). For this analysis, the "Cobb-Douglas production function" is considered. The "Cobb-Douglas production" can be written as:

$$Y = AK^{\alpha}Z^{\beta}L^{1-\alpha-\beta} \tag{4}$$

where $\alpha$, $\beta$, and $1-\alpha-\beta$ are elasticities of capital, polluting inputs, and labour, respectively.

To produce the output $Y$, the firm should pay factor costs known as rent ($r$) for capital, wages ($w$) for labour, payment ($m$) for purchasing polluting inputs, and carbon taxes ($t$) for pollution. The cost function of the firm can be written as:

The total cost function is:

$$TC = rK + wL + mZ + tP \tag{5}$$

The firm's profit function is:

$$\pi = \rho Y - rK - wL - mZ - tP \tag{6}$$

where $\rho$ is the price of output and $\rho Y$ is the total revenue.

### 3.3. Government

The revenue of the government can be generated from equation (7) like taxes on profit ($\pi_t$), taxes on rent ($r_t$), taxes on labour income ($w_t$), taxes on prices of polluting inputs ($z_t$), and taxes on carbon emissions ($p_t$). The revenue ($R$) of the government can be written as:

$$R = \pi_t + r_t + w_t + z_t + p_t \tag{7}$$

The government provides abatement expenditure ($G$) for the regeneration process from the tax revenue ($R$) and borrows from the household ($B$). The functional deficit financed of the government can be written as:

$$B = R - E \tag{8}$$

Where total expenditure (E) consists of.

(I) Expenditure on pollution abatement (G).
(II) Other expenditure (Q).

Thus, the deficit equation becomes:

$$B = R - G - Q \tag{9}$$

The public debt of a country $i$ at year $t$ is $PD_{it}$.

When the total expenditure is greater than total revenue, the deficit will appear and the cumulative summation of this deficit over the year is known as public debt. When public debt increases, expenditure on pollution abatement and other activities increases, and other side interest payments also increase along with the principal amount. In other words, at the initial level when public debt increases, expenditure on pollution abatement and other activities increases, hence the pollution level decreases. But when public debt is high, the country should pay more interest payments for this debt with the principal amount and because of these high interest payments, the government would reduce expenditure on pollution abatement activities on a priority basis, leading to pollution increases.

**Proposition 1**. *In the initial level, public debt (PD) and pollution (P) are substitutable*:

$$\frac{\partial P}{\partial PD} < 0 \tag{10}$$

**Proof**. from equations (3) and (8), the study proposes that an initial or low level of public debt increases the expenditure on pollution abatement activities. Hence pollution level decreases. It also assumes that the initial level of public debt, the elasticity of pollution abatement expenditure are greater than the adverse effects of polluting inputs' elasticity ($\delta > \mu$).

**Proposition 2**. *Public debt at a higher level, public debt* (PD) *and pollution* (P) *are complementary*:

$$\frac{\partial P}{\partial PD} > 0 \tag{11}$$

**Proof**. from equations (3) and (8), the study proposes that in the long run or high level of public debt ($PD^2$) requires a high level of interest payment with the principal amount and because of this high interest payment, expenditure on pollution abatement activities will decrease. Hence, pollution levels increase. It also assumes that at the higher level of public debt, the elasticity of pollution abatement expenditure is less than the adverse effects of polluting inputs' elasticity ($\delta < \mu$).

## 4. Data and methodology

The study considers the top ten debt countries, i.e. Japan, Greece, Italy, United States, Portugal, France, Spain, Canada, Belgium and the United Kingdom, which have 257, 179, 140, 120, 112, 111, 111, 107, 104, and 100 public debts percentage of their GDP, respectively (IMF report 2022). It uses the latest available consecutive annual data from 1996 to 2022 of the selected variables. Environmental debt is considered the response variable in this study and public debt and public debt$^2$ are the focal explanatory variables here. Along with this, the study also contemplates some control variables known as GDP per capita, Renewable energy, Environmental Tax, and FDI inflow. These variables are selected based on the previous literature (Apergis and Payne, 2010; Barro, 1979; Boly et al., 2022; Halkos and Papageorgiou, 2018). A brief description of the variables is presented below in Table 1.

