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Environmental Impact in the Development Indexes, Trends and Comparisons at the World Scale

Marco Filippo Torchio [1,*], Umberto Lucia [1] and Giulia Grisolia [2,*]

[1] Dipartimento Energia "Galileo Ferraris", Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy; umberto.lucia@polito.it (U.L)
[2] Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
* Correspondence: marco.torchio@polito.it (M.F.T); giulia.grisolia@polito.it (G.G.)

Abstract

Environmental factors play a crucial role in shaping human development. This study explores an extension of the United Nations Planetary pressure-adjusted Human Development Index ($PHDI$) by incorporating three methodological refinements: (i) a disaggregated analysis of material footprint data; (ii) the inclusion of a local adjustment factor related to fine particulate matter ($PM_{2.5}$) exposure; and (iii) a variation to the planetary pressure aggregation method for obtaining the $PHDI^*$ index. The geographical scope encompasses 137 countries across the five permanently inhabited continents (Africa, America, Asia, Europe, and Oceania). The analysis first evaluates how these additional parameters deviate from the standard UN framework, followed by a continental assessment of national performances and their underlying drivers. A revised global ranking is presented, with countries categorised into four development levels based on Jenks Natural Breaks-derived cut-off values. Comparative cartographic visualisations highlight the shifts among the standard indexes and the proposed $PHDI^*$, illustrating that while some high-development countries—primarily in Europe—maintain their status, the inclusion of environmental aspects change the categories of important countries. These results suggest that accounting for localised environmental stressors and a more detailed material footprint analysis provides a more granular representation of the constraints on human development.

Keywords: Human Development Index; planetary pressures; material footprint; greenhouse gases; fine particulate matter; environmental world ranking

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1. Introduction

During the second half of the 20th century, the concept of development has been primarily understood as a synonym for economic growth. In this context, the Gross Domestic Product (GDP) was conventionally adopted as the sole indicator to assess progress [1]. However, since the final decades of the 20th century, the development concept has progressively shifted from a narrow focus on economic growth toward a broader, human-centred perspective [2]. This transition was driven by several studies, such as those of Cornia and Court [3], which analysed the relationship between well-being and growth, emphasising that high poverty rates can persist despite economic growth. Therefore, the objective shifted toward defining development through the fulfilment of citizens' needs. This recognition led to a redefinition of development as a process aimed at expanding people's capabilities and freedom, rather than merely increasing aggregate income [4–6]; thus, to achieve a high level of well-being, it was also considered essential to address cultural, geographical, institutional, and historical elements [7].

In 1990, a major institutional response to this conceptual viewpoint change was the introduction of the Human Development Index (HDI), promoted by the United Nations Development Programme (UNDP). The HDI was explicitly designed as an alternative to GDP, with the objective of capturing key aspects of human well-being through a simple and communicable composite metric [8], taking also into account—beyond economic performance—the quality of life and social advancement; thus, the HDI is a statistical composite index that encloses life expectancy, education including both average years of completed schooling and expected years of schooling for newcomers to the education system, and per capita income indicators, aiming to incorporate socio-economic factors in assessing a nation's development. Its methodological intuitiveness, transparency, and global coverage have contributed to its widespread adoption in academic research and international policy debates. Indeed, this index can be adopted to categorise countries into four levels of human development [8,9]. A country achieves a higher HDI score when its lifespan, education attainment, and gross national income (GNI) per capita—adjusted for purchasing power parity—are all significantly elevated.

Building on its widespread recognition, the HDI has evolved through a continuous scientific debate regarding its methodology and conceptual scope. Scholars have pointed out limitations related to data quality, aggregation procedures, and the implicit assumptions underlying the choice and weighting of dimensions [10]. More recently, it has been argued that the HDI reflects a conception of development that is largely socio-economic, while omits the aspects related to environmental conditions under which human development is achieved [11]. Nevertheless, the inclusion of the three selected components of HDI was a methodological choice to maintain a parsimonious focus on human capabilities and well-being—going beyond GDP—while facing limited global data standardisation [4]. However, the shortcoming of environmental aspects has been pointed out and considered as a limitation by many scholars [12]. For instance, Bravo [13] argued that the environmental component should be included with the same weight as the already existing components, while Biggeri and Mauro [14] suggested enhancing the HDI with environmental metrics, specifically by incorporating CO_2 emissions. Similarly, Li and Wang [15] highlighted the importance of a multidimensional approach to environmental sensitivity, incorporating resource consumption and emission levels within regional development assessments. Zhang et al. [16] have highlighted the trade-offs between socio-economic progress and environmental pressures, particularly in rapidly developing economies where improvements in human development may be accompanied by increasing resource use and emissions. Recently, new approaches have been introduced to build new composite indexes which include HDI combined with others composite indexes, as the Environmental Performance Index (EPI) [17]. Indeed, the human-centred interpretation of development has been increasingly challenged by the growing relevance of global environmental factors and pressures [18–20]: phenomena such as climate change, biodiversity loss, and environmental pollution are largely driven by anthropogenic activities and directly influence both present and future well-being [16,21–23]. Therefore, in recent studies, many environmental and technological aspects that can influence the HDI resulting value have been deeply investigated, e.g., CO_2 emissions [24]; renewable energy and socio-economic combined with institutional factors [25]; the green energy transition combined with decarbonisation aspects [26]; Information and Communication Technology (ICT) [27]; ICT and renewable energy development and diffusion [28]; climate risk, ICT and pollution factors [29].

These dynamics highlight the need for developing frameworks capable of accounting for environmental constraints and policies alongside socio-economic achievements [30–35].

More generally, the growing complexity of sustainability challenges has stimulated the development of indicators and composite indices designed to support policy-making and monitor progress toward sustainable development objectives. Additionally, enhancing human development significantly affects environmental and social sustainability. In this context, Neumayer [36] claimed an existing close connection between sustainability and human development. Therefore, evaluating development through the lens of sustainability demands an integration of several aspects, including environmental and economic considerations, green economy practices, and the link between environmental and social goals [37,38]. According to Gupta and Vegelin [39], understanding the factors that reinforce the connection between social elements and human development is crucial [12].

Due to its unique characteristics, human development can be seen as a complex, multidimensional concept that requires both theoretical investigation and empirical research. Indeed, composite indexes of human development have been developed to capture broader aspects of human progress, identify groups that are lagging, and monitor the distribution of human development. In addition to the Human Development Index HDI, these indices include the Multidimensional Poverty Index (MPI), the Inequality-adjusted Human Development Index ($IHDI$), the Gender Inequality Index (GII), the Gender Development Index (GDI), the Planetary pressure-adjusted Human Development Index ($PHDI$), and the Gender Social Norms Index ($GSNI$). In Table 1, a summary of some HDI-related indicators has been listed, pointing out when an environmental component is available in the definition of each indicator.

Notably, the $PHDI$ adjusts the HDI for environmental pressures to address intergenerational inequality, just as the $IHDI$ focuses on intragenerational inequality. In particular, the $PHDI$ is calculated as the product of the HDI and index of planetary pressures, with the latter serving as an adjustment factor. This index reflects levels of human development while accounting for carbon dioxide emissions, based on production, and the material footprint, both considered per capita, recognizing the significant impact of human activities on the planet. The $PHDI$ acts as a catalyst for transformation. Ideally, when there are no environmental pressures, the $PHDI$ would equal the HDI. However, as these pressures increase, the $PHDI$ will be lower than the HDI, effectively measuring human development levels in light of environmental considerations.

Since its introduction, the $PHDI$ has attracted increasing attention in the literature as a tool to investigate the relationship between human development and environmental pressures. Several studies have applied the index in empirical analyses to explore how the inclusion of planetary pressures affects the assessment of development performance across countries and regions. For instance, Jiang et al. [40] used the $PHDI$ to analyse regional disparities in China, showing that accounting for planetary pressures reveals spatial inequalities that are not fully captured by the traditional HDI. Similarly, recent research has employed the $PHDI$ framework to investigate the interactions between human development, environmental sustainability, and resource consumption patterns across countries, with an innovative framework [41]. Recently, a proposal of reassessing the $PHDI$ through the lens of scalability has been developed [35], which examines the global feasibility of replicating specific national development patterns within the Earth's biophysical constraints.

These contributions confirm the growing interest in integrating environmental pressures into development assessment frameworks. Nevertheless, the environmental dimension of the current $PHDI$ formulation primarily captures global environmental pressures through carbon emissions and material footprint indicators, while other environmental stressors that directly affect human health and well-being remain less explicitly represented. Air pollution, and in particular particulate matter, represents a major risk factor for morbidity and mortality and constitutes a critical channel through which environmental degradation influences human well-being.

Table 1. Summary of some of the HDI-related indexes proposed in literature.

Indicator	Acronym	Conceptual Approach	Environmental Dimension	Reference
Human development Index	HDI	Capability approach	×	[8]
Pollution-sensitive HDI	$HDPI$	Adjusts the income component via CO_2 emissions from industrial processes	✓	[30]
Inequality-adjusted-HDI	$IHDI$	Distribution-adjusted HDI	×	[42]
Multidimensional Poverty Index	MPI	Acute poverty identification	×	[42]
Gender Inequality Index	GII	Gender disparity in reproductive health, empowerment, and labor market	×	[42]
Human Sustainable Development Index	$HSDI$	Inclusion of CO_2 emissions	✓	[13,20]
Sustainability adjusted HDI	$SHDI$	Four-dimensional framework, including CO_2 emissions	✓	[43]
Gender Development Index	GDI	Gender gap in HDI dimensions	×	[44]
Gender Social Norms Index	$GSNI$	Beliefs and attitudes towards gender equality	×	[45]
Gender Social Norms Index	$GSNI$	Beliefs and attitudes towards gender equality	×	[45]
Planetary-adjusted HDI	$PHDI$	HDI adjusted for CO_2 emissions and material footprint	✓	[46]
Sustainable Development Index	SDI	Divides HDI weighting it by the ecological efficiency	✓	[11]
Planetary Boundaries-adjusted HDI	$PB\text{-}HDI$	Product of adjusted HDI and Ecological Overshoot Index	✓	[47]
Planetary pressures and inequality-adjusted HDI	$PIHDI$	HDI adjusted for CO_2 emissions, material footprint, and inequalities	✓	[21]

The composition of the Planetary pressure-adjusted Human Development Index is a key element, and in this paper, we will propose some modifications to this index (denoted by the symbol $PHDI^*$). The aim of these modifications is to enhance the environmental representativeness of the index by refining material footprint data and explicitly incorporating particulate matter emissions to the planetary pressures adjustment factor. Moreover, a revised version for the calculation of the planetary pressures adjustment factor is proposed.

