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Exploring the Association between Climate Change and Human Development: A Visual Analytics Study

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Abstract

This study explores the complex relationship between climate change and human development. The aim is to understand how climate change affects human development across countries, regions, and the global population. Visual analytics were used to examine the impact of various climate change indicators on different aspects of human development. The study highlights the urgent need for climate change action and encourages policymakers to make decisive moves. Climate change adversely affects numerous aspects of daily life, leading to significant consequences that must be addressed through policy changes and global governance recommendations. Key findings include that regions with higher CO_2 emissions experience a significantly higher incidence of life-threatening diseases compared to regions with lower emissions. Additionally, higher CO_2 emissions correlate with consistent death rates. Increased pollution exposure is associated with a higher prevalence of life-threatening diseases and higher rates of malnutrition. Moreover, greater mineral depletion is linked to more frequent life-threatening diseases, suggesting that industrialization contributes to adverse health effects. These results provide valuable insights for policy and decision-making aimed at mitigating the impact of climate change on human development.

Keywords

Air Pollution, Climate Change, CO_2 Emissions, Death Rate, GDP, Human Development, Visual Analytics

1. Introduction

Climate change refers to the long-term changes in global weather patterns which have implications on the global climate. The United Nations, in its definition of climate change, attributes the global changes in temperatures and weather patterns to human activities related to the burning of fossil fuels [1]-[4]. The burning of fossil fuel increases the greenhouse gas levels, thereby elevating the Earth's surface temperature [4] [5]. In addition to human activities, natural factors such as cyclical oceanic patterns (like El Niño, La Niña and the Pacific Decadal Oscillation), volcanic activity, changes in the energy output of the Sun, and variations in the Earth's orbit, have an influence on the phenomenon [6]-[8]. Some of the consequences of climate change include rising sea levels, increased global land and ocean temperatures, depleted ice in mountain glaciers and at the North and South poles, extreme weather patterns (such as heatwaves, droughts, hurricanes, floods and precipitation), and vegetation changes [2] [5] [9]. These catastrophic disasters have had a devastating impact on human life [10].

While climate change has been at the forefront of debate and research, a new approach for advancing human wellbeing was introduced in 1990, called the human development approach [11]-[14]. This approach is centered on enriching human lives rather than just enriching the economy. It focuses on people and empowering people to make their own choices [15]-[17]. The emphasis is on improving peoples' lives rather than on economic growth alone; offering people the opportunity and freedom to live lives they value; and empowering people to make their own choices. The three tenets that the human development approach focuses on are: living a long and healthy life, having knowledge, and having access to necessary resources to ensure a decent standard of living [11] [14] [18] [19]. The human development approach contributes to improving the well-being of people and subsequently, to ensuring an equitable and sustainable planet [14] [20]. Investing in people and their human capital is investing in a livable planet. Therefore, to strengthen the resilience of societies and economies, countries must invest in clean air, water, health, education and jobs—and by helping to protect the most vulnerable. One has to build climate resilience, support a just transition, and protect people from the increasingly dire health impacts of climate change [21]-[23]. At a time when climate change is dramatically outpacing our efforts to stop it, investing in people is the way toward a low carbon future [24] [25].

Along these lines, the World Bank has a program that helps countries assess their health and climate vulnerabilities and make investments in climate-resilient health systems to reduce the impact of climate change on people's health and living [26]. According to the Intergovernmental Panel on Climate Change (IPCC), human activity-induced climate change continues to be detrimental to human development, despite efforts to reduce the risks. The panel reinforces the consequences of inaction on the future of the planet [27] [28]. Over the next two decades, the world will inevitably encounter many climate hazards due to global warming reaching 1.5˚C (2.7˚F) [27] [28]. Even a temporary exceedance of this warming threshold will lead to additional severe and potentially irreversible impacts. This will heighten risks to human development and society, particularly affecting infrastructure and low-lying coastal settlements [29]-[31]. Increased heatwaves, floods and droughts, are already surpassing the tolerance thresholds of plants and animals, leading to mass mortalities in species such as trees and corals [29]-[31]. These weather extremes are occurring simultaneously, resulting in cascading impacts that are increasingly difficult to manage [27] [28].

Scientists have emphasized that climate change interacts with global trends such as the unsustainable use of natural resources, increasing urbanization, social inequalities, losses and damages from extreme events, and the effects of a pandemic, jeopardizing future development [27] [32] [33].

Given the detrimental impact of climate change on human development, it is imperative to empirically study the association between the two. This will allow us to gain a better understanding of the specific effects of individual climate change factors on various human development indicators. To effectively inform future climate change and human development policies, it is essential to observe and analyze the specific climate change factors that negatively impact human development [34]-[36] at the country level. This requires adopting some fundamental premises in research. Research must extend beyond purely examining climate change dimensions and consider the associated effects on human development aspects both preceding and succeeding the changes [37]. It should consider the variations caused by the climate change-human development association across different locations and times, including the drivers that influence these variations [38]. Very few empirical studies exist that connect the dots.

Current research analyzes the association between the indicators for climate change and for human development using country-level empirical data from the World Bank. While most studies investigate the relationship between climate change and particular segments such as economic growth or health at a conceptual level, we deploy an empirical approach in investigating the patterns and relationships between the two sets of indicators. In addition to exploring climate change indicators such as energy and mineral depletion, freshwater withdrawal, emissions and pollution, we also control corruption, political stability, and electricity [3]. On the human development side, we investigate the influences of climate change indicators on country-level economic indicators such as GDP & unemployment, health indicators such as death rate, incidence of life-threatening diseases, undernourishment, and access to contemporary necessities such as internet usage and use of basic sanitary services [26].

Our key research question is:

What are some of the key influencers/drivers in the relationship between climate change and human development at a country level?

The current study is important because policy makers have an increasing concern about the impact of climate change on overall human development and on the policies that support mitigating the adverse effects [14]. The significance of the study lies in policy changes based on the findings. This includes implementing governmental regulations that address climate change challenges and regulating emissions and resource consumption. For example, governments may develop and implement early detection systems of significant indicators [22] [39]. Implement social welfare programs to withstand climate change pressure, and increase investment in renewable energy, promoting circular economy, and investing in sustainable transportation and resource management [40] [41].

The global climate change crisis is the defining issue for humanity in the 21st century. Its economic, environmental, and health consequences disproportionately affect low-income countries and impoverished populations in high-income countries, profoundly impacting human rights, quality of life, and social justice [39]. These consequences threaten rights enshrined in the Universal Declaration of Human Rights, such as the right to security and an adequate standard of living for health and well-being [40]. They jeopardize civil and political rights outlined in the International Covenant on Civil and Political Rights, including the inherent right to life and rights related to culture, religion, and language. They also endanger the economic, cultural, and social rights in the International Covenant including the right to self-determination, education, and attaining a good standard of physical and mental health [39] [40]. The consequences of climate change also threaten the rights of women and children that are outlined in the Convention on the Elimination of All Forms of Discrimination Against Women [41]. The most vulnerable are women living in rural areas of developing countries. Governments of countries need to take measures to make sure that these human rights are promoted and protected [41]. The United Nations Framework Convention on Climate Change (UNFCCC), an international framework that works to facilitate cooperation in stabilizing atmospheric concentrations of greenhouse gases, declared that the development and implementation of climate-related policies should primarily be guided by human rights considerations [1] [30] [39]. Collectively, the impact of climate change is far reaching, impacting all aspects of human development.

The latest State of the Global Climate Report from the World Meteorological Organization (WMO) states that the past few years have been the warmest on record, with unprecedented levels relating to sea rise and ocean warmth [5]. The report outlines that record level changes of greenhouse gases have led to large scale transformations to land, ocean and atmosphere [5]. This is in line with the United Nations call for faster emissions control limiting global temperature rise to 1.5 degree Celsius, and for targeted climate-resilience investments for vulnerable countries [3]. Some of the detrimental environmental effects of climate change include increases in temperature, heatwaves, droughts, precipitation events, tropical cyclones, rising sea levels, chemical air pollutants [39], melting of ice glaciers and changing ecosystems that lower the biodiversity [2] [5].

Climate change has a huge impact on human health [42] and development [14]. It alters the balance in terms of widespread disease, famine, injury, displacement and even death. For example, the increased air pollution exposes people to hazardous events like wildfires and ozone smog which impacts respiratory health.

Increased warmth around the world increases the incidence of malaria and Zika virus. In the United States, the Environmental Protection Agency (EPA) reported that the incidence of Lyme disease has almost doubled over the past thirty years. A rise in the global average temperature of 2 degrees Celsius can expose an estimated one billion people to heat stress risk [3]. In 2022 the record-breaking heat wave across Europe, and the flooding in the United States, South Korea, and Pakistan resulted in the death of over 1500 people. The effects of climate change and the impending threat of what may come can have a toll on mental health too. A study published in the journal Nature in 2021 showed that out of 10,000 people surveyed in over 10 countries, about 45% expressed anxiety and powerlessness in their feelings about climate change [3].

At a universal level, the climate crisis can magnify existing inequities between countries. While developed nations are the ones contributing the highest to greenhouse gas emissions, developing countries are the ones that will bear the consequences since they lack the infrastructure and resources to handle the impact [43]-[45]. In this regard, Hsiang *et al.* (2017) analyzed market and non-market sectors (agriculture, human mortality, energy expenditure, labor, coastal damage, crime) in developed and developing nations and found the adverse effect of high temperature to be stronger in poorer countries [46].

Even within wealthy developed nations, disparities exist regionally in terms of the ability to withstand the impact of climate change [34] [44]. For example, with Hurricane Katrina, while more than 1 million people around the Gulf Coast were displaced, in New Orleans (in the United States) due to economic segregation, people in economically affluent areas were able to recover and rebuild their homes much better than those in economically backward areas [46]-[48].