**Table 1**
List of variables and data sources.

| Variables | Symbol | Source |
|---|---|---|
| Environmental Debt (Per Capita) | ED | Authors' own calculation from Global Footprint Network Data[a] |
| Public Debt (% of GDP) | PD | International Monetary Fund (IMF) |
| Public Debt$^2$ (% of GDP) | PD$^2$ | Authors' own calculation from IMF Data |
| GDP Per Capita (Constant US $ 2015) | GDP | World Development Indicators |
| Renewable Energy (% of Total Energy) | RE | Our World in Data |
| Environmental Tax (% of GDP) | ET | OECD database |
| FDI Inflows (% of GDP) | FDI | World Development Indicators |

[a] Environmental debt $(ED_{it}) = \sum_{j}^{t} (D_{ij})$ where $i$ represnts the country, $j$ is the start year, $D$ stands for environmental deficit.
Source: Authors' Compilation.

The "Global Footprint Network, International Monetary Fund (IMF), World Development Indicators, Our World in Data, and OECD database" are the data sources of this study. The environmental debt is the cumulative summation of ecological deficit, representing the standard quantitative measure of environmental degradation (Boly et al., 2022). As per Baret and Menuet (2024), public debt contains all the liabilities that the government has to repay the principal amount with the interest payment to the lenders at dates or dates in the future. Similarly, GDP per capita measures the quantitative growth of economic activity, and this variable is more reliable than GDP. It also considers the distribution of GDP and people's standard of living (Grossman and Krueger, 1995).

The renewable energy as a percentage of total energy is defined as the total energy derived from naturally replenishing sources that are sustainable and not depleted as compared to total energy use (Apergis and Payne, 2010). The environmental tax explains a tax whose tax base is a physical unit that has been imposed on a negative impact on the environment (Halkos and Papageorgiou, 2018). As stated in Wei et al. (2022), foreign direct investment (FDI) inflows as a percentage of GDP reflect the net investment in the host country by foreigners with more than 10 percent voting share. The summary statistics of the variables are presented in Table 2. Here, all the variables are converted into natural logarithmic form through the "Asinh transformation" technique, which is helpful when the variables contain negative values.

To measure the non-linear effect of public debt on environmental debt, the following basic econometric equation is written as:

$$ED_{it} = \beta_0 + \beta_1 PD_{it} + \beta_2 PD^2{}_{it} + \beta_3 GDP_{it} + \beta_4 RE_{it} + \beta_5 ET_{it} + \beta_6 FDI_{it} + \epsilon_{it} \tag{12}$$

Here $i$ and $t$ represent the country and time period, respectively, $\beta_0$ represents the intercept, $\beta_i$ indicates the slope coefficient, and $\epsilon$ represents the error term.

### 4.1. Empirical estimation

#### 4.1.1. Cross-sectional dependency (CSD) test

During the initial step of the panel data model to avoid misleading regression results, it is essential to check the CSD test in the analysis. It explains the correlation between the panels through socio-demographic and economic factors (Chi et al., 2021). This study uses the CSD (LM) technique, which was first given by Breusch and Pagan (1980), to ensure the precision of the analysis. The LM test can be written as:

$$y_{it} = \alpha_i + \beta_i x_{it} \tag{13}$$

Furthermore, the test of CSD (LM) statistics is as:

**Table 2**
Summary statistics.

| Variables | Environmental Debt | Public Debt | GDP Per Capita | FDI Inflows | Environmental Tax | Renewable Energy |
|---|---|---|---|---|---|---|
| Mean | −43.36 | 104.58 | 34,052.83 | 3.18 | 2.08 | 11.54 |
| Median | −54.09 | 100.42 | 33,999.95 | 1.82 | 2.10 | 8.31 |
| Maximum | 201.94 | 258.30 | 63,720.76 | 46.35 | 4.15 | 33.31 |
| Minimum | −175.25 | 34.96 | 16,280.94 | −7.66 | 0.16 | 0.24 |
| Std. Dev. | 64.60 | 45.39 | 10,557.00 | 5.88 | 0.78 | 8.73 |
| Skewness | 1.55 | 1.21 | 0.29 | 4.38 | 0.18 | 0.92 |
| Kurtosis | 6.40 | 4.62 | 2.70 | 26.76 | 2.68 | 2.73 |
| JB (P value) | 283.68 (0.00) | 95.13(0.00) | 4.85(0.08) | 7213.06(0.00) | 2.61(0.27) | 38.52(0.00) |
| Observations | 270 | 270 | 270 | 270 | 270 | 270 |

Note: author's computation.

$$M = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{P_{ij}}\rightarrow d\chi^2\, N\,(N-1)\Big/2 \tag{14}$$

where $\widehat{P_{ij}}$ denotes the residuals pairwise correlations.

where $T$ represents the temporal dimension, and $N$ denotes the presence of CSD. This study also includes a slope homogeneity test based on the methods presented by Pesaran and Yamagata (2008). The test equation is expressed as "adjusted delta tiled and delta tiled".

### 4.1.2. Panel unit root test

After the CSD test, the next step is to examine the "second-generation (S-G) unit root test" when CSD exists in the model (Li et al., 2021). The study uses the "Cross-Sectional Augmented Dickey-Fuller (CADF)" and "Augmented Cross-Sectional Im Pesaran and Shin (CIPS)" test for the S-G unit root test, which was given by Pesaran (2007). The CADF equation can be written as:

$$\Delta x_{it} = \alpha_{it} + \beta_{it-1} + \delta_i T + \sum_{j=1}^{N}\gamma_{it}\Delta x_{it-j} + \mu_{it} \tag{15}$$

Where $x$ represents the variables, $\Delta$ denotes the difference between these variables, and $\mu$ indicates the error term.

Similarly, the CIPS test can be written as follows:

$$CIPS\,(N,T) = N^{-1}\sum_{i=1}^{N} t_i(N,T) \tag{16}$$

where $t_i(N,T)$ signifies CADF statistics.

## 4.2. Cointegration test

Further, the study considers the Westerlund panel cointegration test to check whether the long-run association exists or not between the variables, and this test is best when the panel has CSD in the cross-section (Westerlund, 2007). The Westerlund Cointegration test can be written as:

$$\Delta y_{it} = \gamma_i \partial_t + \partial_i\left(Y_{i,t-1} - \beta_i X_{I,t-1}\right) + \sum_{j=1}^{k}\delta_{ij}\Delta Y_{i,t-j} + \sum_{j=1}^{k}\vartheta_{i,t-j} + \varepsilon_{i,t} \tag{17}$$

### 4.2.1. Panel ARDL model

This study uses the "Panel Autoregressive Distributed Lag (ARDL)" model (Pesaran et al., 2001) to examine the substitutable and complementary association between environmental debt and public debt. The benefit of the uses of this model is that it considers both I (0) and I (0) order of integration and it gives consistent results when the sample size is small (Chi et al., 2021; Shao et al., 2021). To check the robustness of this model, the study considers the "Feasible Generalized Least Squares (FGLS)" model, which requires the same pre-requisite condition as the ARDL model. Equation (12) can be written as in the panel ARDL framework:

$$\begin{aligned}\Delta ED_{it} &= \alpha_1 + \sum_{j=1}^{p}\delta_{ij}\Delta ED_{i,t-j} + \sum_{i=0}^{q1}\beta_{ij}\Delta PD_{i,t-j} + \sum_{i=0}^{q2}\vartheta_{ij}\Delta PD^2_{i,t-j} \\ &+ \sum_{i=0}^{q3}\omega_{ij}\Delta GDP_{i,t-j} + \sum_{i=0}^{q4}\omega_{ij}\Delta RE_{i,t-j} + \sum_{i=0}^{q5}\omega_{ij}\Delta ET_{i,t-j} + \sum_{i=0}^{q6}\omega_{ij}\Delta FDI_{i,t-j} \\ &+ \theta_1 ED_{i,t-1} + \theta_2 PD_{i,t-1} + \theta_3 PD^2_{i,t-1} + \theta_4 GDP_{i,t-1} + \theta_5 RE_{i,t-1} + \theta_6 ET_{i,t-1} \\ &+ \theta_7 FDI_{i,t-1} + \varepsilon_{it}\end{aligned} \tag{18}$$