From a conceptual standpoint, the $PHDI^*$ differs from traditional sustainability-adjusted frameworks, such as the Environmental Sustainability Index (ESI) or its subsequent iterations, as the Yale's Environmental Performance Index (EPI), by remaining anchored to the human development paradigm. While indices like the EPI primarily measure environmental performance as a standalone dimension, $PHDI^*$ integrates a proxy for localised environmental stressor directly into the socio-economic evaluation of human capabilities. Specifically, the inclusion of fine particulate matter ($PM_{2.5}$) alongside global planetary pressures ($CO_{2,eq}$ and Material Footprint) expands the environmental perimeter to account for immediate and local health-related constraints. Furthermore, the adoption of a geometric aggregation logic (as detailed in Section 2.3) reduces the degree of substitutability between components. This ensures that significant environmental pressures can be more explicitly reflected in the final score, rather than being linearly offset by high socio-economic achievements. In this context, the present study explores how the integration of a localised environmental stressor and the adoption of a less compensatory aggregation logic may alter the assessment of national development performance compared to the original $PHDI$ framework. By expanding the environmental perimeter to include $PM_{2.5}$ exposure alongside global planetary pressures, this approach aims to reflect more closely the immediate health-related constraints on human capabilities, ensuring that significant environmental pressures are explicitly accounted for in the final development scores.

2. Materials and Methods

This Section provides an overview of the methodology and evaluation of the Human Development Index (HDI) (Section 2.1), followed by a review of the Planetary pressure-adjusted Human Development Index ($PHDI$) framework (Section 2.2), as defined by the United Nations. In Section 2.3, the $PHDI$ calculation method is extended by incorporating three specific adjustments aimed at accounting for the impact of local pollution alongside global greenhouse gas effects and material footprint, resulting in the $PHDI^*$ index. The resulting variations in the index values, and their effect on global rankings, are then presented within the case study (Section 3). Finally, Section 2.4 introduces the data sources and datasets required for the index calculation, while Section 2.5 outlines the geographical scope and the criteria for country selection. Moreover, in Section 2.3.2, the goalposts values for all the "Min–Max" normalised indexes required for the different calculations are summarised. For the sake of clarity, the procedure adopted in this study consists of five main steps, presented in Section 2.3: (i) analytical definition of the proposed extension and variation of the $PHDI$ and related planetary adjustment factors; (ii) data collection and synchronisation for the reference year 2022 (data retrieved from the sources presented in Section 2.4); (iii) normalisation of environmental adjustment factors to ensure scale consistency with the HDI methodology, as described in Section 2.3 (see Equations (14)–(17)); (iv) calculation of the $PHDI^*$ through Equation (18); and (v) analysis of the results obtained (Section 3).

2.1. Human Development Index (HDI)

Initially, the United Nations measured human development through a composite normalised index that included life expectancy, education, and economic factors. These components constitute the backbone of Human Development Index (HDI), which nowadays is derived as the geometric mean of three normalised indexes representing each of these socio-economic aspects [8,9]:

$$HDI = \sqrt[3]{LEI \cdot EI \cdot II} \tag{1}$$

where LEI is the Life Expectancy Index, EI is the Education Index, and II is the Income Index. The normalisation of these indexes is performed with the so called "Min–Max" normalisation method [48], where a maximum and a minimum value (thresholds or goalposts) are set for each indicator, to convert the indicator into a value within the $[0, 1]$ interval, which means a common dimensionless scale: $Index_{normalised} = (Indicator_{actual} - Indicator_{min})/(Indicator_{max} - Indicator_{min})$, where $Indicator_{actual}$ is the indicator's value for the considered year, for a given country, while $Indicator_{max}$ and $Indicator_{min}$ are the maximum and minimum thresholds, respectively.

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Therefore, the Life Expectancy Index, LEI, is defined as [9,49]:

$$LEI = \frac{LE_{actual} - LE_{min}}{LE_{max} - LE_{min}} \tag{2}$$

where LE is the life expectancy at birth, which serves as an indicator of a population's overall mortality level, reflecting the average number of years a newborn can expect to live based on current mortality rates [50]. To normalise life expectancy into the Life Expectancy Index, the United Nations established minimum and maximum values of $LE_{min} = 20$ and $LE_{max} = 85$ years, respectively [9]. In the 21st century, no country has a life expectancy at birth below 20 years, and 85 years is considered a practical aspirational target.

The Education Index is evaluated as a function of two different "Min–Max" normalised indexes, based on the following indicators:

- The Mean Years of Schooling (MYS): average years of education attained by inhabitants older than 25 years;
- The Expected Years of Schooling (EYS): average number of years that a child is expected to spend in the educational system.

For both quantities, the minimum threshold value corresponds to the null value ($MYS_{min} = EYS_{min} = 0$), while the maximum thresholds correspond to $MYS_{max} = 15$ and $EYS_{max} = 18$, respectively. This results in the following:

$$\begin{aligned} I_{MYS} &= \frac{MYS_{actual} - MYS_{min}}{MYS_{max} - MYS_{min}} = \frac{MYS_{actual}}{15} \\ I_{EYS} &= \frac{EYS_{actual} - EYS_{min}}{EYS_{max} - EYS_{min}} = \frac{EYS_{actual}}{18} \end{aligned} \tag{3}$$

where I_{MYS} stands for the Mean Years of Schooling Index and I_{EYS} stands for the Expected Years of Schooling Index [9]. Thus, the Education Index EI is defined as [9]

$$EI = \frac{I_{MYS} + I_{EYS}}{2} \tag{4}$$

Reflecting the principle that income is a means rather than an end, the Income Index presents a logarithmic function to model the diminishing returns of wealth on human capabilities [51]. This approach accounts for diminishing marginal utility, meaning that as Gross National Income (GNI) per capita rises, its incremental impact on human development decreases. Consequently, the normalised Income Index, II, is defined as [52]

$$II = \frac{\ln\left(\frac{GNI_{pc,actual}}{GNI_{pc,min}}\right)}{\ln\left(\frac{GNI_{pc,max}}{GNI_{pc,min}}\right)} \tag{5}$$

where GNI_{pc} is the gross national income per capita at purchasing power parity (PPP), with minimum and maximum values set as USD 100.00 and USD 75,000.00, respectively by the United Nations [9]. The threshold's choice to set the GNI per capita minimum value at USD 100.00 stems from challenges in accurately capturing unreported subsistence and non-market production within the official economic data of countries at the lower end of the range [9]. On the other hand, the upper limit of USD 75,000.00 was chosen because, despite the higher income levels, there has been no observed significant improvement in human development and overall well-being [53].

It is important to highlight that this index does not consider the technological advancements and corresponding environmental impact levels of countries.

2.2. Planetary Pressure-Adjusted Human Development Index ($PHDI$)

In 2020, the UN released its "Human Development Report" [46] introducing an index known as the Planetary pressure-adjusted Human Development Index ($PHDI$). The concept, as reflected by the name itself, integrates the HDI by factoring in the environmental impact caused by human activities, highlighting that the environmental component of sustainable development can not be neglected within a human well-being index. Therefore, two different environmental per capita components are taken into account: the material footprint and the greenhouse gas (GHG) emissions, which are subsequently normalised with a "Min–Max" normalisation approach obtaining the related adjustment factors. The material footprint (generally expressed in tons) is calculated as

$$MF = DE + RME_{IM} + RME_{EX} \tag{6}$$

where DE means Domestic Extraction, RME_{IM} means Raw Material Equivalent of Imports and RME_{EX} means Raw Material Equivalent of Exports. DE indicator refers to the direct gross physical domestic extraction of a country, while RME values indicate the embodied material flows associated with imports and exports. Therefore, the Material Footprint value includes both the gross physical domestic material's extraction from the environment within a nation's territory, and the embodied material flows associated with imports and exports. To obtain the Material Footprint per capita, MF_{pc}, the country's MF value (Equation (6)) can be divided by the related number of inhabitants (N_{inh}):

$$MF_{pc} = \frac{MF}{N_{inh}} \tag{7}$$

The further environmental factor associated with a given country is related to its greenhouse gas emissions per capita ($CO_{2,pc}$). The $PHDI$ incorporates these two new components into the HDI, by normalising them and obtaining the adjustment factors, that account for the highest and lowest values as follows:

$$A^{MF} = \frac{MF_{pc,max} - MF_{pc,actual}}{MF_{pc,max} - MF_{pc,min}} \tag{8}$$

$$A^{CO_2} = \frac{CO_{2,pc,max} - CO_{2,pc,actual}}{CO_{2,pc,max} - CO_{2,pc,min}} \tag{9}$$

where max, min and $actual$ represent the maximum, minimum, and actual values, respectively.

Following the UNDP methodology, the minimum values are set to zero, representing the absence of environmental pressure. The maximum thresholds are based on global historical peaks since 1990, specifically 90.27 t per capita for material footprint and 76.61 t per capita for GHG emissions.

These two adjustment factors are then combined through an arithmetic mean to obtain a planetary adjustment factor:

$$A = \frac{A^{MF} + A^{CO_2}}{2} \tag{10}$$

and its complement to 1 represents an estimate of planetary pressure (P):

$$P = 1 - A \tag{11}$$

from which we can obtain the Planetary pressure-adjusted Human Development Index $PHDI$:

$$PHDI = HDI \cdot A = HDI \cdot (1 - P) \tag{12}$$

2.3. Proposed Extension of the PHDI (PHDI)*

The Planetary pressure-adjusted Human Development Index represents a notable methodological advancement in the measurement of human development, yet it remains subject to critical scrutiny concerning its conceptualization of sustainability. This index modifies the conventional Human Development Index, HDI, by incorporating adjustments for per capita carbon dioxide emissions and material footprint, thereby integrating the environmental costs associated with development. The foundational principles of its methodology can be summarised as follows:

- Balancing development and sustainability: the $PHDI$ underscores the inherent tension between the pursuit of elevated human development and adherence to planetary boundaries;
- Penalty for environmental pressure: in the absence of environmental pressures, the $PHDI$ is equivalent to the HDI; however, as environmental pressures intensify, the $PHDI$ correspondingly declines below the HDI;
- Global environmental impact: on a global scale, the adjustment for planetary pressures results in an average reduction of approximately 10% [54] in the development index, highlighting the significant environmental implications of development activities.

