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Review

The Rising Threat of Atmospheric CO_2: A Review on the Causes, Impacts, and Mitigation Strategies

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Abstract: The increasing levels of carbon dioxide (CO_2) in the atmosphere have become a major environmental challenge due to their contribution to global warming. The primary drivers of the increase in atmospheric CO_2 concentrations are the combustion of fossil fuels, deforestation, agricultural practices, or the production of cement, which play a significant role in the increase of CO_2 concentration in the atmosphere. However, efforts are being made to mitigate the negative effects of CO_2 emissions, including carbon capture and storage (CCS) technologies that aim to capture CO_2 from industrial processes and store it in underground geological formations. Methane, another potent greenhouse gas, is another major contributor to climate change and is mainly produced by agricultural activities such as livestock farming and rice cultivation. To address this, sustainable agricultural practices, such as reducing meat consumption and adopting climate-smart farming techniques, are crucial. Ultimately, a sustainable future can be secured for the planet and future generations by implementing effective measures, such as the use of sustainable energy sources, improvements in energy efficiency, responsible land use practices, and reducing the emissions of both CO_2 and methane.

Keywords: climate change; CO_2 emissions; greenhouse gases; mitigation; carbon capture and storage

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1. Introduction

The growing levels of atmospheric carbon dioxide (CO_2) have become a significant environmental challenge in recent years [1], due to the fact that CO_2 is one of the greenhouse gases responsible for causing global warming [2]. The increase in atmospheric CO_2 concentration is largely caused by the combustion of fossil fuels for energy generation, deforestation, and agricultural practices [3]. To safeguard the planet for future generations, it is imperative to implement measures to decrease CO_2 emissions into the atmosphere [4]. The Industrial Revolution is widely recognized as having had a significant impact on the concentration of CO_2 in the atmosphere [5]. The extensive use of fossil fuels, such as coal and oil, for energy production during this period led to a substantial increase in CO_2 emissions into the atmosphere [6]. The increased industrial production and transportation also resulted in the deforestation of vast areas of forest, further exacerbating the issue [7]. These emissions have caused a sustained increase in the concentration of CO_2 in the atmosphere, leading to the current state of global warming and climate change [8]. The role of the Industrial Revolution in the increase of CO_2 in the atmosphere and its ongoing impact on the Earth's climate is well established [9].

The utilization of coal as a source of energy during the Industrial Revolution marked a significant turning point in the history of human civilization [10]. The shift towards coal over traditional sources of energy, such as wood, helped spur on the growth and expansion of industry in Britain and beyond [11]. The increasing demand for energy in the rapidly growing industrial sector led to the widespread use of coal, which provided the energy necessary to fuel the Industrial Revolution and transform the world [10]. The use of coal, however, had significant environmental consequences, including a major increase in the emission of greenhouse gases, such as CO_2, into the atmosphere [12]. This increase in CO_2 emissions was a significant contributor to the current state of global warming and climate change, underscoring the far-reaching impact that the Industrial Revolution and the widespread use of coal as a source of energy had on the world [13].

The shift from coal to other fossil fuels, such as petroleum, by the industrial sector marked a new stage in energy production [14]. With the discovery of vast oil reserves, petroleum became the dominant source of energy for the industrial sector and the transportation industry [15]. The advent of the internal combustion engine, driven by the widespread use of oil, revolutionized transportation through the introduction of the automobile [14]. This marked the start of the era of motorized transportation and further fueled the growth of industry and commerce [16]. The increasing demand for oil also resulted in the expansion of oil extraction and refining, leading to a persistent increase in the emission of greenhouse gases, including CO_2, into the atmosphere [17]. This transition from coal to petroleum and the widespread use of motorized transportation have had a significant impact on the environment, contributing to ongoing global warming and climate change [18].