However, the short-run equation of the ARDL models can be expressed as:

$$\begin{aligned}\Delta ED_{it} &= \alpha_1 + \sum_{j=1}^{p}\delta_{ij}\Delta ED_{i,t-j} + \sum_{i=0}^{q1}\beta_{ij}\Delta PD_{i,t-j} + \sum_{i=0}^{q2}\vartheta_{ij}\Delta PD^2_{i,t-j} \\ &+ \sum_{i=0}^{q3}\omega_{ij}\Delta GDP_{i,t-j} + \sum_{i=0}^{q4}\omega_{ij}\Delta RE_{i,t-j} + \sum_{i=0}^{q5}\omega_{ij}\Delta ET_{i,t-j} + \sum_{i=0}^{q6}\omega_{ij}\Delta FDI_{i,t-j} \\ &+ \rho_1 ECM_{t-1} + \varepsilon_{it}\end{aligned} \tag{19}$$

Where $p$ and $q$ represent the lag order of dependent and independent variables respectively and this lag order is selected based on "Akaike Information Criteria".

## 5. Empirical results

The CSD test is the first step to run the panel ARDL model, the results of the CSD test are presented in Table 3 below. The results of the CSD test show that the CSD exists among the cross-sections at a one percent level of significance. This explains the shock of one country spreading to the other countries (Li et al., 2021).

The next step is to check the S-G unit root test after confirming the existence of CSD among the cross-sections. Because the first-generation unit root test did not take into account the CSD. Here, the study considered the CADF and CIPS for the S-G unit root test. The results of the S-G unit root test are reported in Table 4. These results show that, in the case of CADF all the variables are stationary in the first difference, whereas FDI inflows and renewable energy are stationary in the mixing nature. Similarly, in the case of CIPS, a similar result also arises as the CADF. However, environmental debt is stationary in the mixing nature in the case of CIPS.

To confirm these results, the study uses the Karavias and Tzavalis (2014) unit root test with a structural break. Table 5 explains the results

**Table 3**
Cross-section dependence test.

| Test | Statistics | Prob. |
|---|---|---|
| Breusch-Pagan LM | 816.15*** | 0.00 |
| Pesaran scaled LM | 81.29*** | 0.00 |
| Pesaran CD | 19.42*** | 0.00 |

Note: Author's Own Computation. *** denotes the 1 % level of significance.

**Table 4**
S-G unit root test.

| Variables | CADF | | CIPS | |
|---|---|---|---|---|
| | I (0) | I (1) | I (0) | I (1) |
| Environmental Debt | −0.120 | −6.018*** | −2.467** | −4.880*** |
| Public Debt | 0.037 | −2.287** | −1.343 | −3.178*** |
| Public Debt$^2$ | 0.092 | −2.287** | −1.372 | −3.196*** |
| GDP Per Capita | 0.657 | −3.415*** | −0.703 | −3.279*** |
| FDI Inflows | −2.799*** | −9.499*** | −3.398*** | −5.892*** |
| Environmental Tax | 3.518 | −4.829*** | −0.788 | −4.463*** |
| Renewable Energy | −2.131** | −6.640*** | −2.250** | −5.043*** |

Note: Author's Own Computation. ** and *** denote the 5 % and 1 % level of significance, respectively.