Despite these contributions, the $PHDI$ has attracted several critiques:

- Counterintuitive rankings: critics have noted that the $PHDI$ may yield seemingly paradoxical rankings, exemplified by countries with high per capita emissions, such as Switzerland and Ireland, being classified within the very high development category;
- Under-representation of environmental harm: it has been argued that the index insufficiently reflects the magnitude of environmental degradation. For example, nations categorised as having high development levels may still exhibit resource consumption rates substantially exceeding sustainable thresholds-up to five times higher in some cases-yet maintain elevated $PHDI$ scores;
- Methodological limitations: although the $PHDI$ constitutes an improvement over the traditional HDI, some scholars contend that it does not fully encapsulate the complexities of true sustainability, thereby motivating calls for the development of more nuanced and comprehensive metrics.

The aim of this work is to address some responses to the criticisms in order to improve $PHDI$, obtaining an extended version of the Planetary Pressure Index, and three methodological refinements will be taken into account. The first change concerns the values adopted as material footprint data to obtain the related adjustment factor. This modification starts by observing that the material flows data used for the material footprint calculations are usually disaggregated into four categories, named: biomass, fossil fuels, metal ores and non-metallic minerals. It is therefore possible to calculate the specific material footprint of each category, obtaining four distinct values:

$$MF_j = DE_j + RME_{IM,j} + RME_{EX,j} \tag{13}$$

where j corresponds to:

- 1 = Biomass,
- 2 = Fossil fuels,
- 3 = Metal ores,
- 4 = Non-metallic minerals.

Therefore, an adjustment factor can be associated with each category.

$$A_j^{MF} = \frac{MF_{pc,max,j} - MF_{pc,actual,j}}{MF_{pc,max,j} - MF_{pc,min,j}} \tag{14}$$

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The minimum values are assumed to be zero in all four categories. In contrast, to find the maximum values, all material footprints worldwide were calculated and the maximum value for each j-th category has been selected; the goalposts values will be discussed within the Results section. Thus, the approach encloses the same information with an improved level of granularity, by focusing on both the quantity and the specific categories of resources, while accounting for the inherent challenges of collecting official global-scale data (i.e., the data required for the calculation remain the same). Therefore, the modified overall material footprint adjustment factor can be calculated as follows:

$$A^{MF*} = \frac{1}{4} \sum_{j=1}^{4} A_j^{MF} \tag{15}$$

The second proposed extension to the planetary adjustment factor involves incorporating a proxy for air pollution. As of 2023, air pollution has become the second leading global risk factor for mortality [55], exceeded only by high blood pressure [56], contributing to approximately 7.9 million deaths annually. Among monitored pollutants, fine particulate matter ($PM_{2.5}$, with a diameter lower than 2.5 μm) remains the most consistent proxy of adverse health issues across different populations. To ensure global comparability, this study adopts data from the Emissions Database for Global Atmospheric Research (EDGAR) [57].

Therefore, an additional adjustment factor, linked to particulate matter per capita, can be introduced:

$$A^{PM} = \frac{PM_{pc,max} - PM_{pc,actual}}{PM_{pc,max} - PM_{pc,min}} \tag{16}$$

Moreover, some considerations on the analytical expression of A, as presented in Equation (10) could be introduced. Indeed, A is evaluated as an arithmetic mean of each single adjustment factor. The arithmetic average allows us to account for compensatory effects between different environmental dimensions. Specifically, its additive structure implies a degree of perfect substitutability [58], where a high performance in one indicator can offset significant imbalances in another. Nevertheless, also a geometrical mean could be considered due to its intrinsic definition, which assumes imperfect substitutability among components [58]. Thus, the choice between an arithmetic or a geometric mean carries inherent policy implications. If environmental factors are deemed mutually compensable, the arithmetic mean remains the most appropriate choice. Conversely, a geometric mean would be preferable to penalise unbalanced performances, ensuring that a single critical deficit is not masked by better results in other areas. In the latter case, the severity of a specific environmental impact would more clearly emerge, resulting in a more heavily penalised final index. In order to point out the different impacts of the calculation method of the two means, arithmetic and geometric, a Monte Carlo-based simulation has been developed in Section 2.3.1, while an analysis of the case study related discrepancies between the two types of mean in Section 3. Therefore, a modified version of the global planetary adjustment factor, by using the geometric mean among the single adjustment factors, can be introduced as follows:

$$A^* = \sqrt[3]{A^{CO_2} \cdot A^{PM} \cdot A^{MF*}} \tag{17}$$

Consequently, the modified planetary pressure HDI can be calculated as

$$PHDI^* = HDI \cdot A^* \tag{18}$$

2.3.1. Monte Carlo-Based Simulation in Relation to the Geometric and Arithmetic Mean

To highlight the different behaviour of the calculation method of the two means, arithmetic (μ_{ari}) and geometric (μ_{geo}), referred to the unitary complement of the global planetary pressures adjustment factor, a Monte Carlo-based simulation has been developed to statistically quantify the expected deviation between the two means. In particular, the UN's approach adopts the geometric mean, which would result into:

$$\mu_{ari} = A' = \frac{1}{3} \cdot \left(A^{CO_2} + A^{PM} + A^{MF^*}\right) \tag{19}$$

while, an alternative aggregation method can be related to the use of the geometric mean:

$$\mu_{geo} = A^* = \left(A^{CO_2} \cdot A^{PM} \cdot A^{MF*}\right)^{\frac{1}{3}} \tag{20}$$

Since the deviation function is non-linear and the distributions of the individual adjustment factors are non-Gaussian, a Monte Carlo-based analysis was used. Firstly, for each adjustment factor, its probability distribution has been assessed by using data available in the 2000–2022 time frame. Then, a random sample from each distribution has been generated, by using a sample of 25,000 triplets. For each triplet the arithmetic mean, the geometric mean, and their relative differences have been computed. Lastly, from this sample, the cumulative probability distribution has been estimated, as shown in Figure 1. Each point on the curve represents the proportion of simulated triplets for which the relative difference between the arithmetic mean and the geometric mean is less than or equal to the specified threshold percentage x, i.e., it can be observed that in 90% of cases, the increase resulting from the arithmetic mean overestimation remains below 2%.

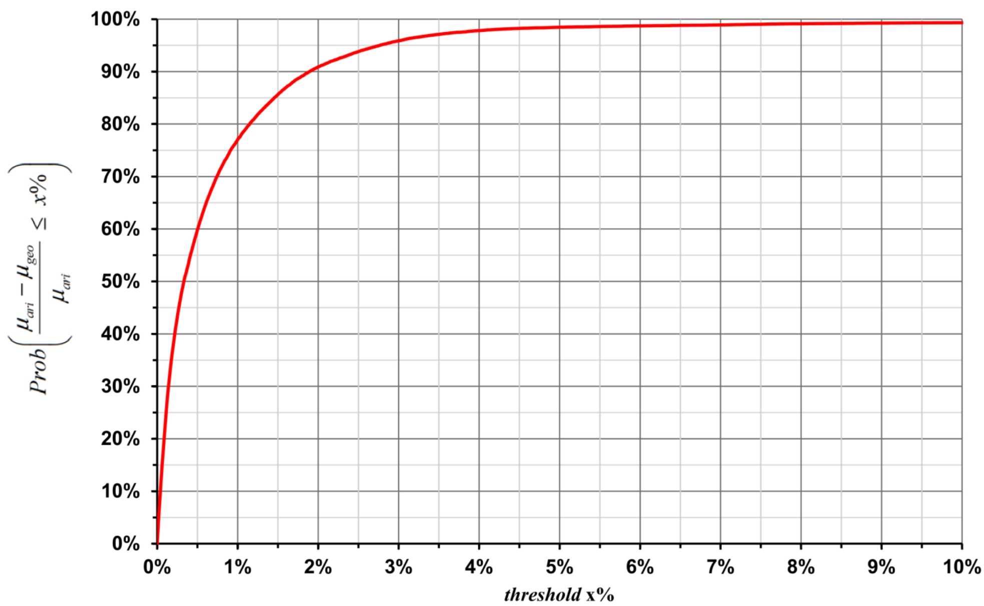


Figure 1. Cumulative distribution function of the relative difference between the arithmetic mean and the geometric mean dependent from the threshold $x\%$, obtained from the Monte Carlo simulation.

2.3.2. Summary of the Normalisation Goalposts

In this Section, the values needed to perform all the "Min–Max" normalisations used for all the indicators are listed (Table 2), to provide in a single point all the required data.

Table 2. List of the goalposts values used for the "Min–Max" normalisations.

Quantity	Unit of Measurement	Minimum Value	Maximum Value
LE	[yr]	20	85
EYS	[yr]	0	18
MYS	[yr]	0	15

Table 2. *Cont.*

Quantity	Unit of Measurement	Minimum Value	Maximum Value
GNI_{pc}	[$\$_{PPP}$ inhabitant^{-1}]	100	75,000
$CO_{2_{pc}}$	[t inhabitant^{-1}]	0	76.61
$MF_{1_{pc}}$ [1]	[t inhabitant^{-1}]	0	19.8
$MF_{2_{pc}}$ [2]	[t inhabitant^{-1}]	0	19.0
$MF_{3_{pc}}$ [3]	[t inhabitant^{-1}]	0	11.0
$MF_{4_{pc}}$ [4]	[t inhabitant^{-1}]	0	62.3
$PM_{2.5}$	[kg inhabitant^{-1}]	0	24.16

[1] biomass; [2] fossil fuels; [3] metal ores; [4] non-metallic minerals.