It is widely recognized that the growth of CO_2 concentration in the atmosphere during the 20th century was a result of increased industrialization and the continued reliance on fossil fuels as the main source of energy [19]. As energy consumption rose, the emission of CO_2 into the atmosphere followed, causing a steady increase in atmospheric CO_2 levels [20]. The proliferation of automobiles and the growth of the transportation sector also contributed to the rise in CO_2 emissions. By the close of the 20th century, the concentration of CO_2 in the atmosphere had surpassed any previously recorded levels in human history [21]. This trend has persisted into the current century, sparking growing concerns about the effects of climate change on the planet and its inhabitants [22]. In addition to the use of fossil fuels, the production of cement has also played a significant role in the increase of CO_2 concentration in the atmosphere [23]. The production of cement involves the release of CO_2 as a byproduct of the chemical reaction between limestone and clay [24]. The rapid growth of the construction industry, particularly in urban areas, has led to a significant increase in the production of cement, resulting in a corresponding increase in CO_2 emissions [25]. This has contributed to the persistent increase in atmospheric CO_2 concentration and has had a significant impact on global warming and climate change [26]. The production of cement, in addition to the burning of fossil fuels, forms one of the primary causes of greenhouse gas emissions [27]. The production of cement involves the heating of limestone to high temperatures, resulting in the release of CO_2 [28]. This process contributes significantly to the increase in atmospheric CO_2 concentration and is considered a significant contributor to global warming and climate change [29]. The widespread use of cement in construction and infrastructure development has led to a continued increase in cement production, resulting in a persistent increase in CO_2 emissions [30]. As such, the production of cement, together with the burning of fossil fuels, plays a critical role in the increase of CO_2 concentration in the atmosphere [31].

The Earth system has natural processes for capturing and sequestering $CO_{2,}$ which play a crucial role in maintaining the balance of CO_2 concentration in the atmosphere [32]. These processes include photosynthesis in plants, which captures and stores carbon from the atmosphere through the process of photosynthesis, and the ocean, which absorbs large amounts of CO_2 from the atmosphere [33]. The carbon cycle, which involves the transfer of carbon between the atmosphere, the ocean, and the land, plays a crucial role in regulating the amount of CO_2 in the atmosphere [34]. These natural processes have been in place for millions of years and have helped to maintain a balance of CO_2 in the atmosphere [35]. However, the increase in human activities, such as the burning of fossil fuels and deforestation, has disrupted these processes and led to a persistent increase in atmospheric CO_2 concentration, leading to the current state of global warming and climate change [36].

Therefore, with the increase in anthropogenic CO_2 emissions, these natural processes are no longer capable of ensuring the stability of the CO_2 concentration balance in the atmosphere [37,38]. The continued emission of CO_2 has resulted in a persistent increase in atmospheric CO_2 concentration, leading to concerns about the impacts of climate change on the planet [8]. This highlights the need for effective mitigation measures to reduce CO_2 emissions and protect the Earth's climate [39]. The impact of elevated levels of greenhouse gases in the atmosphere on the environment and its inhabitants must be recognized [40]. The disruption of the balance of atmospheric gas concentration, resulting in phenomena such as climate change and global warming, is causing a profound effect on the delicate ecosystem and natural processes that support life on Earth [41]. These impacts range from changes in weather patterns and rising sea levels, to the melting of polar ice caps, species extinction, and alterations in water resource availability [42]. Additionally, these changes pose a significant threat to human well-being, including food security, health, and economic stability. To mitigate these negative effects, it is imperative to implement effective measures aimed at reducing and controlling the emission of anthropogenic greenhouse gases [43]. This can be achieved through the use of sustainable energy sources, improvements in energy efficiency, the use of latest carbon capture and storage techniques, and responsible land use practices [44]. By taking these actions, a sustainable future can be secured for our planet and future generations [45].

To mitigate the negative effects of climate change, the use of sustainable energy sources is critical, involving the implementation of effective measures to control and reduce anthropogenic greenhouse gas emissions [46]. These measures include investing in renewable energy sources, promoting energy efficiency and conservation, encouraging low-carbon transportation, implementing policies and regulations to incentivize sustainable energy use, increasing public awareness, and education [47]. For example, the shift to electric vehicles (EVs) can play a crucial role by reducing greenhouse gas emissions from transportation [48]. However, this transition has both positive and negative trends that need to be considered [49]. On the positive side, EVs are more energy-efficient than traditional gasoline-powered vehicles, leading to a reduction in overall energy consumption and greenhouse gas emissions [50]. In addition, advances in battery technology are improving the storage capacity of EVs, making them more practical for longer trips [51]. However, on the negative side, the production of EV batteries requires a significant amount of energy and resources, which could lead to an increase in emissions during the manufacturing process [52]. Additionally, the increased demand for electricity to power EVs could place a strain on the electrical grid, requiring investments in infrastructure and energy generation to support the transition [53]. Therefore, it is also necessary to implement effective measures in terms of energy efficiency, aimed at reducing and controlling the emission of anthropogenic greenhouse gases [54]. This includes promoting and incentivizing the adoption of energy-efficient technologies and practices, such as building insulation, efficient lighting and appliances, and sustainable transportation options [55].