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, an estimated 3.6 billion people are in areas that are highly vulnerable to the effects of climate change [1]. Populations in vulnerable regions had a mortality rate that was 15 times higher than for other regions [49]. Additionally, the fact that more vulnerable and poor communities and regions have higher vulnerabilities despite having lower carbon emissions, highlights the inequity in the adversity from climate change [1]. It emphasizes the need for public policy to be designed with specific consideration of equity [39] [50].

At a country level, structural factors play an important role in the impact of climate change on human development. Agriculture is one such factor through which climate change can affect poverty and income inequality [51]-[53]. Reduced agricultural productivity because of calamities [54] [55] leads to reduced income or job loss [29] [31] [56] [57], particularly in rural agricultural areas, which to begin with, are economically disadvantaged [58] [59] with low adaptive capacity [60]. The distribution of rural and urban population in a country is another factor that contributes to the differential impact of climate change since the urban population will be less vulnerable to adversities when compared to the rural population [53]. Therefore, unless mitigated, climate change will exacerbate economic inequities and vulnerabilities [44]-[46] [52] [53].

The rest of the paper is organized as follows: Section 2 describes the research method. Section 3 offers the analysis and results. Section 4 provides a comprehensive discussion. Section 5 contains the scope and limitations of the research; and Section 6 concludes with implications and directions for future research.

2. Research Methods

2.1. Research Question and Propositions

The key question is, is there a negative association between climate change and human development? The purpose of this exploratory study is to investigate the multifaceted relationships between climate change indicators (e.g., water withdrawals, CO_2 emissions, pollution) and human welfare and development indicators (e.g., life threatening diseases, undernourishment, death rate, etc.). Through the lens of visualization, the study seeks to understand the broad and often interconnected impacts of climate change on societies for sustainable goals and policy development. Therefore, this exploratory study attempts to study the correlation between climate change & human development by identifying and displaying the patterns, trends, and anomalies in the data. We further suggest targeted interventions and policies that could mitigate the consequences.

The visualizations are based on the following propositions which are developed from the background discussion on climate change and human development.

Proposition 1: *Higher CO_2 emissions are correlated with higher levels of life-threatening diseases in a population*.

Higher CO_2 emissions led to increased air pollution and subsequent respiratory and cardiovascular diseases, contributing to a rise in life-threatening conditions in the population.

Proposition 2: *High pollution exposure is associated with high malnourishment rates*.

High pollution exposure contaminates food sources and reduces agricultural productivity, leading to higher malnourishment rates among exposed populations.

Proposition 3: *Higher annual freshwater withdrawals are associated with a malnourished population*.

Higher annual freshwater withdrawals indicate depletion of water resources, adversely affecting water quality and availability necessary for proper nutrition.

Proposition 4: *Higher amounts of pollution exceeding WHO guidelines are correlated to lower labor force participation rates*.

Pollution exceeding WHO guidelines can lead to health issues that reduce individuals' ability to work, thus lowering labor force participation rates.

Proposition 5: *Higher amounts of pollution exceeding WHO guidelines are related to higher death rates*.

Exposure to high levels of pollution worsens health conditions leading to higher death rates in populations exposed to pollutants that are above the WHO guidelines.

2.2. Data and Variables

Data was collected from the World Bank's World Development Indicators (WDI) database for the period 2005-2014 for several countries for which complete data was available (https://databank.worldbank.org/reports.aspx?source=2&country=ARE). Due to missing values, data for recent years is unavailable. It is acknowledged there is a lag in reporting data by numerous countries. The downloaded data was cleaned to remove missing values. Further, as part of preprocessing, the data was normalized so values across indicators could be compared. The two software—R programming language and Excel—were deployed for preprocessing, and Tableau for visualization. Table 1 below summarizes the independent variables (*i.e.*, for climate change) while Table 2 lists the dependent variables (*i.e.*, for human development).

Table 1. Independent variables (climate change).

Variable	Scale	Type	Example	Control (Y/N)
Energy Depletion	Ratio	Continuous	0.0544	N
Mineral depletion	Ratio	Continuous	0.00535	N
Annual freshwater withdrawals	Ratio	Continuous	0.001589	N
CO_2 emissions (kt)	Ratio	Continuous	0.000436	N
PM2.5 air pollution, mean annual exposure	Ratio	Continuous	0.1729	N
PM2.5 air pollution, population exposed to levels exceeding WHO guideline	Ratio	Continuous	1	N
Control of Corruption: Estimate	Ordinal	Continuous	0.223	Y
Electric power consumption (kWh per capita)	Ratio	Continuous	0.0907	Y
Political Stability and Absence of Violence/Terrorism: Estimate	Ordinal	Continuous	0.748	Y
Trade (% of GDP)	Ratio	Continuous	0.286	Y

Table 2. Dependent variables (human development).

Variable	Scale	Type	Example
Access to electricity (% of population)	Ratio	Continuous	0.999
Death rate, crude (per 1000 people)	Ratio	Continuous	0.384
GDP growth (annual %)	Interval	Continuous	0.313
Incidence of Life-threatening Disease (HIV, Malaria, Tuberculosis)	Ratio	Continuous	0.0102
Individuals using the Internet (% of population)	Ratio	Continuous	0.563
People using at least basic sanitation services (% of population)	Ratio	Continuous	0.970
Prevalence of undernourishment (% of population)	Ratio	Continuous	0.0388
Unemployment, total (% of total labor force) (national estimate)	Ratio	Continuous	0.480

2.3. Visual Analytics

We utilize visual analytics, which is the method of analyzing data with visualization using descriptive analytics [61]-[66] to shed light on the association between climate change and human development variables. To this end, the approach is data-driven and does not have any a priori assumptions about the data, analyzing the data as-is. Visual analytics enables analyzing and comprehending large datasets in real-time [67] [68]. The combination of the software capabilities of the visual analytics tool with the conceptual expertise of the analyst helps identify unforeseen patterns that can lend themselves for informed decision making [69] [70]. Visualization, based on the premise that a picture is worth a thousand words, effectively presents the data in user-friendly and elegant charts. Through aggregation, categorization and characterization, the charts can collectively tell a compelling story about the data [65] [67]-[71]. The next section presents the results of the analysis of the relationship between indicators of climate change and human development.

3. Results and Analysis

Figure 1 displays trends of average CO_2 emissions (blue line) and average death rates (orange line) for the study period, with both metrics remaining relatively stable and closely aligned throughout the period. An insight from the chart is the close tracking between CO_2 emissions and death rates, revealing a linkage between environmental quality and public health over the observed years. The implication is that sustained levels of CO_2 emissions, even if stable, correlate with consistent death rates, revealing the importance of implementing environmental policies to reduce emissions and lower the death rate.

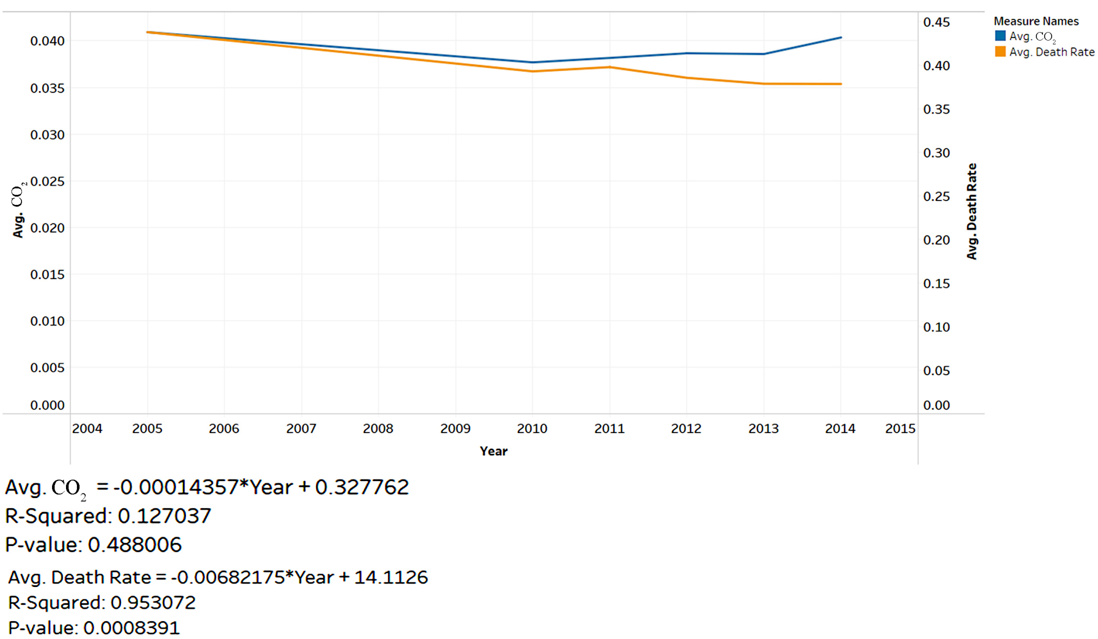

Figure 1. Line chart of CO_2 emissions and death rates.

Figure 2 is a symbol map that visualizes the relationship between pollution exposure and life-threatening diseases across countries. In the map, the size of a dot represents the prevalence of life-threatening diseases, and the intensity of color of a dot represents the extent of average pollution exposure such that the darker the color the higher the exposure level. This chart reveals that higher pollution exposure correlates with a higher prevalence of life-threatening diseases, as the larger dots tend to have darker colors indicating the impact on health due to pollution exposure. The insight gained from this chart can aid policy makers in prioritizing pollution control initiatives to reduce disease prevalence that may be caused or exacerbated by pollution exposure.