2.4. Data

To calculate the index proposed in Equation (18), various types of data are required. Therefore, in this study, to ensure the reproducibility and ease of data retrieval, all indicators were sourced from internationally recognised official databases. The dataset is structured into four main thematic domains:

1. Socio-economic indicators: Human Development indexes and related components were sourced from the Human Development Report Office (HDRO) [59]. This dataset aggregates data from primary United Nations agencies, including the United Nations Department of Economic and Social Affairs (UNDESA) for life expectancy at birth, the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the United Nations Children's Fund (UNICEF) for education metrics, and the World Bank (WB) and International Monetary Fund (IMF) for Gross National Income per capita at PPP, as detailed in the official technical notes [60];
2. Environmental and greenhouse gas-related metrics: Per capita CO_2 emissions were obtained via the United Nations Development Programme (UNDP) database [59], which incorporates data from the Global Carbon Project [61];
3. Resource consumption: Material footprint data were retrieved from the United Nations Environment Programme (UNEP) through the International Resource Panel (IRP) database [62];
4. Air quality and pollution: Data related to $PM_{2.5}$ emissions exposure were retrieved from the Joint Research Center (JRC) of the European Commission [57].

2.5. Study Area

The geographical scope of this study encompasses 137 countries, representing approximately 71% of the 193 UN member states. Following a population-based model, this selection focuses on the five permanently inhabited continents, excluding Antarctica. The distribution of the sampled countries can be summarised as follows: (i) Africa: 40; (ii) America: 23; (iii) Asia: 37; (iv) Europe: 34; (v) Oceania: 3. Further details on the countries considered in the case-study are included in the Results Section (Section 3.1).

The final sample of the analysed countries has been defined according to the following eligibility criteria:

- Data Availability: Full availability (in the above mentioned repositories) of all indicators required for the calculation of the HDI, $PHDI$, $PHDI^*$ was mandatory. It should be noted that certain dimensions—specifically *Material Footprint* and *Mean Years of Schooling*—exhibit the most significant data gaps across international databases;
- Demographic Threshold: A minimum population threshold of one million inhabitants was set in order to ensure statistical robustness and data consistency across UN's and environmental related indicators. This criterion minimises the impact of small-state

outliers, it addresses the limited data availability typical of small island developing states, and ensures robustness by avoiding scale bias, e.g., very small countries that often follow unique economic patterns (such as extreme specialisation in tourism or financial services) that differ significantly from larger national systems.
- Temporal Consistency: The data series must span the 2000–2022 period without significant temporal gaps to ensure the reliability of the analysis over time.

To support transparency and reproducibility, the data used for this study have been made available in the Supplementary Materials (SM) for independent verification and further analysis.

3. Results

3.1. Case-Study Characteristics

The case study encompasses a broad selection of countries worldwide, defined according to the eligibility criteria detailed in Section 2.5. The final sample of countries, categorised by continent, is presented in Table 3. Notably, the aggregate population of the 137 included countries accounts for approximately 96% of the global population (as of 2022). This implies a high demographic coverage that can ensure a sufficient representativeness of global socio-economic and environmental dynamics.

Table 3. List of countries included in the study broken down by continent. The selection follows the geographical scope and the criteria defined in Section 2.5. The reported population represents the aggregate inhabitant count (referred to the year 2022) of the countries included in the analysis [59].

Continent	Analysed Countries	Covered Population [$\times 10^6$ Inhabitants]
Africa	Algeria, Angola, Benin, Botswana, Burundi, Cameroon, Chad, Congo, Congo (Democratic Republic of the), Cote d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Kenya, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, South Africa, Tanzania (United Republic of), Togo, Tunisia, Uganda, Zambia, Zimbabwe	1327
America	Argentina, Bolivia (Plurinational State of), Brazil, Canada, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, United States, Uruguay, Venezuela (Bolivarian Republic of)	1025
Asia	Afghanistan, Armenia, Azerbaijan, Bahrain, Bangladesh, Cambodia, China, India, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Japan, Jordan, Kazakhstan, Korea (Republic of), Kuwait, Kyrgyzstan, Lao People's Democratic Republic, Malaysia, Mongolia, Myanmar, Nepal, Oman, Pakistan, Philippines, Qatar, Saudi Arabia, Singapore, Sri Lanka, Syrian Arab Republic, Tajikistan, Thailand, United Arab Emirates, Uzbekistan, Viet Nam, Yemen	4576
Europe	Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom	729
Oceania	Australia, New Zealand, Papua New Guinea	42

3.2. The Effect of the Changes in the New Proposed Index

Before evaluating the composite $PHDI^*$ index, it is essential to examine how its specific components deviate from the traditional UN framework. Figure 2 illustrates these variations across four comparative dimensions. In Figure 2A, the material footprint adjustment factor proposed by the UN (Equation (8)) is compared with the refined formulation (Equation (15)). The latter requires the preliminary identification of maximum per capita values for each of the four material categories, as detailed in Equation (14). These thresholds (Table 4) were derived from a longitudinal analysis of the 2000–2022 time series across the 137 countries in the sample [62].

Table 4. Maximum values for each category of the material footprint per capita. For each maximum value, the country where it was reached and the year are shown. These values are obtained by analysing all the countries listed in Table 3 and considering the period between 2000 and 2022.

Categories	$MF_{pc,max}$ [metric tons inhabitant^{-1}]	Country	Year
Biomass	19.8	Mongolia	2019
Fossil Fuels	19.0	Canada	2020
Metal ores	11.0	United Arab Emirates	2021
Non-metallic minerals	62.3	Qatar	2014

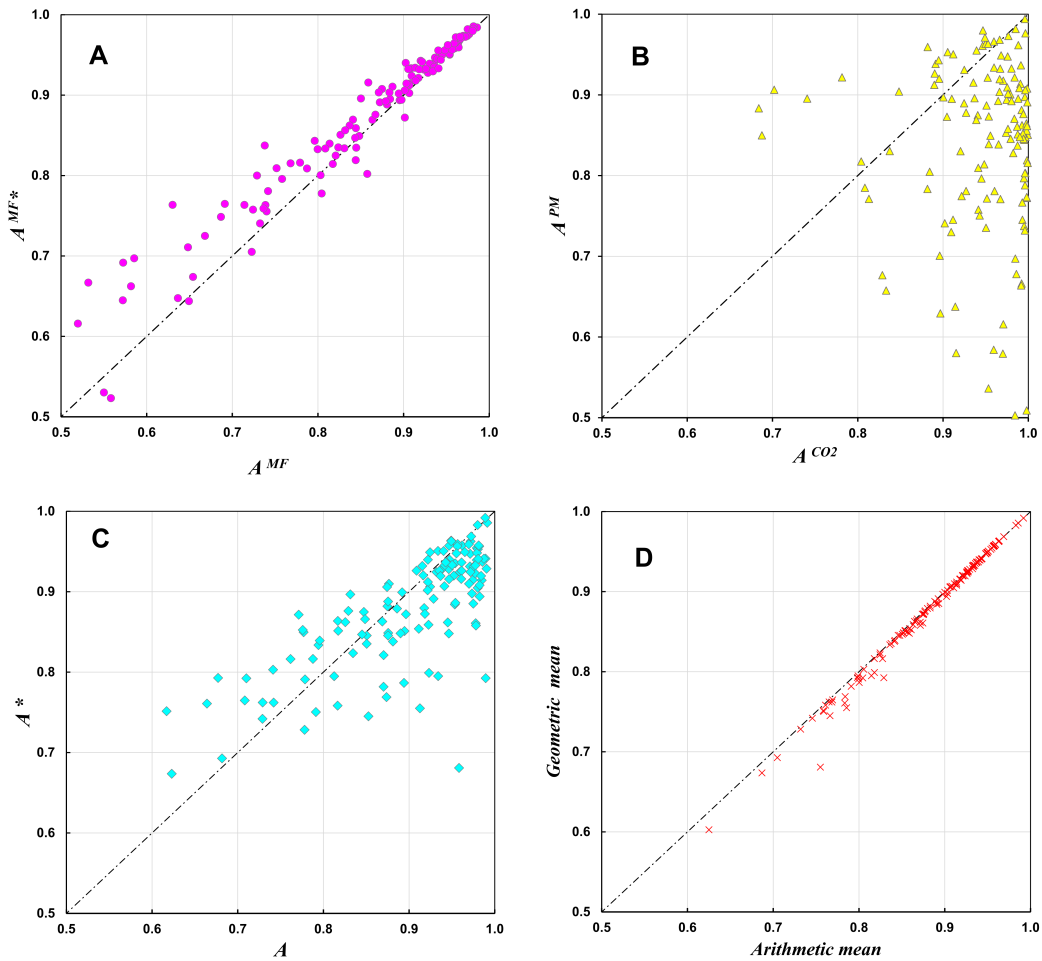


Figure 2. Comparative analysis of environmental adjustment factors for the year 2022. (**A**) Proposed vs. traditional material footprint adjustment. (**B**) PM vs. CO_2 adjustment factors. (**C**) Proposed adjustment factor A^* vs. the standard UN adjustment factor (for the $PHDI$). (**D**) Sensitivity of the planetary adjustment factor to the aggregation method: geometric vs. arithmetic mean. The dot-dash diagonal represents the identity line (axes $x = y$), where the compared metrics are equivalent.

The comparison in Figure 2A indicates that the revised material footprint adjustment leads to an improved score for 44% of the countries, while only 6% experience a decrease.

For the remaining 50% of the sample, the variation remains marginal (defined by a threshold of less than 1% difference between the two indices). Notably, points situated above the diagonal (dot-dashed line) represent nations where the proposed adjustment factor is higher than the traditional one, suggesting a more granular representation of resource consumption patterns.

Figure 2B illustrates the relationship between the CO_2 adjustment factor (Equation (9)) and the proposed PM adjustment factor (Equation (16)). The calculation of the latter required identifying a maximum global threshold of 24.16 kg per capita, derived from the 2000–2022 OECD dataset [57]. The results indicate that the inclusion of particulate matter exerts a greater penalizing effect on the majority of the sample: 78% of countries exhibit a lower adjustment factor compared to the baseline, while only 16% show an improvement, and 6% remain within comparable ranges.

The integrated impact of these environmental dimensions is shown in Figure 2C, which compares the standard UN planetary adjustment factor (Equation (10)) with the proposed $PHDI^*$ adjustment (Equation (17)). Under this refined framework, 56% of countries are penalised, 27% show higher adjustment values, and 17% maintain stable performance.