The latest carbon capture and sequestration technologies also have the potential to contribute to reducing and controlling the emission of anthropogenic greenhouse gases [56]. Carbon capture and sequestration technologies involve capturing carbon dioxide emissions from industrial processes or power plants and storing them underground or in other long-term storage solutions [57]. However, the implementation of these technologies requires significant investment in research and development, as well as the deployment of large-scale demonstration projects [58]. For example, membrane technology is a promising technique that involves the use of selective membranes to capture CO_2 from gas streams, such as those produced in fossil-fuel power plants [59]. The selective membrane is designed to separate CO_2 from other gases in the gas stream, allowing for up to 90% of emitted CO_2 to be captured [60]. Additionally, membrane technology is considered a low-cost and easily maintainable option compared to other carbon capture technologies, such as adsorption or chemical absorption [61]. It is important to consider, however, that policies and regulations that incentivize the adoption of these technologies are also necessary to accelerate their deployment and ensure their effectiveness in reducing greenhouse gas emissions [62].

Responsible land use practices, such as reforestation, afforestation, conservation agriculture, and sustainable forestry, can help sequester carbon from the atmosphere, reducing greenhouse gas concentrations [63]. Responsible land use practices can help prevent deforestation, which is a significant contributor to greenhouse gas emissions [64]. Furthermore, sustainable agriculture practices can reduce emissions by reducing the use of synthetic fertilizers which release nitrous oxide, a greenhouse gas [65].

The deleterious effects of climate change on contemporary societies are numerous and varied [66]. One such effect is climate changes themselves, which can manifest as changes in precipitation distribution, temperatures, and wind patterns [67]. These changes can have far-reaching implications such as negatively affecting agriculture, water availability, and human health. In addition, climate change can increase the frequency and intensity of natural disasters such as storms, floods, and droughts [68]. These extreme weather events can result in damage to properties, infrastructure, and human lives [69]. Another potential consequence of climate change is water resource scarcity, which can exacerbate existing water scarcity in certain regions [70]. This, in turn, can have significant implications for agriculture, energy production, and quality of life [71]. Furthermore, climate change can cause population displacement, wherein individuals are forced to leave their homes and communities due to natural disasters, resource scarcity, or climate changes [72]. This can lead to forced displacement and increased vulnerability. Climate change can have a profound impact on the global economy, affecting sectors such as agriculture, fishing, tourism, and others [73]. Additionally, the costs associated with adapting to and mitigating the effects of climate change can be substantial [74]. These consequences can have a negative impact on the development of societies and can lead to wider social and economic inequalities [75]. Therefore, it is important to act quickly to mitigate climate change and ensure a more sustainable future for all people [76].

The present study aims to provide a systematic analysis of how the increase in the concentration of greenhouse gases (GHGs) interferes with the process of climate change. The study highlights the significant role played by the Industrial Revolution and the subsequent transition from conventional energy sources to fossil fuels in exacerbating the current state of global warming and climate change. The use of coal, oil, and cement production has all contributed to a lasting increase in the concentration of CO_2 in the atmosphere, disrupting the natural processes that regulate atmospheric CO_2 concentration. The study emphasizes the urgent need for effective mitigation measures to reduce CO_2 emissions and protect the planet's climate, including the adoption of sustainable energy sources, improvements in energy efficiency, and responsible land use practices.