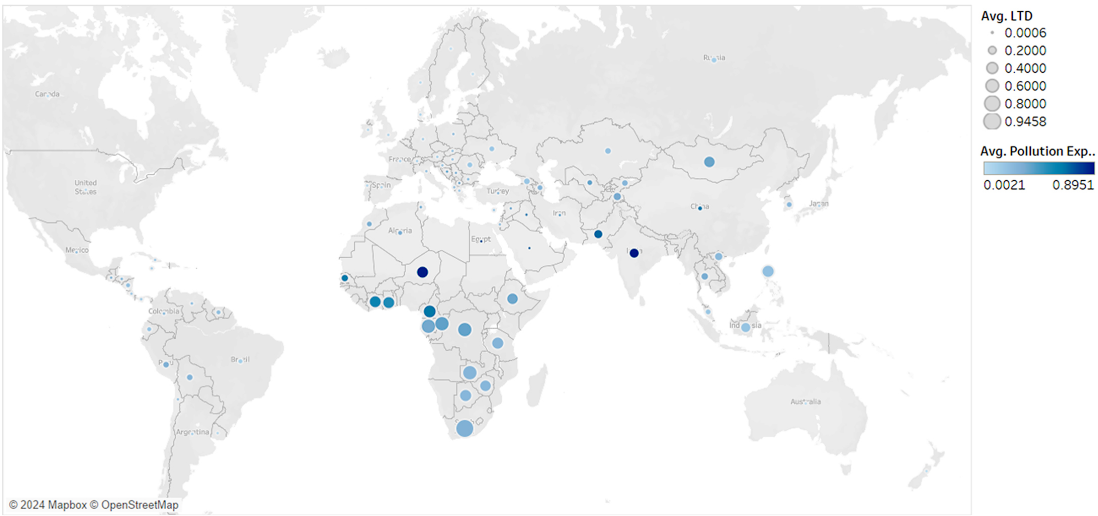

Figure 2. Symbol map of air pollution exposure and life-threatening diseases.

Figure 3 is a box and whisker plot that displays an average percentage of PM2.5 pollution levels exceeding WHO guidelines across continents, and the average malnourishment. This chart suggests a correlation where higher pollution levels are associated with increased rates of malnourishment, particularly in Asia and South America. A recommendation for governments would be to set up combined health and environmental policies that enhance both air quality and nutritional access, especially in regions exhibiting significant dual challenges.

Figure 4 is a side-by-side circle chart that displays average CO_2 emissions and average death rates for each continent. There is variability in both CO_2 emissions and death rates across continents, suggesting a potential correlation between CO_2 emissions and death rates. A recommendation would be for policymakers to further investigate the link between CO_2 emissions and death rates, potentially adjusting environmental regulations to reduce death rates based on findings from more detailed, continent-specific data analyses.

Figure 5 shows a line chart of the trends of average freshwater withdrawals of water and average incidences of life-threatening diseases for the period of study. While the trend of freshwater withdrawals fluctuates slightly, the incidence of life-threatening diseases shows a gradual decline over the same period, with some correlation visible in certain years where both metrics follow similar trends. A recommendation would be for further research to determine the specific aspects of freshwater withdrawals that may impact life-threatening diseases, possibly leading to targeted health and environmental policies to manage both water use and disease control more effectively.

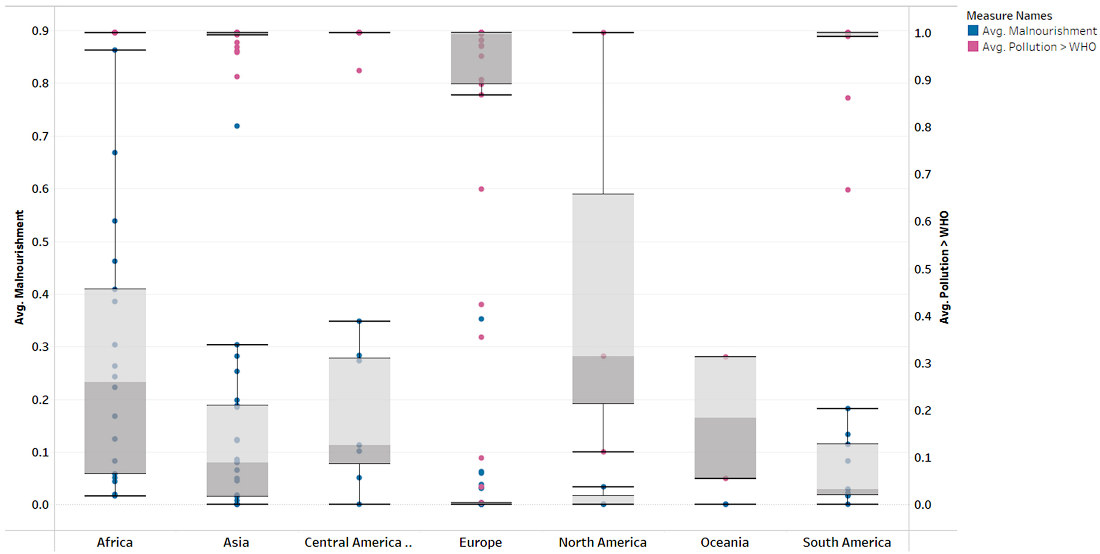

Figure 3. Box and whisker plot of the PM2.5 pollution levels and malnourishment.

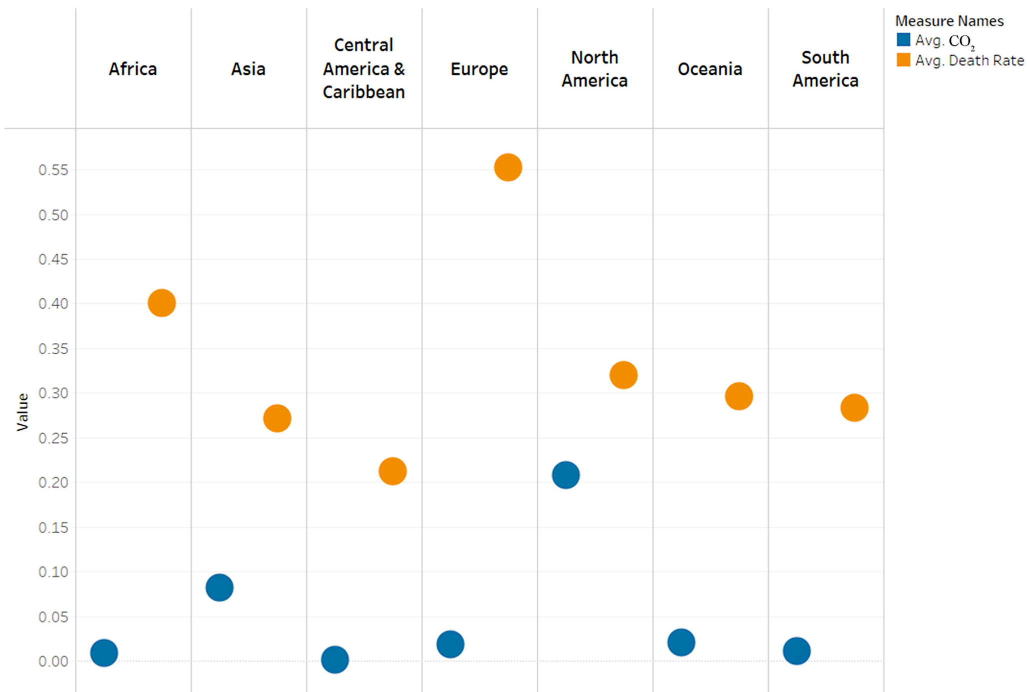

Figure 4. Side-by-side circle chart of average CO_2 emissions and death rates by continent.

Figure 6 is a bubble chart showing the association between mineral depletion and life-threatening diseases by continent. The intensity of the color in a bubble represents the extent of mineral depletion of the continent. The size of a bubble represents the extent of life-threatening diseases. The bubble chart suggests that there is a positive correlation between the two as larger bubbles (more diseases) tend to have darker shades (higher mineral depletion). Recommendations would be to increase education initiatives surrounding mineral mining, and to process environment and vitamin distribution programs in areas experiencing high levels of life-threatening disease to combat such issues.

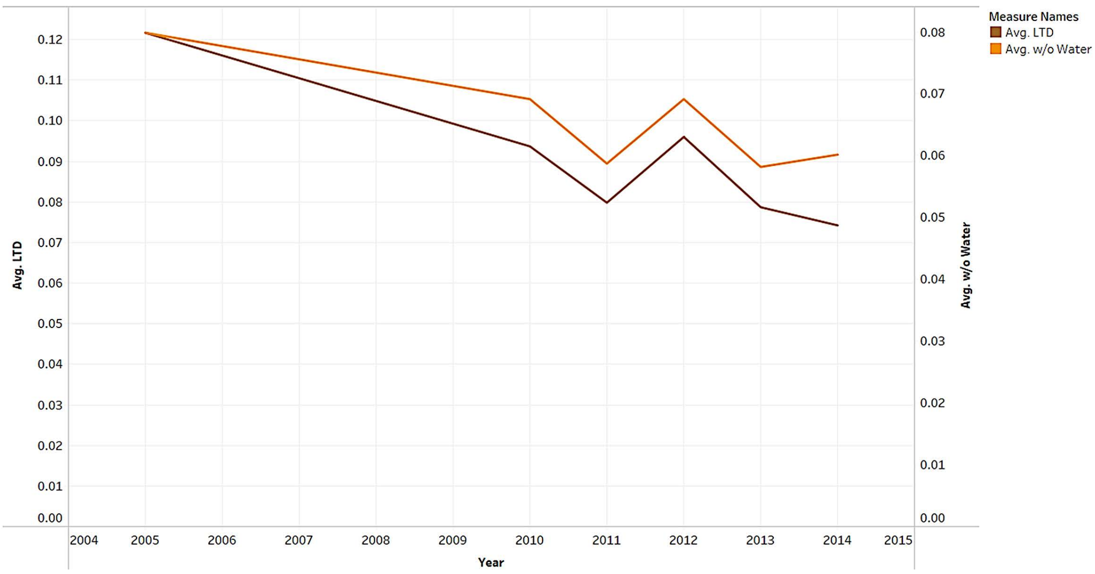

Figure 5. Line Chart of freshwater withdrawal and life-threatening diseases.