Finally, Figure 2D evaluates the sensitivity of the planetary adjustment factor to the choice of aggregation method. In Equation (17), a geometric mean was adopted to reduce the degree of substitutability between components, ensuring that significant deficits in one environmental dimension are not masked by better performance in others. As mathematically expected, the arithmetic mean (the standard UN approach) consistently yields higher adjustment values. However, this discrepancy significantly affects only 15% of the countries analysed, while the remaining 85% show a variation of less than 1%, suggesting a relative stability of the index across different aggregation techniques for the majority of the sample.

3.3. Comparative Continental Analysis

The $PHDI^*$ index was evaluated at both continental and global scales for the reference years 2000 and 2022 (Figure 3), based on the data related to continents and countries included in Table 3. For each country, six primary indices (LEI, EI, II, A^{MF*}, A^{CO_2}, and A^{PM}) were aggregated to obtain the proposed indicator. Continental weighted averages were then calculated using population as the weighting factor, with the final $PHDI^*$ derived according to Equation (18). In 2000, Europe exhibited the highest continental $PHDI^*$ (0.705), followed by America (0.633), while Africa recorded the lowest value (0.436). By 2022, all continents showed an upward trend in their development scores. Europe maintained its leading position (0.776), while Oceania showed a more pronounced relative growth compared to America. Despite the overall improvements, Africa remained at the lower end of the global distribution.

Demographic trends influence the World $PHDI^*$ values. Europe's high index performance is associated with a relatively stable and limited population size, in contrast to the rapid demographic expansion observed in other regions. Specifically, Africa recorded the highest relative growth (74%), while Asia exhibited the largest absolute increase, adding approximately 1 billion people during the period under analysis. Globally, the $PHDI^*$ rose from 0.576 in 2000 to 0.662 in 2022, a trend that underscores the substantial weight of Asia's demographic volume on the global weighted average.

Figure 4 displays the countries with the highest and lowest $PHDI^*$ values within each continent, alongside their six constituent indices (LEI, EI, II, A^{MF^*}, A^{CO_2}, and A^{PM}) for the years 2000 and 2022.

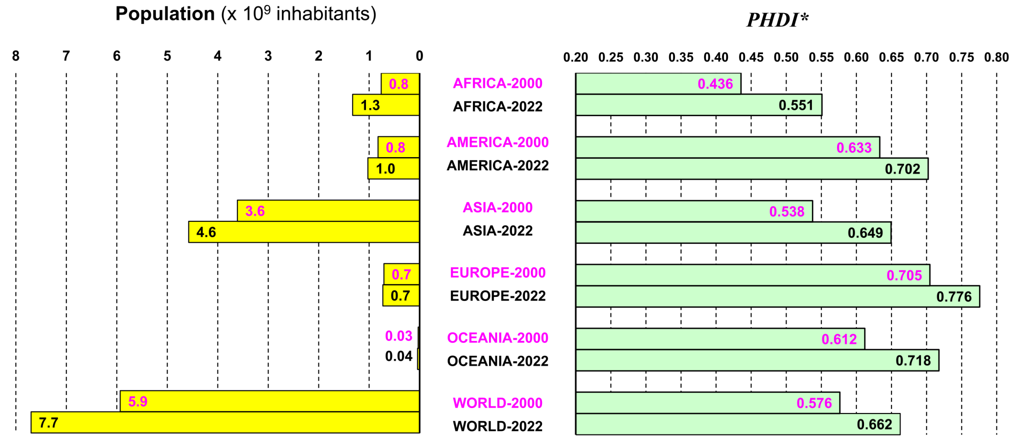


Figure 3. Continental $PHDI^*$ performance and population distribution (2000 vs. 2022). The $PHDI^*$ values (green bars) are calculated as population-weighted averages of the countries within each continent. The yellow bars represent the aggregate continental population for the year 2022 (refer to Table 3). Comparative data for 2000 (pink font) and 2022 (black font) illustrate the developmental trajectory over the two-decade period.

Figure 4. Continental extremes and $PHDI^*$ component breakdown (2000 vs. 2022). The chart compares the six sub-indices for the best and worst performing countries within each continent: LEI (Life

Expectancy Index), EI (Education Index), II (Income Index), A^{MF^*} (Material Footprint Adjustment Factor), A^{CO_2} (Carbon Dioxide Adjustment Factor), A^{PM} (Fine Particulate Matter Adjustment Factor). Data are presented for the 2000 and 2022 reference years to illustrate the evolution of developmental and environmental pressures. Composite $PHDI^*$ values for each reported country are shown in parentheses.

The analysis of the 2000 baseline reveals the following patterns:

- Africa: Niger exhibited the lowest overall performance, primarily driven by critical deficits in the education and income dimensions;
- Europe: Sweden recorded the highest global $PHDI^*$, supported by a robust HDI baseline and planetary pressure components consistent with other high-income nations. Europe also showed the smallest internal deviation, with a gap of only 0.137 between its extreme values;
- Asia: Japan emerged as the leading regional performer, showing levels of development comparable to top-tier European nations;
- America: Haiti was identified as the lowest-performing country in the region;
- Oceania: Papua New Guinea recorded the lowest regional values, characterised by low values in the education and income indexes.

By 2022 (the last year with complete data available), the following developmental trends were observed:

- Africa: Chad exhibited the lowest global performance; similar to the 2000 baseline for Niger, the primary constraints remained education and income levels;
- Europe: The United Kingdom reached the highest global performance. Conversely, Bosnia and Herzegovina recorded the lowest continent-related $PHDI^*$, showing a specific vulnerability in the particulate matter ($PM_{2.5}$) component;
- Asia: Japan maintained its leading position, while Yemen emerged as the most critical regional performer;
- America: Haiti remained the lowest-performing country; despite a slight increase in its $PHDI^*$ since 2000, stagnant income levels prevented a significant shift in its relative ranking;
- Oceania: Papua New Guinea continued to show the lowest regional performance, although a notable upward trend was observed in the education index compared to the 2000 levels.

Figures 5 and 6 show some results disaggregated by continent. Each continental chart is divided into two functional sections: the upper section displays the $PHDI^*$ values (diamond markers), with vertical segments connecting each marker to its corresponding HDI value. The horizontal axis lists the countries alongside their respective global ranking according to the $PHDI^*$ framework. The lower section features coloured bars illustrating the rank deviation between the $PHDI^*$ and the HDI global rankings. In this context, positive values indicate an improvement in ranking position when accounting for planetary pressures, while negative values represent a decrease in the country's relative standing.

The comparative analysis of $PHDI^*$ and HDI rankings reveals distinct regional patterns (Figures 5 and 6).

- Africa (see Figure 5): out of 40 countries, 24 improved their global standing. Notably, Algeria, Egypt, and Morocco advanced by over 20 positions, while Tunisia and Equatorial Guinea improved by at least 10 places. Conversely, 11 nations experienced a decline, with Gabon recording the most significant drop (39 positions), reflecting a sharp contraction from an HDI of 0.730 to a $PHDI^*$ of 0.497. Moreover, 5 countries maintained the same ranking;
- Americas (see Figure 5): among the 23 countries analysed, 16 showed an improvement in their relative ranking. In contrast, 7 nations saw a decrease, most notably Canada

and the United States, which fell by 65 and 39 positions, respectively. No country in this region maintained its original *HDI* rank;

- Oceania (see Figure 5): the analysis of the three available countries shows divergent trajectories. Papua New Guinea improved its standing by 10 positions, while Australia and New Zealand experienced significant declines in the global ranking when accounting for planetary pressures;
- Asia (see Figure 6): among the 37 countries under analysis, 21 improved their relative standing, with 13 nations advancing by at least 10 positions. Conversely, 16 countries experienced a decline in their rankings; the most significant contractions were observed in Qatar (−72 positions) and the United Arab Emirates (−68 positions). No country in this region maintained its original *HDI* rank;
- Europe (see Figure 6): the analysis of the 34 European countries shows that 19 improved their global ranking, with Georgia (+29) and Albania (+25) exhibiting the most substantial improvements. In contrast, 13 nations saw a decrease in their relative positions, most notably Finland (−40), Latvia (−39), and Bosnia and Herzegovina (−34). Two countries maintained their ranking positions under the $PHDI^*$ framework.

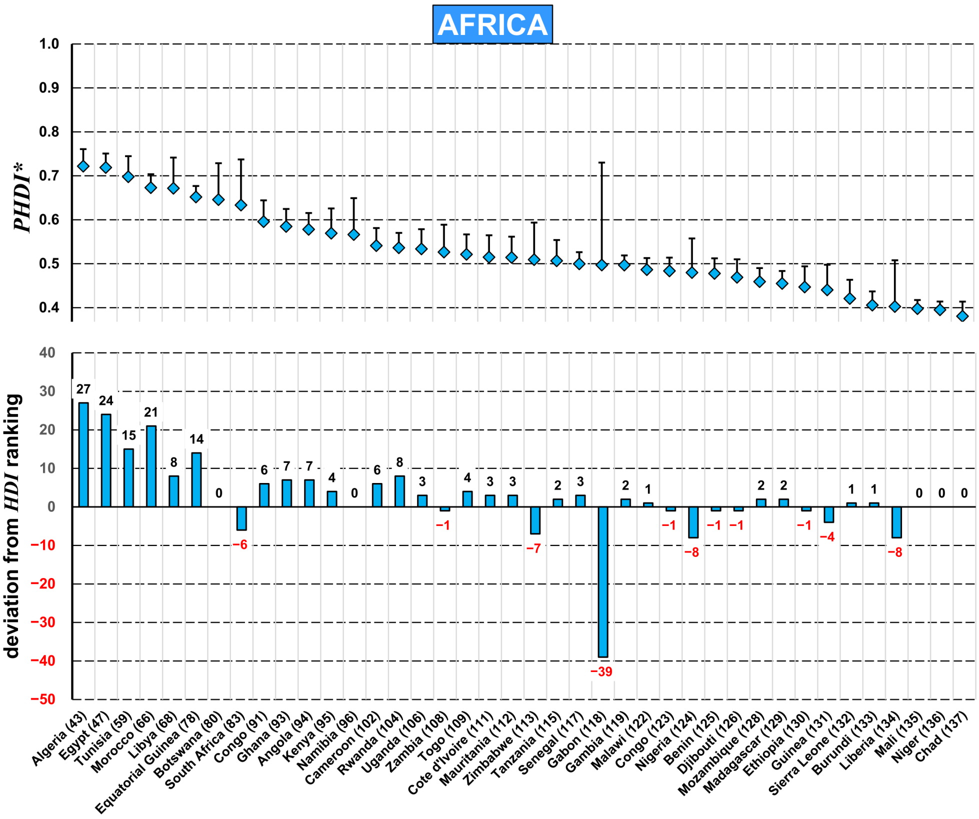
3.4. Comparison Among $PHDI^*$ and Other Conventional Indices

The United Nations traditionally categorises *HDI* results into four development tiers using fixed quartiles. However, this approach may overlook natural clusters or be influenced by skewed distributions. In this study, we adopt the Jenks Natural Breaks method [63] to define the four development categories (Table 5). This method enhances internal homogeneity by identifying boundaries inherent in the data structure, offering greater resilience to outliers compared to standard quartiles.