2. Materials and Methods

2.1. Bibliometric Analysis

The present study employed the Bibliometrix package, specifically the Biblioshiny routine, in RStudio, following the methodology outlined by Aria and Cuccurullo (2017), to conduct a comprehensive literature review using the Web of Science TM (Clarivate) search engine [77]. To identify relevant studies, a set of keywords listed in Table 1 were employed. The lists of documents generated for each set of keywords were then assessed for relevance and subsequently merged to eliminate duplicates using a routine in RStudio. The resulting file contained a total of 282 selected documents, which had been cited 13,613 times, and were thus deemed appropriate for the bibliographic analysis.

The documents cover a time horizon from 1969 to 2023, distributed among 174 articles, 1 book, 34 book chapters, 26 conference papers, 1 note, 1 editorial, and 45 reviews. The documents feature a total of 1068 authors and are distributed across 235 sources. As for the most important sources, those with three or more publications on the subject (based on the keywords used in the search) were selected, as shown in Figure 1.

Table 1. Keywords used in the search.

Keywords	Nr. of Documents
"Climate Change"	508,594
"Climate Change" and "CO_2"	36,478
"Climate Change" and "CO_2" and "Causes" and "Consequences"	282

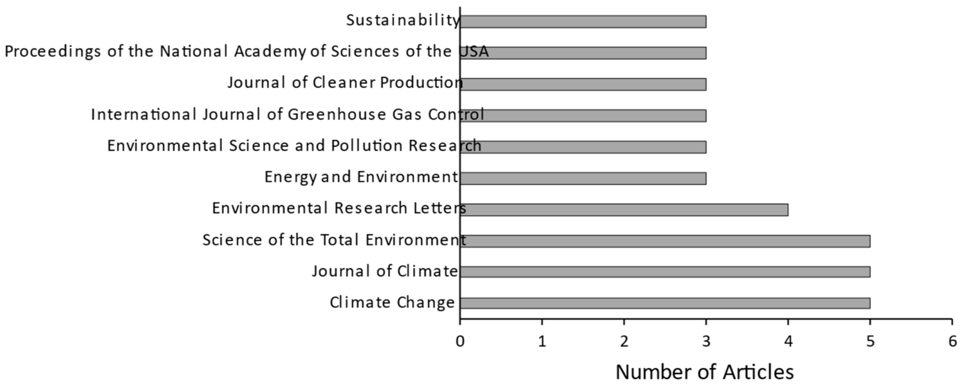

Figure 1. Main sources with three or more articles published on the subject.

There is also some consistency in the most used keywords in the articles, with those appearing with a frequency of 20 or more being selected as the most relevant. Thus, as shown in Figure 2, the most relevant keywords are "carbon dioxide", with 166 occurrences, followed very closely by "climate change", with 157 occurrences. Terms such as "global warming", "greenhouse gases", "extreme weather events", and "greenhouse effect" have significantly fewer occurrences, of 41, 30, 27, and 24, respectively.

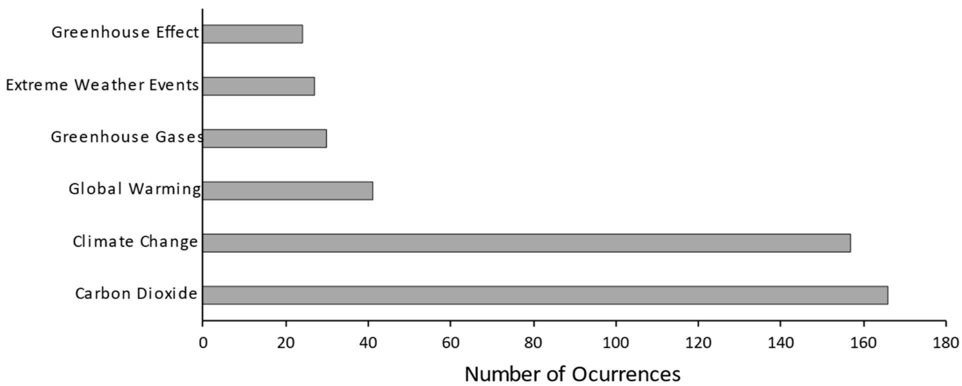

Figure 2. Most relevant keywords identified in the 282 documents identified in the SCOPUS search.