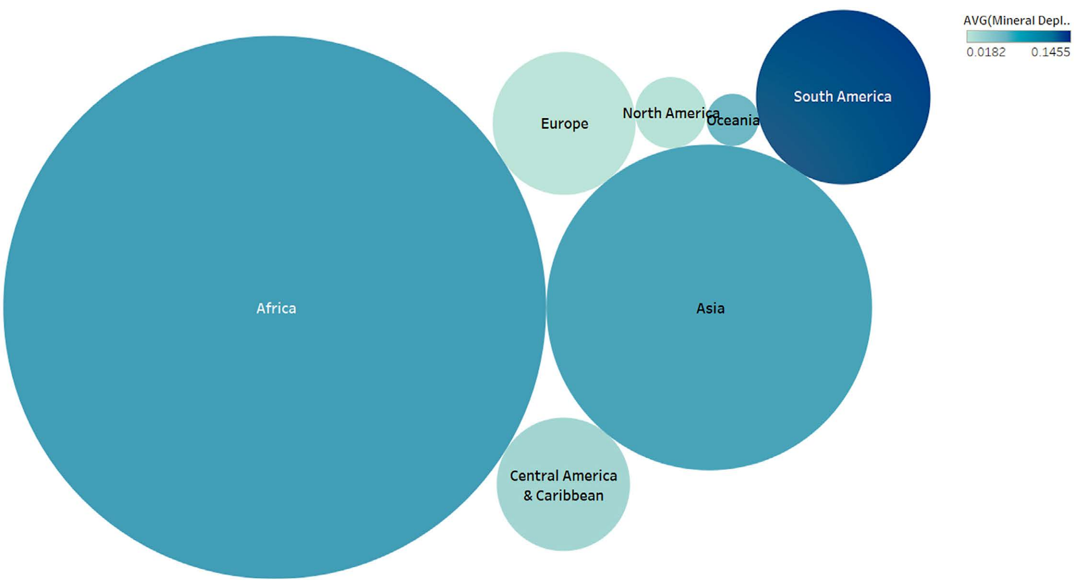

Figure 6. Bubble chart of mineral depletion and life-threatening diseases by continent.

Figure 7 shows a bullet graph of the relationship between average CO_2 levels and average pollution exposure levels by continent. The blue bars represent CO_2

levels, and the bullets represent pollution exposure. The analysis shows countries with high air pollution exposure as having lower CO_2 emissions, and countries with low air pollution exposure having higher CO_2 emissions. A more in-depth analysis at the country level may reveal the complex dynamics between CO_2 levels and air pollution exposure.

Figure 8 shows sanitation and unemployment by country. It indicates that there is a complicated and multifaceted relationship between sanitation and unemployment because while sanitation improves, unemployment increases. A more in-depth analysis at the country level is needed to determine the complex dynamics between sanitation and unemployment because while the p-value is significant at the 0.05 level, the R-squared is very weak.

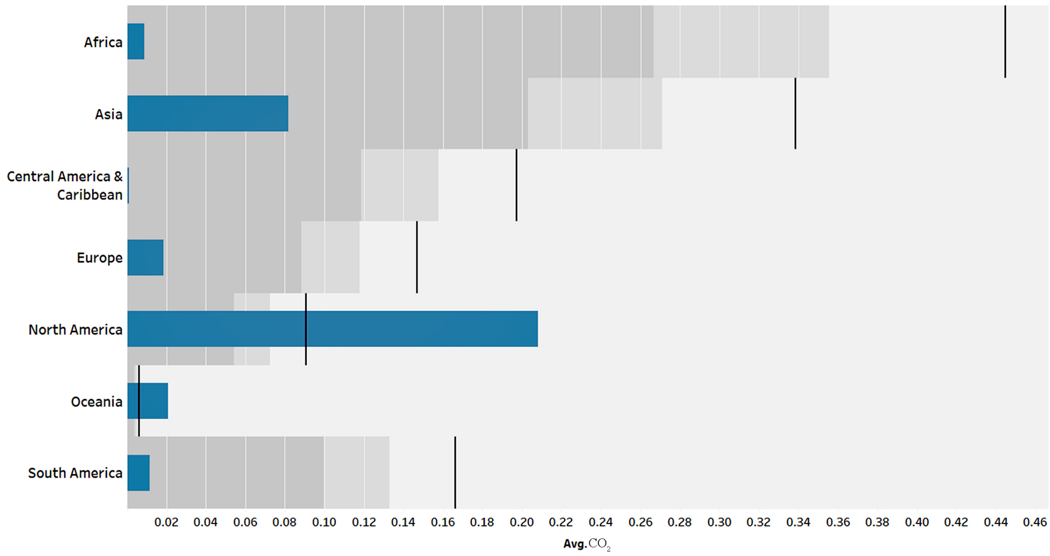

Figure 7. Bullet graph of CO_2 levels and Pollution Exposure by continent.

Figure 9 is a heat map of the relationship between population and water withdrawals at a country level. The intensity of the color in a box represents the level of water withdrawal for the country, while the size of the box indicates the size of the population. The chart shows a strong positive correlation between population size and water withdrawals—the larger the population, the higher the water withdrawals. Recommendations would be for countries with high populations to focus on strategies for efficient water management. This is important considering the growing size of the population, along with the paucity of available global water resources.

Figure 10 is a dashboard with two world maps depicting population and air pollution exposure by country. This map shows that countries in Asia have the largest population, while those in Asia and Africa are experiencing the most air pollution exposure. Recommendations would be for government agencies in high pollution areas to enforce strict rules for air quality and invest in cleaner energy sources to reduce pollution levels and protect public health. Simultaneously, population control and management ought to be discussed.

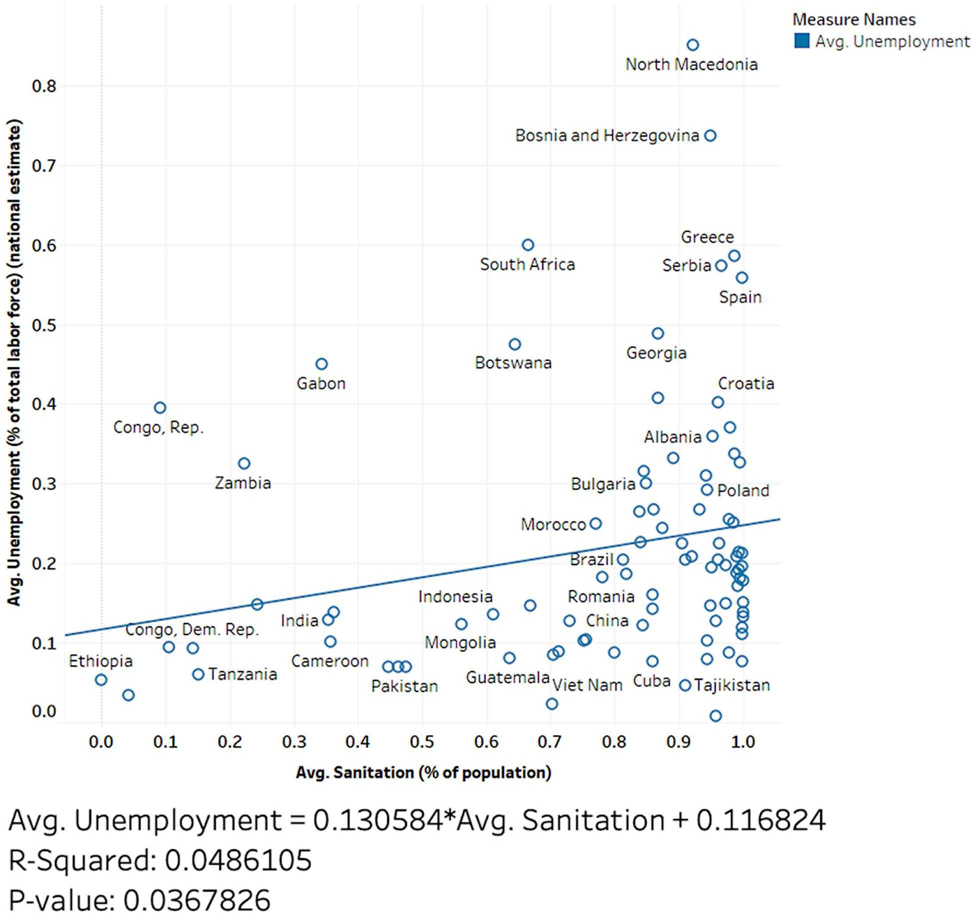

Figure 8. Scatter plot of sanitation and unemployment by country.

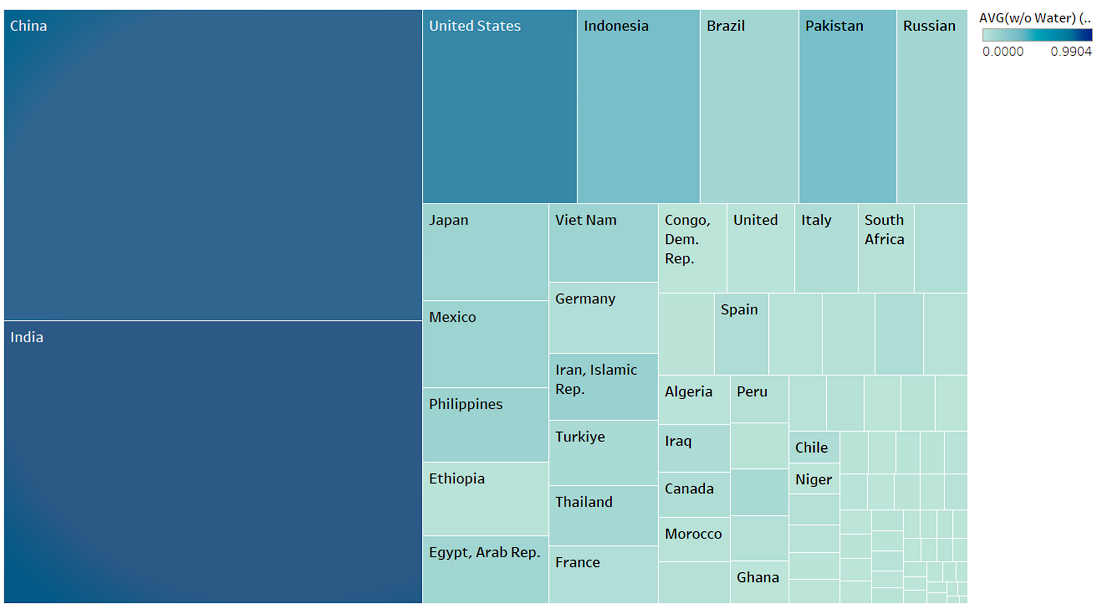

Figure 9. Heat map of population and water withdrawals by country.