Table 5. Jenks Natural Breaks Optimization cut-off values (year 2022).

		HDI		***PHDI***		***PHDI****	
	Limits	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**
Categories	*Very High*	0.845	1.000	0.721	1.000	0.717	1.000
	High	0.695	0.840	0.626	0.718	0.613	0.713
	Medium	0.552	0.687	0.521	0.620	0.497	0.596
	Low	0.000	0.544	0.000	0.509	0.000	0.491

In Figure 7, a comparison among three indices: *HDI*, *PHDI*, and $PHDI^*$, is presented. Figure 7A illustrates the relationship between the *HDI* and the proposed $PHDI^*$. All countries plot below the identity diagonal (dot-dashed line), as the $PHDI^*$ incorporates environmental adjustment factors that are by definition less than unity. The distance from the diagonal quantifies the discrepancy between socio-economic performance and environmental pressure. Of the 43 countries originally classified as *Very High* development (green markers) by the *HDI*, 9 shifted down to the *High* category and 1 to the *Medium* category under the $PHDI^*$ framework. A notable case is Qatar, which experiences a significant drop due to high CO_2 emissions and material footprint impact. Conversely, within the *HDI High* category (blue markers), 16 countries improved their relative status, while 3 declined. For the *Medium* group (yellow markers), 4 nations advanced to *High*, whereas 2 dropped to *Low*. The majority of countries in the *Low* development tier (red markers) remain stable.



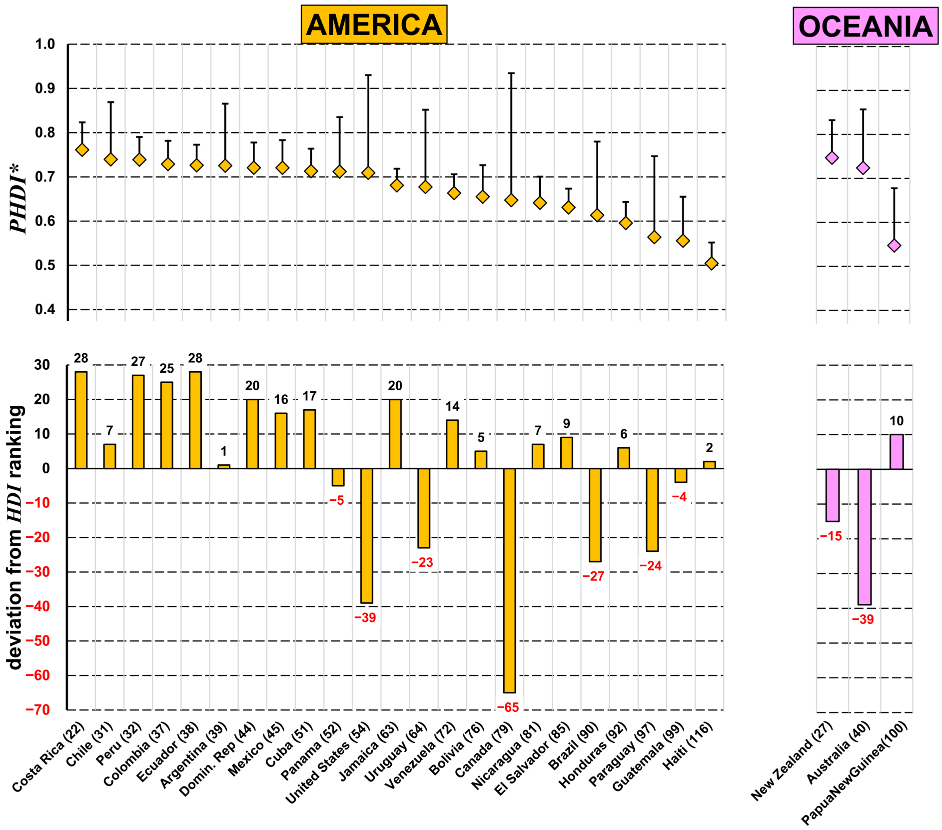


Figure 5. Comparative analysis of $PHDI^*$ and HDI values for African, American, and Oceania countries (2022). The upper section of each continental chart displays values (diamond markers) and the corresponding values, with vertical segments illustrating the gap between the two indices. The lower section presents the rank deviation (coloured bars) between the global $PHDI^*$ and HDI rankings.

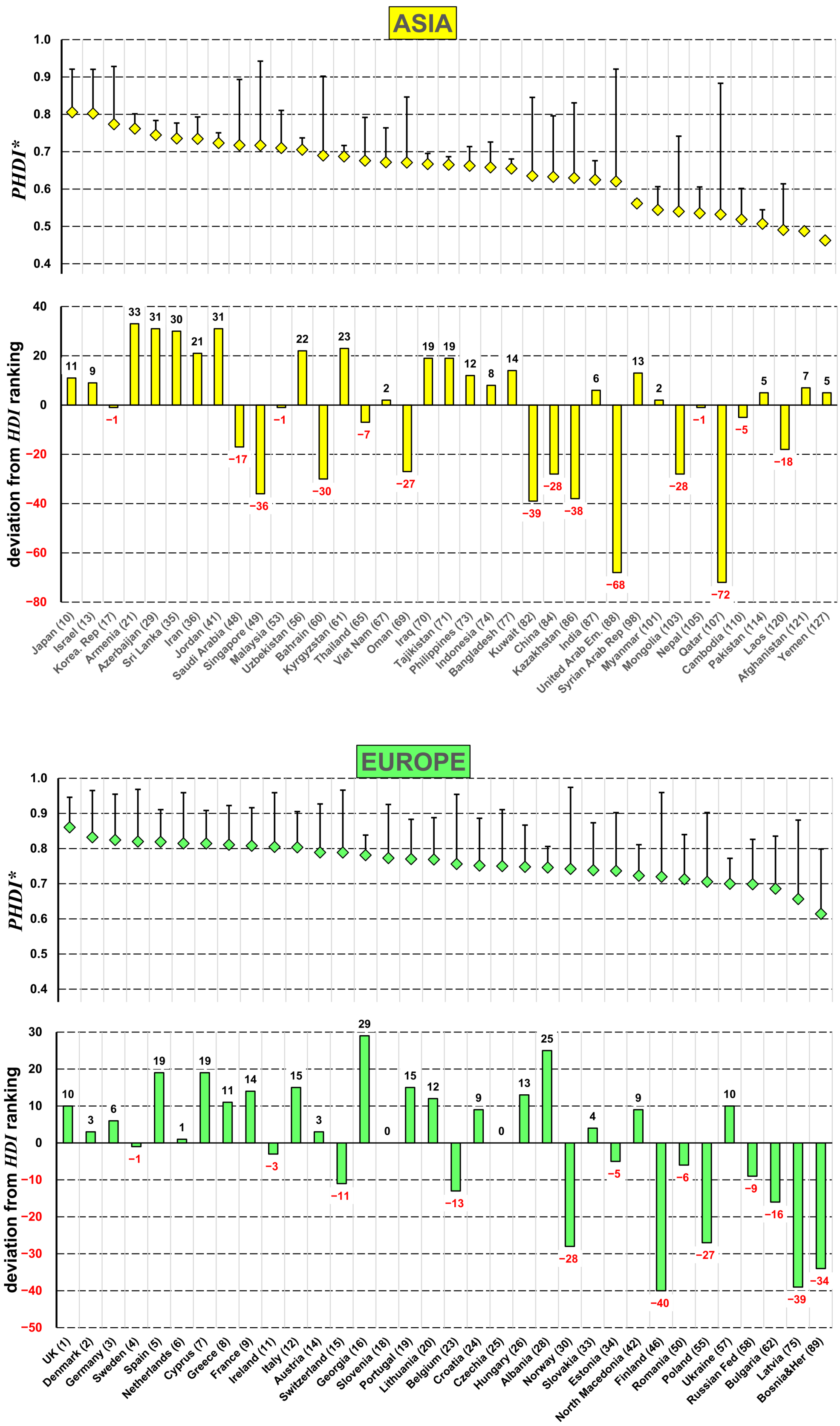


Figure 6. Comparative analysis of $PHDI^*$ and HDI values for Asian and European countries (2022). The upper section of each continental chart displays values (diamond markers) and the corresponding values, with vertical segments illustrating the gap between the two indices. The lower section presents the rank deviation (coloured bars) between the global $PHDI^*$ and HDI rankings.