It was found that there is a significant number of documents that have high recognition within the scientific community, as confirmed by the number of citations they receive. In this analysis, a document was considered relevant if it had a set of citations equal to or greater than 250, highlighting the documents shown in Figure 3, and with the distribution of the nationality of the authors' affiliation presented in Figure 4. As can be seen, there is a very clear dominance of authors with affiliation in the USA, with 144 of the analyzed documents.

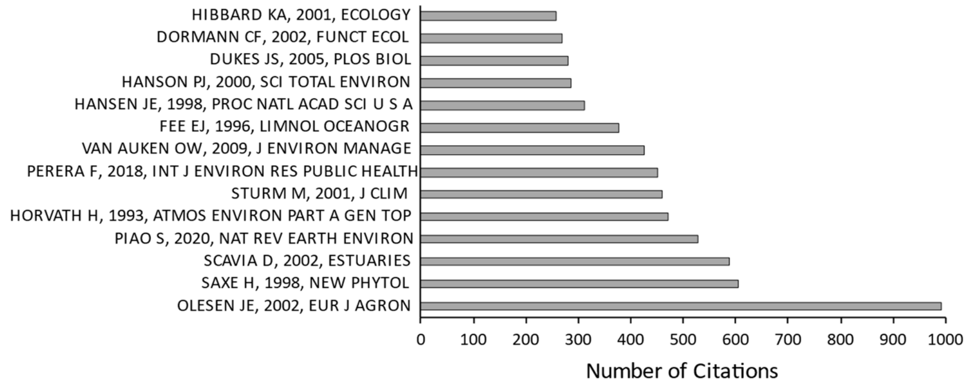

Figure 3. Documents selected for the literature review and presenting a citation count equal to or greater than 250.