Figure 11 shows a bubble chart that illustrates the relationship between freshwater withdrawals and malnourishment across different continents. The color of the bubble indicates the extent of freshwater withdrawals, and the size of the bubble indicates the level of malnourishment. The chart indicates no consistent global pattern linking water scarcity and malnourishment. A more in-depth analysis at the country level may reveal the complex dynamics between water access and malnourishment, as well as identify other factors that contribute to malnourishment in specific regions.

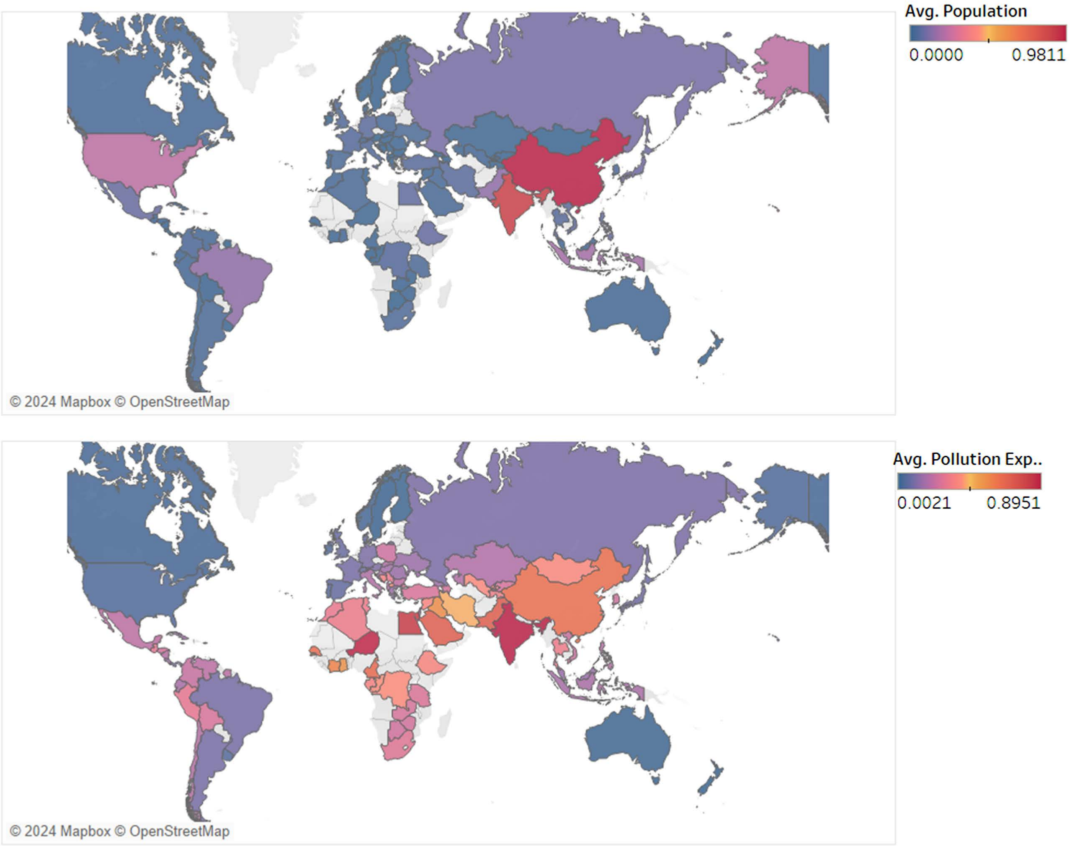

Figure 10. Dashboard of maps of population and air pollution exposure by country.

The stacked bar chart in **Figure 12** details the relationship of air pollution exceeding WHO guidelines and labor force per continent. The chart indicates that typically countries with higher amounts of pollution exceeding WHO guidelines have lower labor force participation rates, suggesting a possible impact of pollution on productivity. It is likely pollution is causing health problems resulting in less of the citizens going to work. A recommendation would be for regions to reduce pollution to meet WHO guidelines to protect the health of the labor force as well as to increase productivity.

Figure 13 shows the box and whisker plot displaying the average fossil fuel consumption and sanitation services across different continents. There are two separate box plots for each continent. Regions such as North America and Europe that have higher average fossil fuel consumption also tend to show higher levels of sanitation services, revealing a correlation between industrial development and improved sanitation infrastructure. A recommendation would be to focus development efforts on sustainable energy sources in continents like Africa and Central America, where both fossil fuel consumption and sanitation services are lower, to improve basic services without exacerbating environmental impacts.

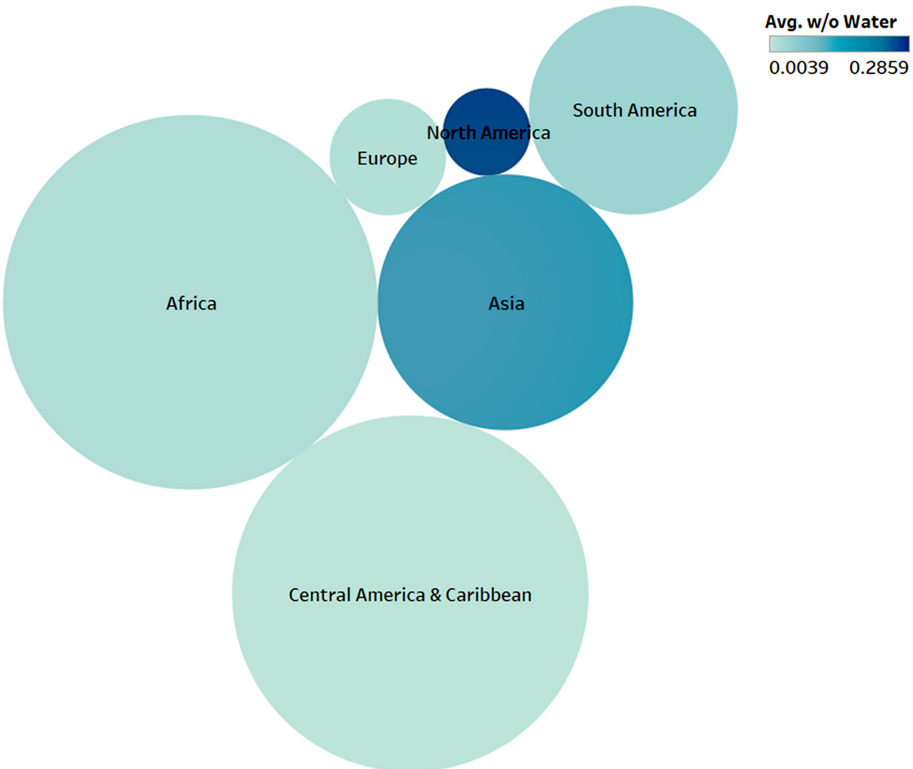

Figure 11. Bubble chart depicting freshwater withdrawals and malnourishment by continent.

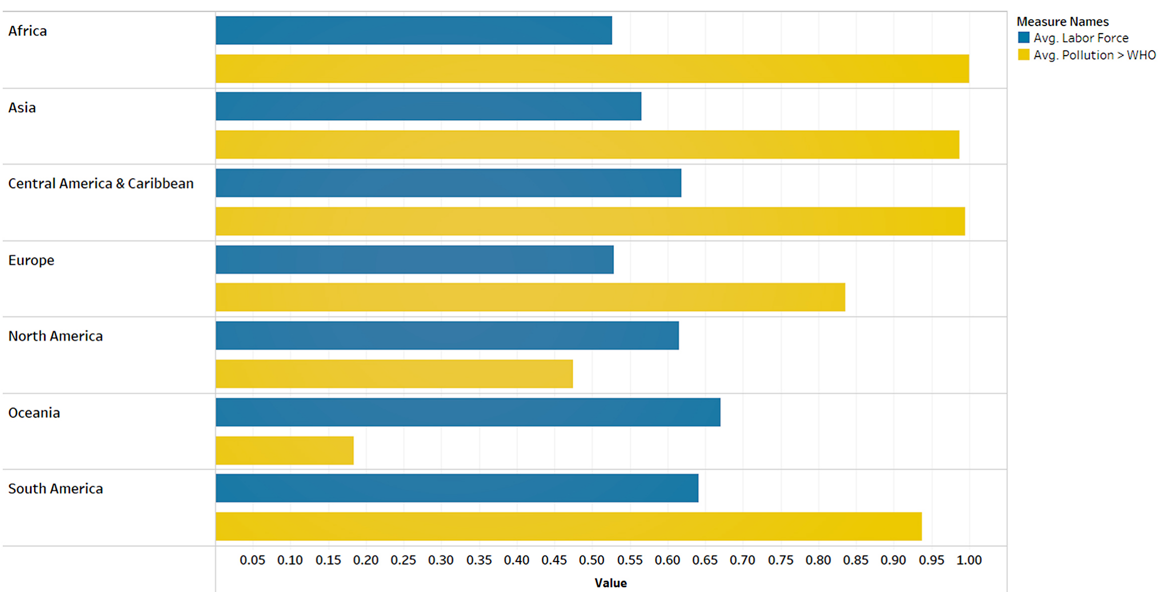

Figure 12. Stacked bar chart depicting pollution exceeding WHO guidelines and labor force by continent.