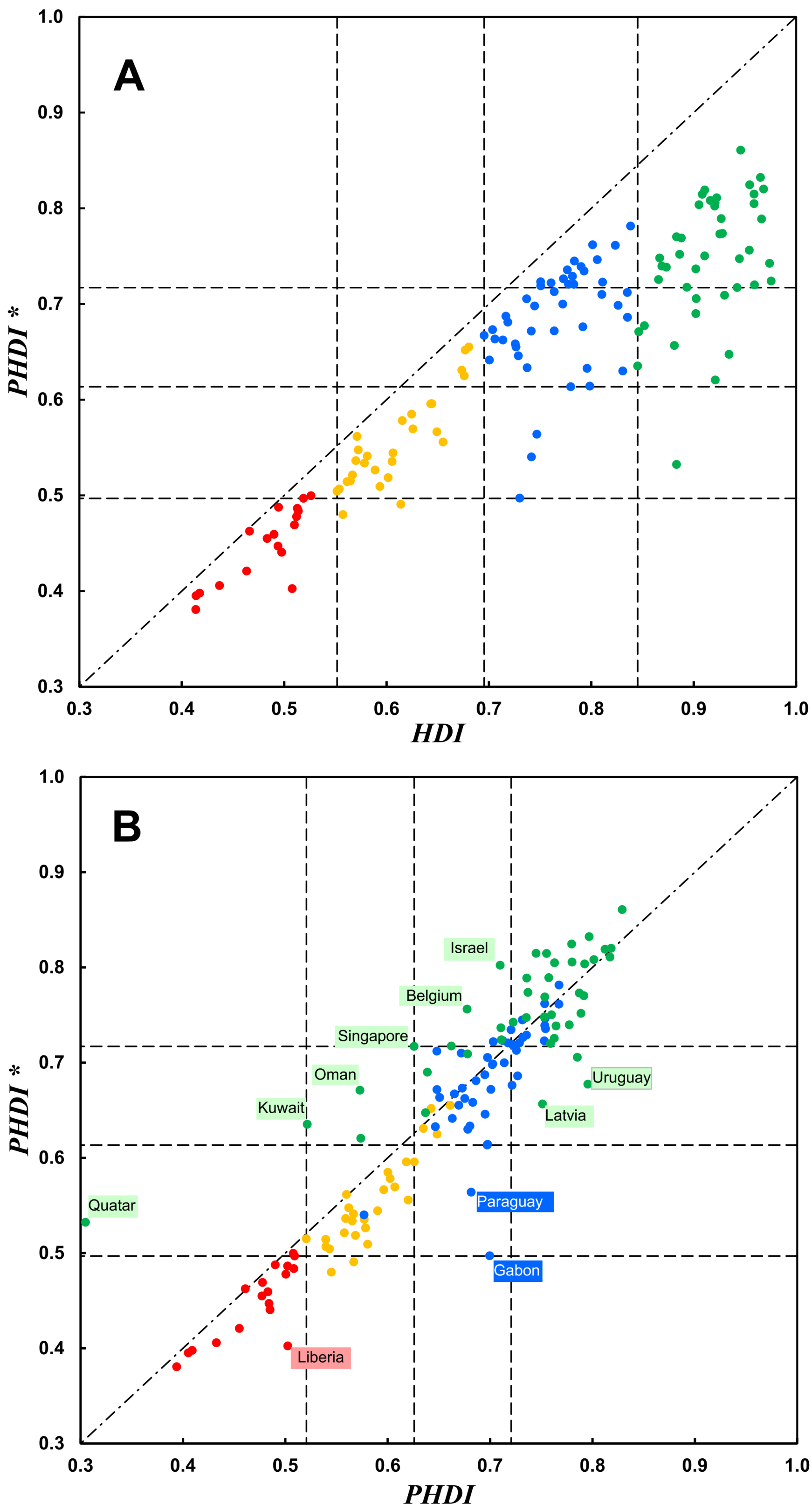


Figure 7. Cross-index comparison and developmental categorisation (2022). (**A**) *HDI* vs. *PHDI**; (**B**) *PHDI* vs. *PHDI**. The dot-dashed diagonal represents the identity line ($x = y$), while dashed lines indicate the category thresholds defined in Table 5. Marker colours denote the original *HDI* classification: *Low* (red), *Medium* (orange), *High* (blue), and *Very High* (green).

Figure 7B compares the $PHDI^*$ with the standard $PHDI$. Points above the diagonal represent an improvement in the proposed index relative to the UN baseline. Specifically, 28% of countries show an improved standing, 55% experience a decline, and 17% remain stable (variation <1%). Significant upward shifts are observed for Qatar, Kuwait, Oman, Singapore, Belgium, and Israel, while marked declines affect Uruguay, Latvia, Paraguay, Gabon, and Liberia. For instance, Qatar—while ranked as *Very High* in the HDI—shifts to *Medium* in the $PHDI^*$ and falls to the *Low* category in the standard $PHDI$, highlighting the impact of the different adjustment formulations.

3.5. World-Scale Distribution Maps of Indexes

Figure 8 presents the global distribution of the HDI, $PHDI$, and $PHDI^*$ categories through coloured comparative cartographic visualisations. In the HDI baseline map, the *Very High* development tier (green) is concentrated in Europe, North America, Australia, Japan, and parts of the Arabian Peninsula and South America. Major emerging economies, including China, Brazil, and the Russian Federation, are situated within the *High* category (blue), while the majority of the African continent exhibits *Medium* (orange) and *Low* (red) development levels.

The transition to the $PHDI^*$ framework reveals significant geographical shifts. In North America, both the United States and Canada declined from the *Very High* to the *High* category. Conversely, some Andean nations (Peru, Ecuador, and Colombia) advance to the *Very High* tier. In Asia, notable improvements in relative standing have been observed for India (from *Medium* to *High*) and Pakistan (from *Low* to *Medium*), while China and the Russian Federation maintained their original HDI categories. Most African nations show categorical stability, with the exception of Egypt, which exhibits an upward shift from the *Medium* to the *High* development tier. These spatial variations underscore the heterogeneous impact of environmental pressures on national development profiles.

The comparison between the standard $PHDI$ and the proposed $PHDI^*$ further highlights specific geographical shifts. In the Americas, Mexico advances from the *High* to the *Very High* category, while Brazil experiences a decline from *High* to *Medium*. Within the European context, the majority of nations maintain their *Very High* status, with the notable exception of Poland, which recedes by one category. In Africa, significant transitions are observed for Nigeria, which shifts from *Medium* to *Low* development. Conversely, Algeria and Senegal present categorical improvements. In Asia, Thailand's standing decreases, while several nations in the Arabian Peninsula exhibit upward shifts. Overall, the framework results in categorical reclassifications for 25 countries compared to the standard $PHDI$: 13 countries (representing approximately 600 million people) see a decrease in their development tier, while 12 countries (totalling approximately 300 million people) show a relative improvement.

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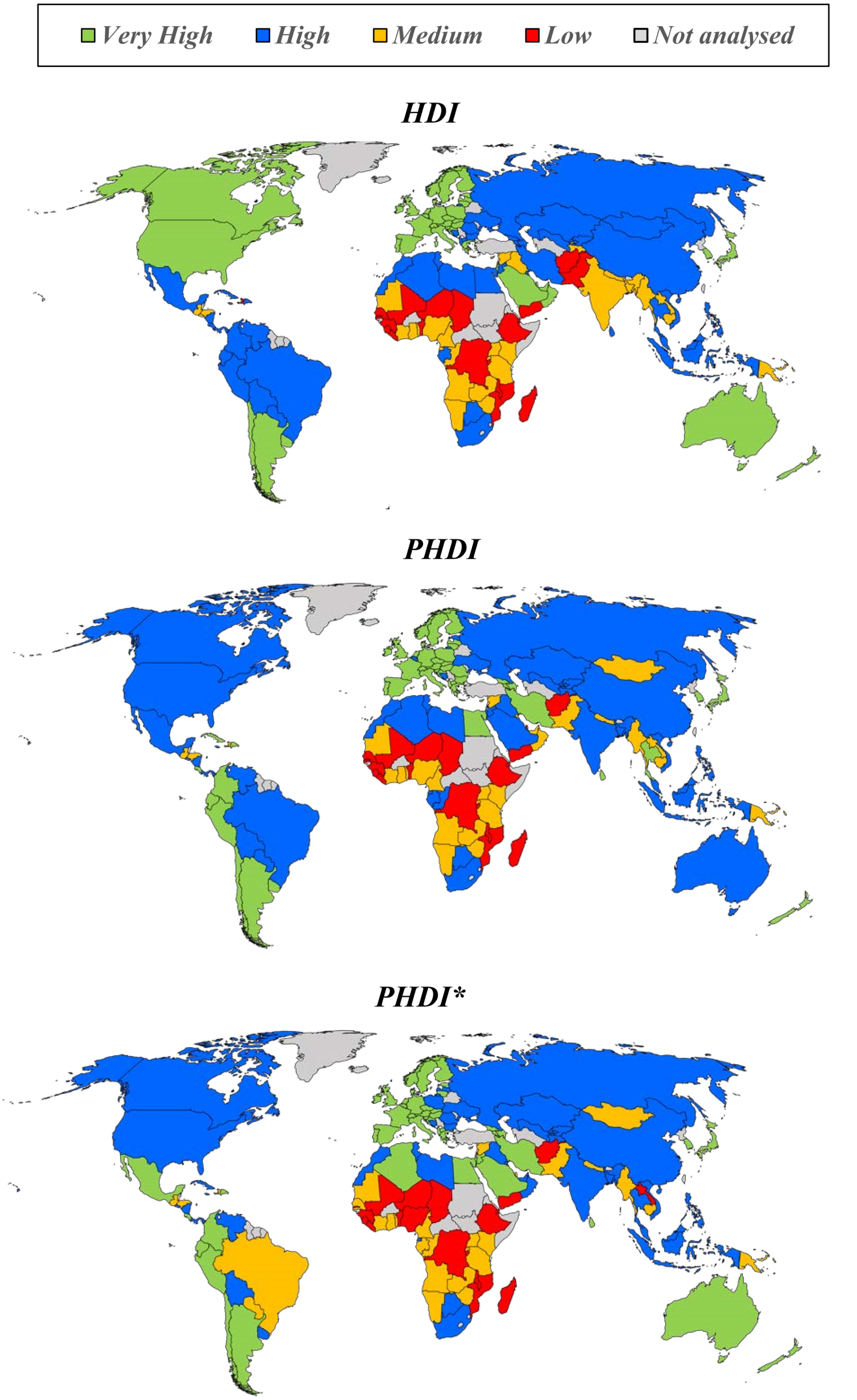

Figure 8. Comparison of maps showing the HDI, $PHDI$, and $PHDI^*$ (categories for the year 2022). The range of categories is detailed in Table 5. The term "Not analysed" refers to countries for which the complete data set needed to calculate the indices was unavailable.