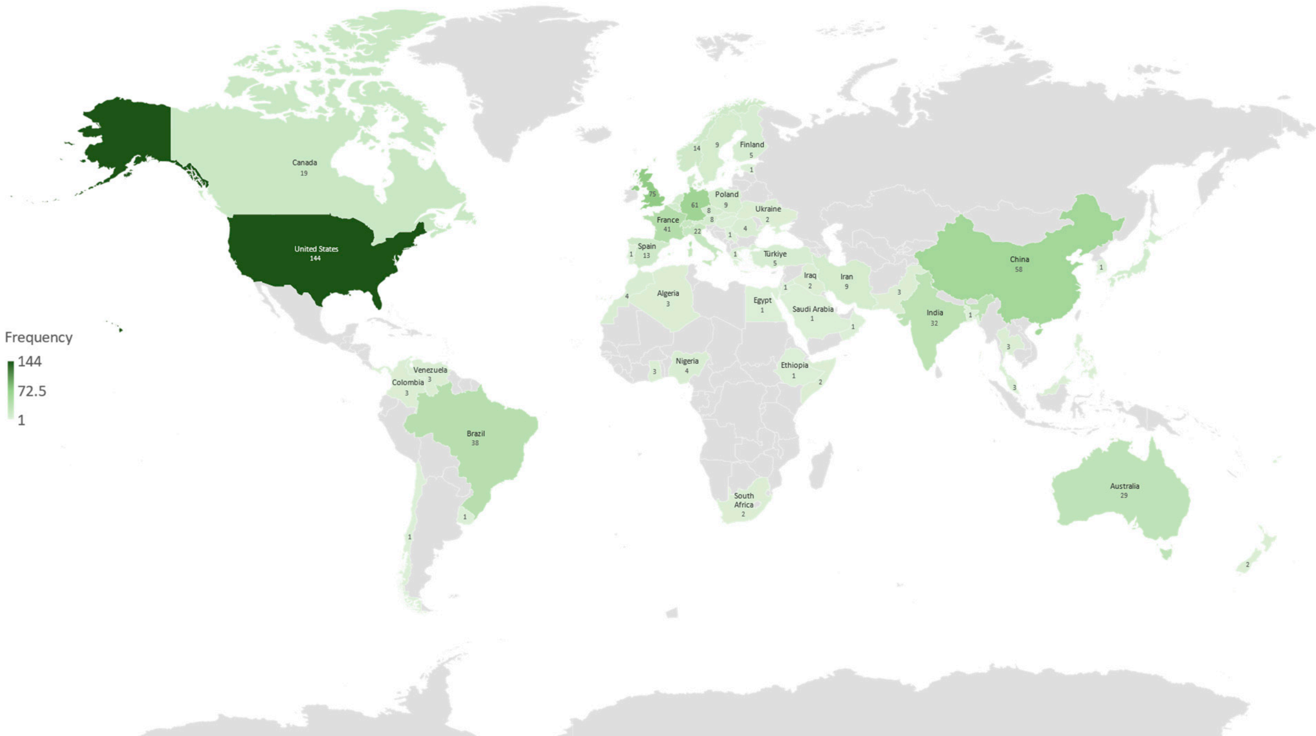

Figure 4. Distribution of the affiliation of the authors of the analyzed documents.

The state of development of the topic can be analyzed from the construction of a thematic map, as presented in Figure 5. The subtopics that make up the main theme are more developed and relevant the closer they are to the center of the scheme. Thus, it is noted that studies carried out on subtopics such as temperature, weather conditions, extreme weather events, carbon, the carbon cycle, and ecosystems are already in a high degree of development due to the high number of works found. On the other hand, basic themes such as climate change, carbon dioxide, and global warming, because they serve as a basis for the development of various subtopics, are still in a state of development and relevance that indicates a broad space for further research. Niche themes, such as sustainable development, risk assessment, and consequence analysis, because they are more specific themes resulting from applied research processes, also present a growing state of development and relevance, which anticipates the need for further research in these various fundamental subtopics for concrete and specific situations.

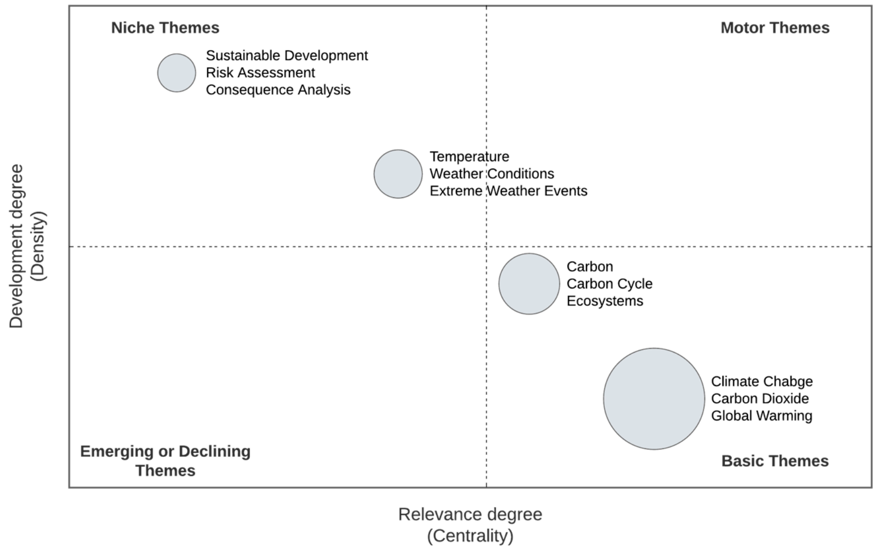

Figure 5. Thematic map.

2.2. Literature Review

To review the literature on the topic, the documents identified in the bibliometric analysis and described in the previous section were consulted. In addition to the documents identified on the topic (defined by the keywords selected for the search on the SCOPUS platform), other reference documents of a more fundamental nature were also used, which allowed for the framing of topics such as "climate change" or "carbon capture and storage".