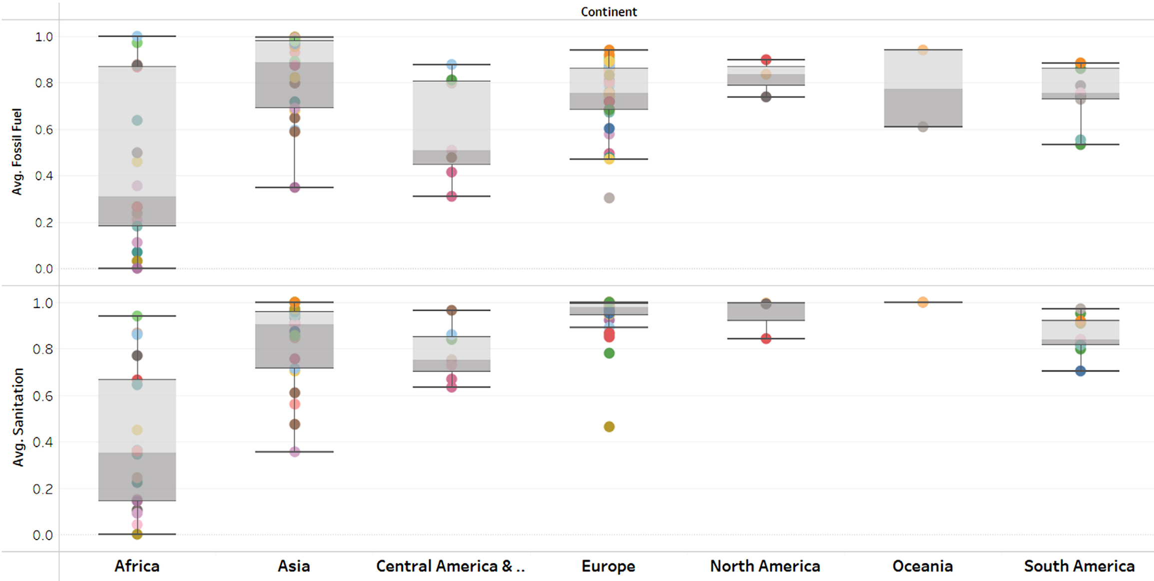

Figure 13. Box and whisker plot of average fossil fuel consumption and sanitation services by continent.

Figure 14 depicts energy depletion (blue area) and unemployment rate (orange area) for the years of study, revealing the evolution of their relationship over time. This chart reveals that there seems to be an inverse relationship between energy depletion and unemployment rates, especially noticeable in 2009 when energy depletion decreases and unemployment increases. An implication of this chart is that periods with lower energy consumption may coincide with higher unemployment rates, meaning that energy-intensive industries/sectors play a significant role in employment.

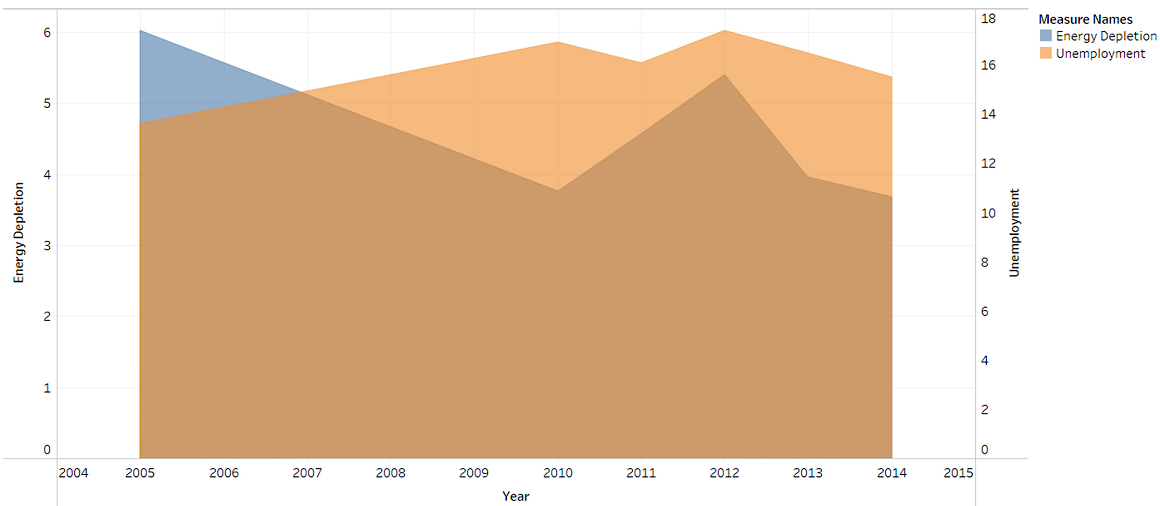

Figure 14. Area chart of energy depletion and unemployment rates.

Figure 15 compares continents by mineral depletion, which is represented by the intensity of the color, and labor force participation rate which is indicated by the size. This chart reveals that Asia and Africa are experiencing more exploitation of mineral resources compared to other continents, despite them having the smallest sized bars, indicating they have higher demands for natural resources. Lower mineral depletion is associated with higher labor force participation. The pattern of high mineral depletion in continents with higher mineral depletion activities can lead to environmental degradation, thus stressing the need for governmental implementation of sustainable resource management practices to prevent long term damage.

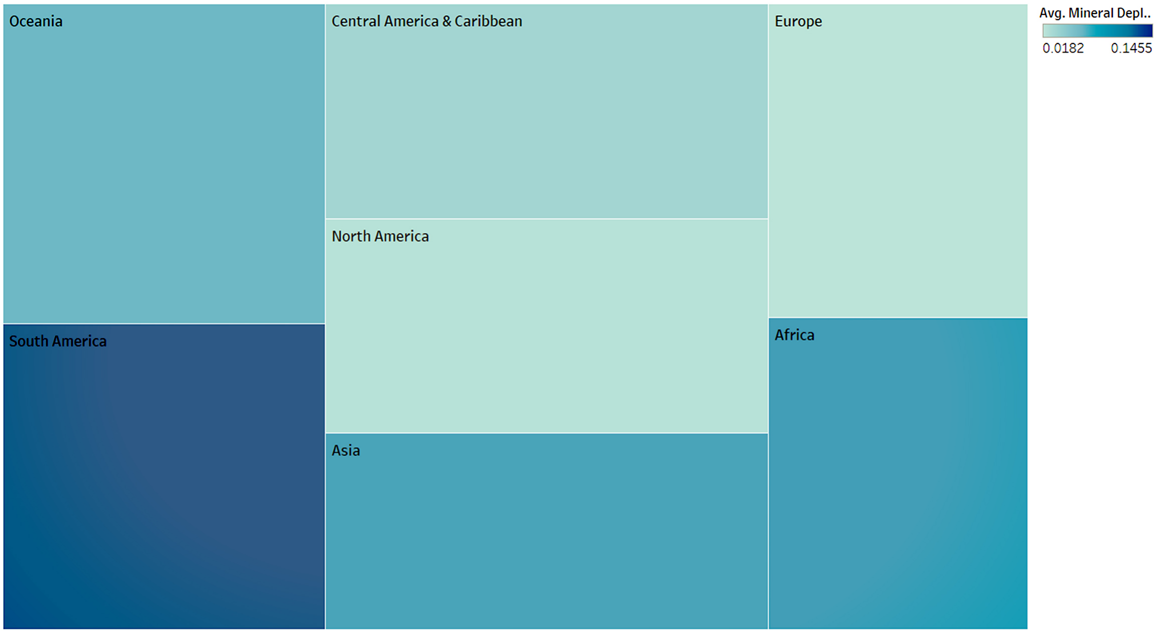

Figure 15. Treemap of mineral depletion and labor force by continent.

Figure 16 is a bar chart that displays a comparison of average political stability and average labor force size across different continents. Continents like Oceania and Europe show higher levels of political stability, and exhibit higher average labor force sizes, suggesting a potential positive correlation between political stability and labor force metrics. A recommendation would be for countries with lower political stability to invest in strengthening their political institutions as this might contribute to enhancing their labor force participation and overall economic performance.

Figure 17 shows a treemap with the average power consumption and electricity access for each continent, where the color indicates the level of average power consumption, and the size of each rectangle represents the average electricity access. An insight from the chart is that continents like Asia, which are shown in a lighter shade, have relatively higher power consumption, while also exhibiting larger areas, suggesting significant electricity access, compared to other regions like Africa, that displays both a lighter shade and a smaller area. A recommendation based on this chart would be for energy policy makers to focus on enhancing infrastructure and increasing electricity access in regions like Africa, where both power consumption and access are low, to foster economic development and enhance human development.

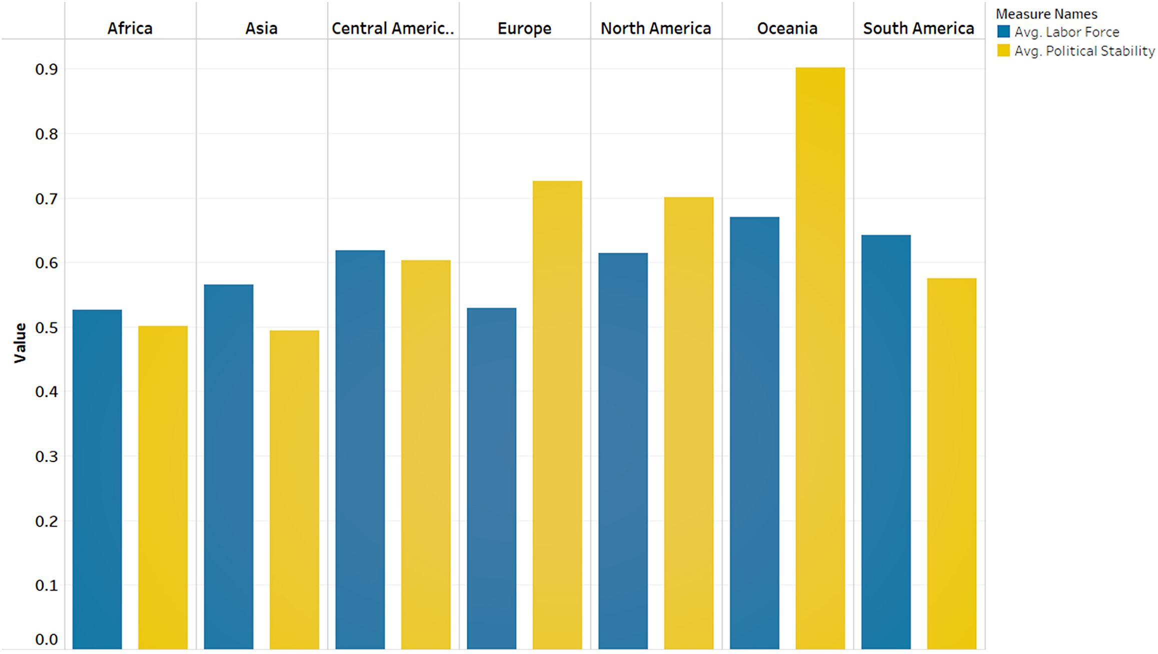

Figure 16. Bar chart of political stability and labor force across continents.