**Table 5**
Structural break unit root test.

| Variables | I (0) | I (1) |
|---|---|---|
| Environmental Debt | −15.961***(2021) | −16.767***(2020) |
| Public Debt | −16.196***(1997) | −17.953***(1997) |
| Public Debt$^2$ | −16.620***(1997) | −18.576***(1997) |
| GDP Per Capita | −15.107***(2021) | −19.522***(1997) |
| FDI Inflows | −15.503***(2012) | −30.149***(2020) |
| Environmental Tax | −8.538***(2011) | −26.960***(2020) |
| Renewable Energy | −15.484***(1997) | −27.903***(1997) |

Note: Author's Own Computation. *** denotes the 1 % level of significance.

of the unit root test with a structural break. These results explain that all the variables are stationary at both orders of integration at a one percent level of significance with the structural break in 1997, 2011, 2012, 2020, and 2021. The cause behind the structural break of public debt and GDP in 1997 may be because of the spillover effect of the "1997 Asian Financial Crisis" on the global economy and a rise in country-specific high fiscal pressure. The structural break in 1997 in renewable energy arises because in 1997, the Kyoto Protocol was adopted. Similarly, the reason behind the 2011 structural break in environmental taxation is that many advanced countries implemented the "Clean Energy Act 2011" and at the same time Japan legislation passed in 2011 on implementing a tax for climate change mitigation. The European Sovereign Debt Crisis is the main reason for the 2012 structural breakdown in FDI. This leads to financial instability in Europe. And finally, COVID-19 is the focal cause of the structural break that will arise in 2020 and 2021 by negatively affecting the global economy.

To check the presence of variability among the cross-sections, the study considered the "Pesaran-Yamagata Slope Heterogeneity Test". These results are reported in the upper part of Table 6. The results show that a one percent level of significance rejected the null hypothesis that the slope coefficient is homogeneous and concluded that variability exists in the cross-section. The bottom part of Table 6 presents the results of the different panel cointegration tests. It confirms that all the variables are cointegrated and that a long-run association exists between these variables.

To obtain robust findings in the presence of CSD and heterogeneity, the study considers the panel ARDL model to estimate the coefficient parameter of the variables which is reported in Table 7, and the lag order is selected (1,1,1,1,1,1,1) based on minimum "Akaike Information Criteria" in Model 1 (See Fig. 2). The Akaike Information Criterion (AIC) is used to determine the optimal model by balancing model fit and complexity. The lag order (1,1,1,1,1,1,1) indicates the respective lag order for each variable used in the panel ARDL estimation.

In the short run, the results show there are no significant effects of any of the independent variables on environmental debt. It denotes that the effect on environmental debt is a long-term process. However, the ECM in this instance is −0.25, denoting an adjustment to the long-run equilibrium after a shock with the speed of 25 % at a one percent level of significance and it also confirms that the long-run relationship exists in the model. The existing research also talks about the long run equilibrium relationship with short run correction between public debt and environment degradation (Shaari et al., 2023; Zeraibi et al., 2024).

The long-run results of the panel ARDL model are shown in the upper part of Table 7. It shows that in the long run, public debt is positively associated with environmental debt at a 1 % level of significance. It indicates a one percent increase in public debt, environmental debt increases by 3.76 percent. It denotes that at the initial level, public debt and ecological debt are complementary. Similarly, public debt$^2$ is negatively associated with environmental debt at a one percent level of significance. It defines a 1 % increase in public debt$^2$, environmental debt decreases by 0.41 percent. It shows that public debt at a higher level is substitutable with ecological debt, which is the opposite of the hypothesis of this study. This result indicates that in these higher-debt countries, public debt management is economically sound and shows that an inverted "U" shape relationship exists between public and environmental debt, with the turning point 98.49 % of public debt to GDP (see Appendix I for the detailed calculation). The results of this study are also aligned with the previous literature Farooq et al. (2023). Further, the country-wise trends of environmental deficit and public debt are presented in Appendix II. Moreover, our sample of highly