4. Discussion

The Kyoto Protocol [64], adopted in 1997, represents a seminal international agreement establishing binding commitments for industrialised nations and economies in transition to reduce key anthropogenic greenhouse gas emissions by 5% between 2008 and 2012, targeting CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6, with reduction baselines set at 1990 and 1995 levels, respectively. Developing countries are exempt to avoid impeding their socioeconomic development. This framework represents a foundational step toward addressing climate change and sustainable development through enhanced global cooperation. The United Nations emphasises the need for objective evaluation methods of technological and systemic changes, proposing the use of indices to analyse complex human-environmental systems influenced by economic, social, and environmental factors [65]. Indicators represent variables reflecting system conditions, often aggregated into composite indices [66], which provide multidimensional insights essential for policy-makers to monitor sustainability trends and prioritise interventions. Despite their growing use, sustainability indices face challenges regarding validity, theoretical assumptions (e.g., weak vs. strong sustainability), and methodological limitations [65,66]. As emphasised in international policy frameworks, indicators play a fundamental role in translating the complex interactions between the environment and development into measurable information that can effectively guide decision-making processes. The interplay of environmental, economic, social, and political factors is crucial in identifying which areas require strengthening to enhance human development [12]. Initially, the HDI proposed a development model that is fundamentally inconsistent with the principles of sustainable development. Recognizing these complexities, this work aims to refine a UN index to better integrate social and environmental dimensions of sustainability.

Starting from the premise that development cannot overlook the pressure exerted on our planet, a proposal was made to update the Planetary pressure-adjusted Human Development Index. An analysis of a case study encompassing a large number of the countries worldwide highlight that

- The effect of pollutants such as particulate matter is important and generally changes the value of the adjustment factor and consequently the final index for the worse;
- A more detailed material footprint analysis allows us to obtain more representative information;
- The choice of the geometric mean can also be a useful approach to aggregate the adjustment factors;
- The clustering method proposed by the UN (quartiles), despite its simplicity, does not guarantee homogeneous clusters, so an alternative approach has been proposed.

In the literature, the Planetary Human Development Index is often used in its original formulation as proposed by the United Nations. For example, Jiang et al. [40] analyse the $PHDI$ across Chinese provinces, identifying regional disparities both between the eastern and western regions as well as between the northern and southern regions. They also place their findings within a global context. Similarly, Lian et al. [15] use the $PHDI$ as a measure of human development levels, examining seven regions and discussing spatial disparities in $PHDI$ values. In these studies, no modifications to the original $PHDI$ are made, based on the assumption that the $PHDI$ is already a more comprehensive indicator than the traditional Human Development Index (HDI). An interesting variation of the $PHDI$ is proposed by Zhang and Zhu [47], who introduce a new index called the Planetary Boundaries-adjusted HDI. Their approach modifies both the HDI and the adjustment factor. For the HDI, they replace the Life Expectancy Index LEI with a Healthy Life Expectancy Index and introduce a threshold value for Gross National Income per capita in the calculation of the Income Index. For the environmental components, they retain CO_2

emissions and material footprint but incorporate the concept of planetary boundaries. This means that instead of setting minimum values at zero, they use environmental thresholds as the lower bounds during normalization. Zhang and Zhu consider the two environmental factors proposed by the UN (CO_2 emissions and material footprint) to be sufficiently representative. However, in our work, we propose to complement these with an additional environmental factor: particulate matter. From the 2014 Human Development Report [44] to the present [54], the United Nations has classified countries into four categories based on their HDI values. These categories and their UN-established cut-off points, determined using quartiles, are as follows:

- Very High Human Development: HDI greater than 0.800;
- High Human Development: HDI between 0.700 and 0.799;
- Medium Human Development: HDI between 0.550 and 0.699;
- Low Human Development: HDI less than 0.550.

When comparing these UN cut-offs with those proposed in Table 5, the most significant difference appears in the threshold separating the Very High and High categories. Applying the UN cut-offs would classify 12 countries as Very High Human Development instead of High. Among these, the two most populous are the Russian Federation and Malaysia. The selection of cut-off values can also be influenced by political considerations—essentially, the level of HDI that is deemed necessary for a country to belong to a particular category. This perspective could similarly be applied to environmental indices. However, doing so would require addressing the complex question of defining acceptable environmental levels and determining which environmental indicators best represent these standards.

In this work, starting from the understanding that development must account for the environmental pressures placed on our planet, a proposal has been made to update the Planetary pressure-adjusted Human Development Index into Extended Planetary pressure-adjusted Human Development Index ($PHDI^*$). In this paper, the proposed index is built upon three key environmental pillars. The first pillar is CO_2 emissions, which have global consequences since emissions from any single country contribute to worldwide environmental impact. The second pillar is the material footprint, which provides a detailed understanding of the types of material flows characterizing each country. To achieve this, the material footprint is disaggregated into four categories: biomass, fossil fuels, metal ores, and non-metallic minerals. The third pillar introduces a novel element in this study: the inclusion of a pollutant with primarily local impacts, directly affecting the population within the country. Among various pollution sources, atmospheric pollution is the most critical [56], including pollutants such as particulate matter, nitrogen dioxide, and ozone. Additionally, concerns about water pollution [67] are rising, particularly regarding the accumulation of toxic substances and insufficient purification, issues especially relevant for poorer countries. Soil pollution [68], involving heavy metals, pesticides, and industrial waste, is also an important environmental concern. However, this paper focuses solely on fine particulate matter ($PM_{2.5}$) as the reference pollutant for two main reasons: it is the pollutant most strongly linked to mortality [56,69], and it benefits from extensive, large-scale monitoring data. In contrast, systematic data collection for many other pollutants is lacking across the countries included in this case study. Regarding normalization boundaries, this paper follows the UN's guidelines for the $PHDI$. Specifically, for the environmental components, minimum values are set at zero, representing no emissions and no material footprint. Maximum values are determined from the highest recorded data across all countries and throughout the entire time period under study. When multiple aspects are combined into a single index, it remains essential to provide policymakers with detailed information about the individual components that contribute to the overall index, as illustrated, for example, in Figure 5.

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5. Conclusions

The $PHDI^*$ proposed in this study represents a methodological refinement to the United Nations' framework by broadening the scope of environmental stressors and enhancing the granularity and the representativeness of the planetary pressure adjustment factor. This approach is rooted in the principle that sustainability metrics must reflect the direct impact of development on the quality of life for both present and future generations. This was achieved through three key modifications: (i) the disaggregation of material footprint into its core components (biomass, fossil fuels, metal ores, and non-metallic minerals), which provides a more detailed perspective on specific environmental pressures; (ii) the inclusion of $PM_{2.5}$ emissions, incorporating a localised pollutant emissions that directly impact human health and mortality; (iii) the adoption of a geometric mean to aggregate the environmental adjustment factors, which reduces the compensatory effects inherent in the arithmetic mean, and ensures that critical environmental deficits are more explicitly reflected.

From the analysis of a case study encompassing a large number of countries worldwide, the following key findings emerged:

- Pollutants such as particulate matter have a significant impact, generally lowering the value of the adjustment factor and, consequently, the final index;
- The disaggregated analysis of the material footprint categories provides more accurate and representative information about a country's environmental impact, without requiring additional data sources, thus maintaining global comparability;
- The use of the geometric mean serves as a more robust aggregation method by assuming imperfect substitutability among components. This ensures that significant environmental pressures are not masked by better performances in other areas, leading to a more transparent assessment of national development;
- The implementation of Jenks Natural Breaks for clustering offers a more homogeneous classification of countries compared to standard quartile-based methods, better identifying the real disparities in global development levels.

The global mapping illustrates that a high level of human development can be maintained even when environmental pressures are integrated into the framework. This trend is predominantly observed in European nations; however, due to the continent's relatively small population, these developmental benefits apply to a limited share of the global population. Conversely, several major Western economies exhibit a categorical decline when ecological impact is factored into the $PHDI^*$ calculation. This suggests that the proposed index provides a more granular representation of the actual constraints on human development.

To further refine this assessment, future research could address the following areas:

- Incorporation of parameters reflecting the internal distribution of wealth to account for socio-economic inequalities;
- Integration of additional metrics beyond material footprint, such as land-use intensity and soil consumption;
- Expansion of the pollution index to include water-borne pollutants and a broader spectrum of atmospheric contaminants. The implementation of this broader scope is currently contingent on improving global data availability and consistency;
- Exploring alternative normalisation thresholds, with particular focus on both minimum and maximum values. This exploration will help ensure that normalisation accurately reflects environmental realities and improves the robustness of the index.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18094179/s1, Table S1: Check Data Availability; Table S2: Data.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

A	Adjustment Factor (proposed by United Nations)	[-]
A^*	Adjustment Factor (proposed in this paper)	[-]
CO_2	Carbon dioxide	
DE	Domestic Extraction	
EI	Education Index	[-]
EYS	Expected Years of Schooling	[yr]
GDI	Gender Development Index	[-]
GII	Gender Inequality Index	[-]
$GSNI$	Gender Social Norms Index	[-]
GDP	Gross Domestic Product	[$]
GHG	Greenhouse gases	
GNI	Gross National Income	[$\$_{PPP}$]
GNI_{pc}	Gross National Income per capita	[$\$_{PPP_{pc}}$]
HDI	Human Development Index	[-]
HDRO	Human Development Report Office	
II	Income Index	[-]
$IHDI$	Inequality-adjusted Human Development Index	[-]
LEI	Life Expectancy Index	[-]
MF	Material footprint	[t] (metric)
MYS	Mean Years of Schooling	[yr]
N_{inh}	Number of inhabitants	[people]
P	Planetary pressure	[-]
$PHDI$	Planetary pressure-adjusted Human Development Index (proposed by United Nations)	[-]
$PHDI^*$	Planetary pressure-adjusted Human Development Index (proposed in this paper)	[-]
PM	Particulate matter (here considered the $PM_{2.5}$, with a diameter <2.5 μm)	[kg]
RME_{EX}	Raw Material Equivalent of Exports	[t] (metric)
RME_{IM}	Raw Material Equivalent of Imports	[t] (metric)
UN	United Nations	
UNDP	United Nations Development Programme	
μ_{ari}	Arithmetic mean of environmental adjustment factor	
μ_{geo}	Geometric mean of environmental adjustment factor	

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