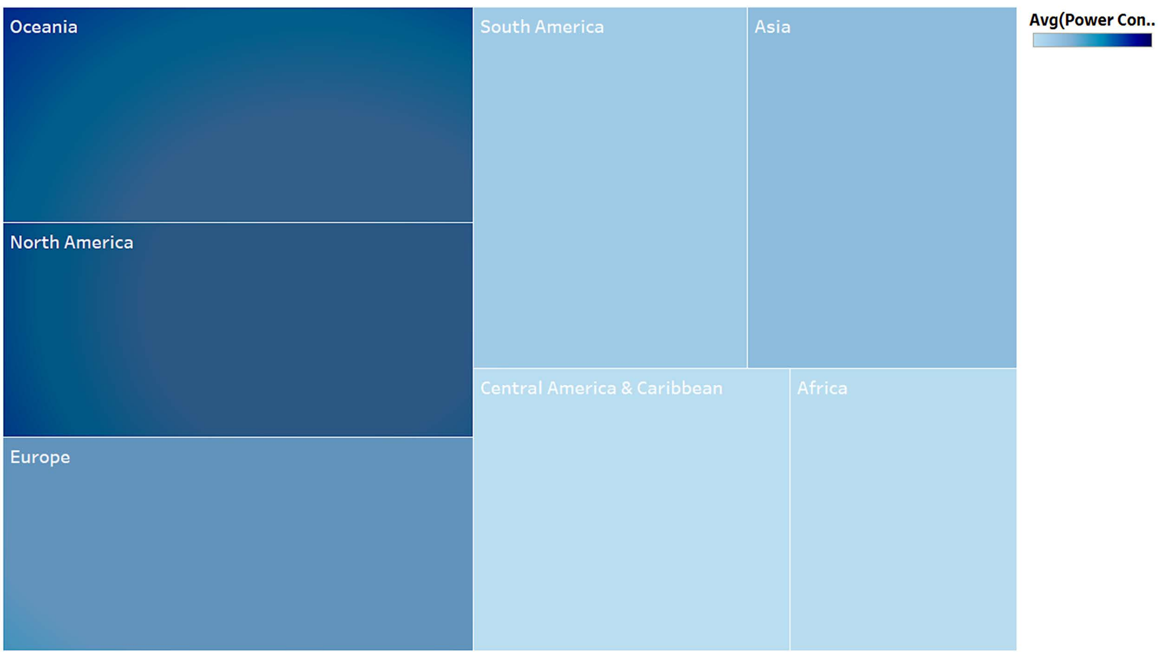

Figure 17. Treemap of electric power consumption and access to electricity by continent.

Figure 18 is an area chart that depicts the correlation between CO_2 emission vs life-threatening diseases. The visual representation suggests a correlation wherein fluctuations in CO_2 emissions might align with life-threatening diseases. Recommendation for this would be for the government to enforce environmental regulations that target a reduction in CO_2 emissions.

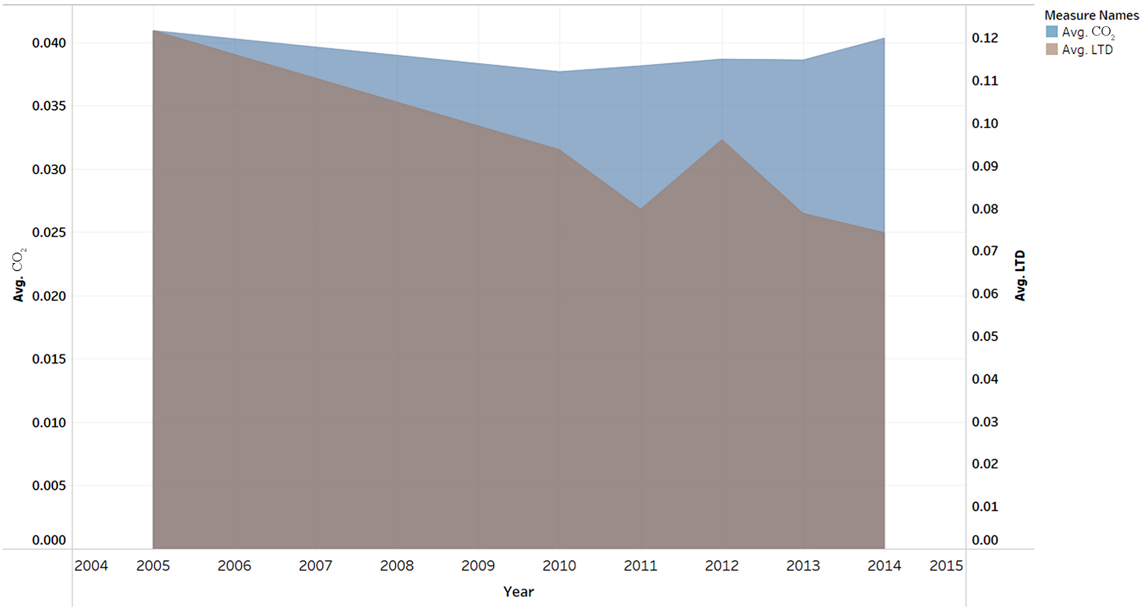

Figure 18. Area chart for CO_2 emissions and incidence of life-threatening diseases.

Figure 19 is a symbol map that visualizes global pollution level and undernourishment rates. As shown in the map, regions with large dark bubbles, especially in South Asia and Africa, are experiencing higher rates of pollution and malnourishment. Implementing environmental policies to reduce pollution, alongside enhancing agricultural and food distribution systems, could reduce malnourishment in high-risk regions like South Asia and Africa. Such integrated approaches may yield sustainable improvements in public health and environmental quality.

Figure 19. Symbol map of pollution exposure and malnourishment rates by country.

Figure 20 shows the average sanitation levels plotted against the average unemployment rates for various countries. The trend line suggests a general relationship between the variables. There appears to be a positive correlation between sanitation levels and unemployment rates; as sanitation improves, unemployment rates tend to increase. This could suggest that more developed, urbanized countries with better infrastructure might have slightly higher unemployment rates due to various economic factors. A recommendation based on this observation would be for policymakers to consider holistic approaches when improving sanitation infrastructure, ensuring that economic development and job creation are integrated into public health initiatives to counterbalance potential increases in unemployment.

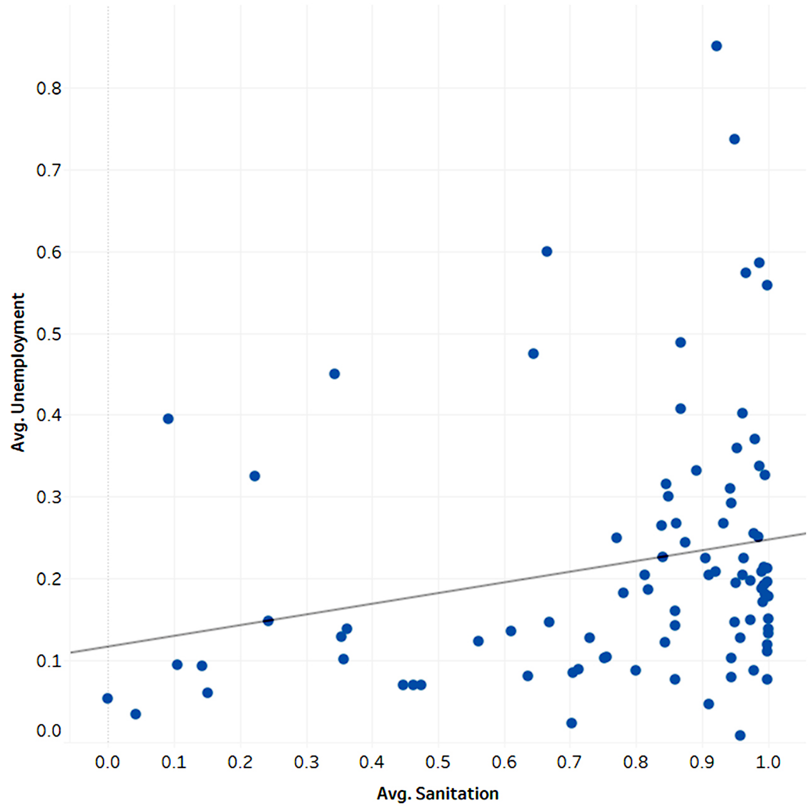

Figure 20. Scatter plot of sanitation and unemployment rates by country.

4. Discussion

Table 3 summarizes the propositions, sub-questions, analytic type, variables, chart type, and conclusions in this study.