**Table 6**
Slope heterogeneity and panel cointegration test.

| Test | Statistics | Prob. |
|---|---|---|
| **Pesaran-Yamagata Slope Heterogeneity Test** | | |
| Delta | 11.042*** | 0.000 |
| Adj. Delta | 13.163*** | 0.000 |
| **Panel Cointegration Test** | | |
| **Westerlund test** | 1.9192** | 0.027 |
| **Pedroni test** | | |
| Modified Phillips Perron Test | 2.651*** | 0.004 |
| Phillips Perron Test | −7.772*** | 0.000 |
| Augmented Dickey-Fuller Test | −2.207** | 0.013 |
| **Kao test** | | |
| Modified Dickey-Fuller Test | −3.955*** | 0.000 |
| Dickey-Fuller Test | −8.122*** | 0.000 |
| Augmented Dickey-Fuller Test | −2.836** | 0.002 |

Note: Author's Own Computation. ** and *** denote the 5 % and 1 % level of significance, respectively.

**Table 7**
Results of panel ARDL model.

| Variables | Long-run | | | |
|---|---|---|---|---|
| | Coefficients | Std. Error | t-Statistics | Prob. |
| PD | 3.76*** | 0.35 | 10.90 | 0.00 |
| PD$^2$ | −0.41*** | 0.03 | −12.04 | 0.00 |
| GDP | −1.73*** | 0.17 | −10.26 | 0.00 |
| FDI | 0.02** | 0.01 | 2.56 | 0.01 |
| ET | −0.14* | 0.08 | −1.78 | 0.08 |
| RE | −0.16*** | 0.02 | −6.86 | 0.00 |
| | **Short-run** | | | |
| ECM | −0.25*** | 0.02 | −14.53 | 0.00 |
| D(PD) | −0.18 | 1.25 | −0.14 | 0.89 |
| D(PD$^2$) | 0.02 | 0.11 | 0.18 | 0.85 |
| D (GDP) | 0.17 | 0.17 | 1.03 | 0.31 |
| D (FDI) | −0.001 | 0.00 | −0.07 | 0.95 |
| D(ET) | 0.01 | 0.05 | 0.29 | 0.77 |
| D(RE) | −0.03 | 0.03 | −0.91 | 0.37 |
| Con | 1.84*** | 0.15 | 12.61 | 0.00 |
| Root MSE | 0.03 | Mean dependent var | | −0.10 |
| S.D. dependent var | 0.16 | S.E. of regression | | 0.03 |
| Akaike info criterion | −3.88 | Sum squared resid | | 0.20 |
| Schwarz criterion | −2.74 | Log-likelihood | | 609.95 |
| Hannan-Quinn criter. | −3.42 | | | |

Note: Author's Own Computation. *, ** and *** denote the 10 %, 5 %, and 1 % level of significance, respectively.

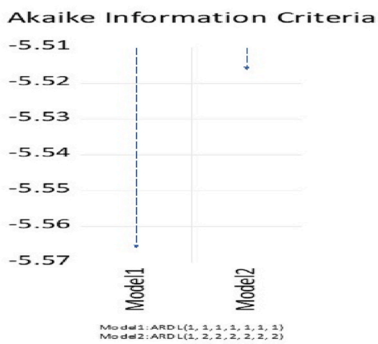



**Fig. 2.** Akaike information criteria.

indebted countries, like Japan, France, and the United Kingdom, have actively pursued green transitions as part of their fiscal strategies at their high debt levels. Countries at higher levels of debt may adopt embraced green strategies as a response to fiscal stress, using environmental reforms to attract climate-linked financing and align with best standards. This may be expensive, but it is environmentally sustainable. On the contrary, low public debt levels for these high-debt countries might reflect limited state capacity for environmental protection. Thus, the empirical result indicates that public debt management in these countries is economically sound and consistent with a non-linear environmental response. To better validate the presence and nature of the non-linear association between public and environmental debt, the study reports the "Lowess Plot" (seen in Fig. 3 below). This shows that a non-linear association exists between public debt and environmental debt with an inverted U shape, which supports the empirical results.

In the case of economic growth, environmental debt is adversely influenced by it. This indicates that environmental debt mitigates 1.73 percent when economic growth increases by one percent. It denotes that when economic growth increases, people are more conscious about environmental degradation. Similarly, environmental tax and renewable energy are helping to mitigate the environmental debt burden at 10 and 1 percent levels of significance, respectively. It shows a one percent increase in environmental tax and renewable energy, environmental debt decreases by 0.14 and 0.16 percent, respectively. The environmental tax imposes financial pressure on polluters by increasing the cost of production and on another side, it also increases the revenue of the country by helping to increase environmental abatement expenditure. Renewable energy usage increases recyclable and sustainable power consumption, which leads to decreased environmental degradation. These results are also supported by some previous work (Grossman and Krueger, 1995; Halkos and Papageorgiou, 2018; Yasmeen et al., 2023). However, in the case of FDI inflows, it increases the environmental debt by supporting the "pollution Haven Hypothesis". It shows that a 1 % increase in FDI, environmental debt increases by 0.02 percent at a 1 % level of significance. These results also corroborate with some previous work (Eskeland and Harrison, 2003). To check the robustness of the panel ARDL model results, the study considers the FGLS model, which requires the same pre-requisite conditions as the ARDL model. The result of this model presented in Table 8, shows as similar to the results of the ARDL model. However, the effect of FDI and renewable energy on environmental debt is insignificant.

### 5.1. *Discussion*

From the above findings, the study concludes that public and environmental debt associations are complementary in nature at the initial level of public debt and substitutable in nature at the higher level of public debt. It shows that an inverted "U" shape relationship exists between these variables. Which is the opposite of the hypothesis of this study. The cause behind these results is that the selected country of this study is highly debated in nature, along with the other characteristics of these countries, they are coming under the high-income group as per the World Bank classification 2022. When a country has in high-income country, if they are at taking initial level of debt, they may spend on some economic activities that lead to environmental degradation, but at a higher level of public debt case, they may be cautious about the environment, which leads to them spending more on environmental abatement activities. Hence, at the initial level public debt is the "curse" and at the higher level it is the "benediction" for the environmental debt in these countries.

## 6. Conclusion and policy suggestion

Public debt has been a longstanding concern for economic stability, yet its implications on environmental debt remain underexplored. This study examines the impact of public debt (PD) and its quadratic term ($PD^2$) on environmental debt across ten highly indebted countries:

**Table 8**
Results of FGLS model.

| Variables | Coefficients | Std. Error | Z | Prob. |
|---|---|---|---|---|
| PD | 4.80*** | 0.41 | 11.72 | 0.00 |
| $PD^2$ | −0.57*** | 0.04 | −14.08 | 0.00 |
| GDP | −3.48*** | 0.08 | −46.12 | 0.00 |
| FDI | 0.01 | 0.00 | 1.32 | 0.19 |
| ET | −0.02 | 0.03 | −0.90 | 0.37 |
| RE | −0.19*** | 0.01 | −13.63 | 0.00 |
| Con | 26.77*** | 1.28 | 20.87 | 0.00 |

Note: Author's Own Computation. *** denotes the 1 % level of significance.

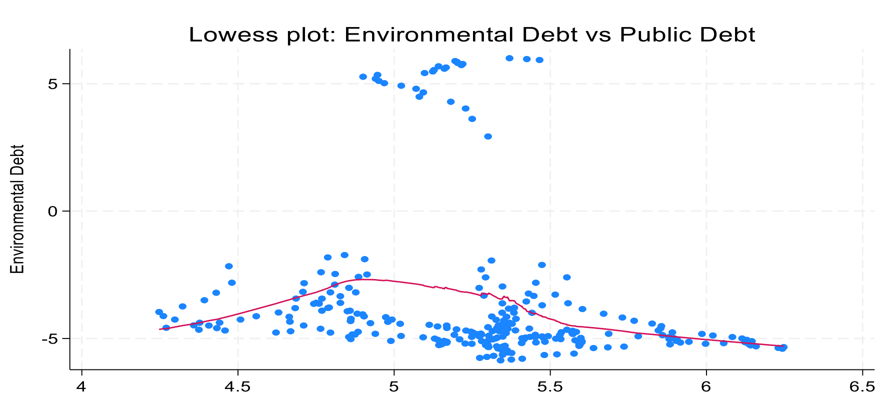



**Fig. 3.** Lowess plot for non-linearity test.

Japan, Greece, Italy, the United States, Portugal, France, Spain, Canada, Belgium, and the United Kingdom. By incorporating GDP per capita, Renewable Energy (RE), Environmental Tax (ET), and Foreign Direct Investment (FDI) inflows as control variables, this study seeks to uncover the complex relationships between financial and environmental liabilities.