The results present a complex picture of the relationship between climate change and human development. Key findings indicate that regions with higher CO_2 emissions experience significantly higher incidences of life-threatening diseases compared to those with lower emissions. Additionally, higher levels of CO_2 emissions correlate with consistently elevated death rates, highlighting the need for countries to implement dual policies aimed at reducing both emissions and associated health risks. Paradoxically, higher CO_2 emissions are linked to lower pollution exposure, suggesting that highly industrialized countries actively work to reduce pollution levels. However, overall, greater pollution exposure is correlated with a higher prevalence of life-threatening diseases and increased malnutrition rates, indicating the need for more aggressive pollution control measures. Additionally, higher mineral depletion is associated with an increase in life-threatening diseases, implying that industrialization may have adverse health effects. Clear findings include a positive correlation between larger populations and higher freshwater withdrawal (consumption) as well as increased exposure to air pollution. An interesting and policy-relevant finding is the inverse relationship between air pollution and labor force participation: as air pollution rises, participation declines likely due to health-related issues. Similarly, greater pollution exposure is linked to higher rates of malnutrition. In terms of governance, greater political stability is associated with higher labor force participation, as seen in regions like Europe and Oceania. Overall, the visualization reveals a clear connection between climate change and its adverse effects on human development.

Table 3. Summary of propositions, analytic type, variables, chart, and conclusions.

#	Proposition	Question	Analytic type	Variable(s)	Chart type	Conclusion
1	Higher levels of CO_2 in the atmosphere correlate positively with higher death rates.	Do increased CO_2 emissions lead to increased death rates?	Predictive	CO_2 & Death rate	Line Chart	Increased CO_2 Z coincides with higher death rates.
2	Increased annual exposure to PM2.5 air pollution correlates with a higher incidence of life-threatening diseases within the population.	Does pollution exposure show an increase in life-threatening diseases in the population?	Predictive	PM2.5 air pollution, mean annual exposure (micrograms per cubic meter) & Life-threatening diseases	Symbol map	There is an increase in disease in areas affected by higher annual air pollution levels.
3	Countries where PM2.5 air pollution exceeds WHO guidelines experience a higher prevalence of malnourishment in the population.	Does the percentage of the population in countries where PM2.5 air pollution exceeds WHO guidelines have an impact on the prevalence of malnourishment in the population?	Descriptive	PM2.5 air pollution exceeds WHO guidelines & Prevalence of malnourishment (% of population)	Box and whisker plot	Countries that have air pollution exceeding WHO guidelines have higher rates in prevalence of malnourishment.
4	Levels of CO_2 emissions are correlated with a country's death rate.	Are higher CO_2 levels associated with death rate?	Predictive	CO_2 emissions & Death Rate	Side by side circles	Increased CO_2 emissions are associated with higher death rates.
5	An increase in freshwater withdrawals is associated with incidences of life-threatening diseases.	Does an increase in freshwater withdrawals have an association with incidences of life-threatening diseases?	Predictive	Freshwater withdrawals & incidences of life-threatening diseases	Line chart	Higher freshwater withdrawals are correlated with incidences of life-threatening diseases.
6	Higher mineral depletion (% of GNI) is associated with incidences of life-threatening diseases.	Is there a correlation between mineral depletion and incidences of life-threatening diseases?	Descriptive	Mineral Depletion & Incidence of Life-threatening disease.	Bubble Chart	There is a positive correlation between mineral depletion and life-threatening diseases.

Continued

7	Higher CO_2 rates are associated with higher Pollution exposure.	Is there a correlation between CO_2 levels and pollution exposure?	Descriptive	Region, CO_2, Air Pollution,	Bullet Graph	There is an inverse association between CO_2 rates and pollution exposure rates.
8	Higher sanitation is associated with lower unemployment.	Is sanitation related to unemployment?	Predictive	Country, Sanitation & Unemployment	Scatter plot	There is a positive correlation between sanitation and unemployment.
9	Countries with larger populations are more likely to have less access to water	Is populations size related to access to water?	Descriptive	Population, Country, % without water	Heat Map	Countries with large populations will have less access to water.
10	Countries with higher population will have an association with pollution exposure greater than WHO recommendations.	Are countries that have larger populations more likely to have an association with greater pollution exposure?	Descriptive	Population, Country, & Air pollution	Map	Countries with large populations will have greater air pollution exposure.
11	Higher annual freshwater withdrawals are associated with an undernourished population.	Is malnourishment associated with freshwater withdrawals?	Descriptive	Freshwater withdrawals & malnourishment	Bubble Chart	There is no association between annual freshwater withdrawals and the prevalence of malnourishment.
12	Higher exposure to PM2.5 air pollution is associated with a lower labor force participation rate.	Does an increase in exposure to PM2.5 air pollution lead to less labor force participation?	Predictive	PM2.5 air pollution & labor force participation	Stacked bar Chart	Higher pollution levels are associated with lower labor force participation rates.
13	Higher fossil fuel energy consumption is associated with lower people using at least basic sanitation services.	Does an increase in fossil fuel energy consumption result in less basic sanitation services?	Descriptive	Fossil fuel consumption & basic sanitation services	Box and whisker Plot	Higher fossil fuel consumption is associated with higher access to basic sanitation services, in developed regions.
14	Higher energy depletion (% of GNI) is associated with unemployment.	Is there any association between energy depletion and unemployment?	Predictive	Energy depletion & Unemployment rate	Area chart	As energy depletion decreases unemployment increases coinciding with energy-intensive industries.
15	Higher mineral depletion is associated with a lower labor force participation rate.	Are mineral depletion and labor force participation rates correlated?	Descriptive	Mineral Depletion & Labor Force Participation Rate	Tree Map	Continents with lower mineral depletion rates have higher labor force participation rates.
16	Higher political stability in a country correlates with increased labor force participation and improved economic productivity.	How does political stability impact the labor force?	Predictive	Political Stability, Labor Force Participation Rate	Bar chart	Countries with greater political stability tend to have higher labor force participation and better economic productivity.
17	Higher power consumption per capita is associated with improved access to electricity.	Does higher per capita power consumption improve electricity access?	Descriptive	Power Consumption, Electricity Access	Heat map	Regions with increased power consumption per capita likely have better access to electricity.

Continued

18	An increase in CO_2 emissions correlates with higher mortality rates due to life-threatening diseases.	Is there a correlation between CO_2 emissions and mortality from life-threatening diseases?	Predictive	CO_2 emissions, Life-Threatening Diseases	Area chart	Higher CO_2 emissions are linked with increased mortality rates from life-threatening diseases.
19	A higher percentage of the population exposed to WHO-exceeding pollution levels results in greater instances of malnourishment.	Does exposure to high pollution levels increase malnourishment rates?	Predictive	Pollution Exposure (WHO guideline exceedance), malnourishment	Symbol map	Populations exposed to high levels of pollution experience higher rates of malnourishment.
20	Improved basic sanitation services leads to lower unemployment rates.	How does access to basic sanitation affect unemployment rates?	Predictive	Sanitation, Unemployment	Scatter Plot	Enhanced sanitation services contribute to economic activities and lower unemployment rates.

5. Scope and Limitations

While our study is constrained by data availability in terms of time frame and countries, it has some limitations. For instance, the number of countries included is limited, and because the data source is the World Development Indicators (WDI) of the World Bank, there is a reporting lag that results in numerous missing values. Additionally, we considered only a limited set of variables from the climate change category and key variables from human development. A more comprehensive study could include a wider range of variables from diverse sources, cover more countries, and extend over a longer period. To gain a macro perspective on the climate change–human development association, we also incorporated additional control variables. However, there may be additional intervening or compounding variables influencing the adverse relationship with human development. Furthermore, while our study examines associations and relationships between variables, it does not investigate causality. Lastly, this is a descriptive study based on visual analytics and visualization; more advanced analytical methods could be applied in future research.

6. Conclusions and Future Research

Our exploratory study demonstrates that climate change has a negative impact on human development. Both climate change and human development are critical to the health and well-being of individuals and society. To conceptualize these phenomena, it is essential to extend the focus beyond the individual context and incorporate the broader social and structural context in which these relationships occur. This requires a multi-faceted approach, including interdisciplinary research, diverse data sources, and innovative conceptual models. Given the expanding disparities in economy, health, and the environment, new policy and research initiatives are needed to address the adverse effects of climate change on human development and vice versa.

When formulating interventions and policies, governments should consider the dual role of human development: as both a facilitator of quality of life and a contributor to climate change, especially through unchecked industrialization. Addressing these large-scale inequalities requires macro-level interventions. Researchers and policymakers must collaborate in this effort: researchers should investigate and share insights and recommendations with policymakers, while policymakers need to communicate the challenges and needs of healthcare and education to researchers. Researchers can leverage variations in national political systems to explore how different forms of governance impact the relationship between climate change and human development. Due to constraints such as fiscal limitations and time, countries need to prioritize specific aspects of climate change to advance key dimensions of human development. Education plays a crucial role in enabling informed decisions to mitigate the negative impacts of climate change. Additionally, new models and empirical studies are needed to capture the nuances of this relationship and validate the largely anecdotal evidence currently available.

Our study also presents several opportunities for future research. Future research could integrate additional cultural, regional, and social variables—such as population demographics, local cultural and religious beliefs, governance structures, and historical context—for a more comprehensive analysis. Further, incorporating data from other sources could expand the study to include more countries and variables, particularly a more precise classification of income levels, geographic regions, population size, and other factors, thereby broadening the scope of the analysis. Additionally, case studies and action research can complement empirical studies. Methodologically, future research can deploy predictive analytics and meta-regression analysis to assess the relationships between climate change and human development variables. Future studies should also move beyond individual factors to explore the broader social context in which climate change and human development occur, such as gender inequality, impacts on children, and other societal dimensions. This approach will generate insights that can inform effective policies and interventions to address disparities in climate change and human development. Additionally, ensuring adequate funding, political commitment, technology transfer, and fostering partnerships is essential for more effective climate change mitigation and human development efforts. Although the study of the relationship between climate change and human development is still in its early stages, further empirical research and case studies can help accelerate its advancement.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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