Public debt significantly influences environmental debt, as evidenced by the Panel ARDL Model results. The positive and highly significant coefficient for public debt (3.76***) suggests that rising national debt exacerbates environmental debt, aligning with Sachs (2015), who argues that fiscal constraints limit environmental policies. However, the negative quadratic term (−0.41***) indicates a nonlinear relationship, implying that at higher debt levels, policy shifts may mitigate environmental harm, consistent with Krugman (1999). Higher GDP per capita (−1.73***) reduces environmental debt, supporting Nordhaus (2013), who emphasizes the role of economic growth in promoting cleaner technologies. Foreign Direct Investment (FDI) has a minor but positive effect (0.02**), indicating that FDI inflows may contribute to environmental degradation, reinforcing the "Pollution Haven Hypothesis" (Eskeland and Harrison, 2003). Conversely, environmental tax (−0.14 *) and renewable energy usage (−0.16***) significantly mitigate environmental debt, demonstrating the effectiveness of taxation and clean energy adoption in addressing climate concerns.

Among the countries analysed, Japan has the highest debt-to-GDP ratio (~260 %), and its debt burden limits aggressive climate funding despite its advancements in renewable energy. Greece has faced severe austerity measures, prioritizing economic recovery over green investments, which has worsened environmental degradation. While the United States confronts a mixed policy scene where state-level programs lead in environmental accomplishments, but high federal debt limits broad climate legislation, Italy battles high borrowing rates that limit fiscal capacity for sustainability initiatives. Despite budgetary limits, Portugal has expanded its renewable energy industry; France uses green tax policies efficiently, but public resistance has restricted more ambitious changes. Though debt worries have caused uneven policy execution, Spain has advanced in renewable energy. Though its growing public debt jeopardizes future sustainability initiatives, Canada has kept strong environmental policies. Though it carries debt, Belgium has effectively used environmental charges to lower pollution. Though post-Brexit financial concerns have limited its climate expenditure, the United Kingdom still tops offshore wind energy.

Supporting literature underlines the limiting character of high debt on green investments (Sachs, 2015), the environmental hazards of FDI (Eskeland and Harrison, 2003), and the nonlinear relationship between debt and environmental outcomes (Krugman, 1999). Contradictory points of view claim that while economic development might result in technical innovations that reduce environmental debt (Nordhaus, 2013), focused public investments in sustainability can counteract debt-related environmental concerns (Stiglitz, 2017). Some research contends that more than financial limits, regulatory systems are more important in shaping environmental results. Policy suggestions call for responsible fiscal policies to balance economic and environmental sustainability, green investments being given top priority despite debt limits, enhanced environmental taxes, support of renewable energy use, and use of FDI for sustainable projects. This paper shows a nonlinear relationship between governmental debt and environmental debt, hence underlining their complexity. Although high debt usually aggravates environmental quality, beyond a particular point austerity and fiscal consolidation could restrict more harm. Furthermore, this paper shows an inverted U-shaped nonlinear relationship between government debt and environmental debt. The turning point is at the level, when public debt is 98.49 % of GDP. This finding has important implications for the design of budgetary spending. At lower levels of public debt, the budget allocation should take care of the fiscal space required for green public investments and ensure long-term environmental sustainability. Therefore, fiscal rules, like the Growth Pact can play a crucial role in maintaining a balance between debt sustainability and environmental goals.

## CRediT authorship contribution statement

**Akash Kumar Biswal:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Biswajit Patra:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Malayaranjan Sahoo:** Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126550.

## Data availability

Shared in the File Upload section

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