3. The Earth's Atmosphere Equilibrium Equation

The high levels of atmospheric CO_2 in the Earth's geological past played a crucial role in the development of the current Earth system, characterized by a set of processes that enabled the capture and storage of CO_2 [78]. During past geological periods, the levels of CO_2 in the Earth's atmosphere were significantly higher than currently observed [79]. For example, during the Cretaceous period approximately 100 million years ago, atmospheric CO_2 levels were estimated to be around 1000 parts per million (ppm), compared to around 415 ppm currently [80]. During the Paleozoic era, which occurred between 541 and 252 million years ago, atmospheric CO_2 levels were even higher, estimated at several thousand ppm [81]. These high levels of CO_2 were partly a result of large-scale volcanic eruptions, which released significant amounts of greenhouse gases into the atmosphere [82]. These high levels of CO_2 played an important role in the evolution of the Earth, contributing to the formation of the atmosphere and influencing the climate and environmental conditions that shaped life on the planet [83]. For example, CO_2 was an important factor that allowed for the development of land plants during the Paleozoic era, as photosynthesis requires CO_2 as a source of carbon [84]. Additionally, the high levels of CO_2 in the atmosphere during the Cretaceous period were associated with a warmer and more humid climate, with tropical forests present at high latitudes and high levels of biodiversity [85]. However, it is important to note that these high levels of CO_2 were achieved over very long periods of time and are not comparable to the rapid changes occurring currently in the Earth's atmosphere, as a result of human activities [86]. Human activity, particularly the burning of fossil fuels, has contributed to a significant increase in CO_2 levels in the atmosphere since the Industrial Revolution, with CO_2 concentrations reaching unprecedented levels in millions of years [87]. This rapid increase of CO_2 in the Earth's atmosphere is leading to significant climate changes, with potentially severe consequences for climate, the environment, and humanity [88]. Inclusively, this scenario of climate change, with the increment of the global temperature shall promote, for example, the unfreezing of the permafrost, which is a layer of frozen soil, rock, and organic matter that can be found in polar and subpolar regions [89]. As permafrost thaws due to rising temperatures caused by climate change, it can release large amounts of CO_2 and CH_4 into the atmosphere [90]. This is a result of the organic matter in the permafrost, such as dead plant and animal remains, beginning to decompose as the permafrost thaws, and the decomposition process releases CO_2 and CH_4 [91]. The release of these greenhouse gases into the atmosphere contributes to further global warming and exacerbates climate change [92]. The released CO_2 contributes to the increase in atmospheric CO_2 concentrations, which traps more heat in the atmosphere, leading to a rise in temperatures [90]. Methane is an even more potent greenhouse gas than CO_2, so its release from permafrost has an even greater impact on climate change [93]. As the permafrost thaws, it can cause land subsidence and destabilize infrastructure, such as roads, buildings, and pipelines, which can have economic and social impacts [94].

The processes described in the geological past of the planet were instrumental in the formation of the atmosphere in which humans evolved and thrived [95]. As the dominant species on the planet, humans possess the unique ability to significantly alter the environment through the utilization of resources made available by the Earth system [66]. This includes the reversal of natural processes and the alteration of the composition of the atmosphere through the release of gases that were previously captured and stored [96]. From a mathematical perspective, this phenomenon can be represented as an additional term in the Earth system's equilibrium equation, reflecting the impact of human activities on the system and the ability to alter it drastically.

How can the system be rebalanced? The process can be described in a straightforward manner, as it only requires adding a term to the equation with an opposite sign and equal magnitude to the anthropogenic emission factor, to initiate the capture and storage of CO_2. As depicted in Equation (1), the balance between the natural factors responsible for the emission of greenhouse gases and the natural factors responsible for capturing and storing CO_2 always tends towards equilibrium, regardless of the quantities involved at any given time, as it is only a matter of time for the balance to be restored. Clearly, there will be fluctuations between warmer and colder periods while the balance is being restored.

$$\sum_{i=1,\ldots,n} NEF = \sum_{i=1,\ldots,n} NMF, \tag{1}$$

where *NEF* represents the natural greenhouse gas emission factors and *NMF* represents the natural greenhouse gas mitigation factors. The equation is expected to approach zero, indicating the attainment of balance. Thus, Equation (1) can be re-expressed as shown in Equation (2), where the *NMF* term is expressed as a function of time (t):

$$\sum_{i=1,\ldots,n} NEF = f(t) \sum_{i=1,\ldots,n} NMF \tag{2}$$

The variable t defines the moment when the system's equilibrium will be restored as a function of the quantity (q) of emitted greenhouse gases. As depicted in Equation (3):

$$f(q) \sum_{i=1,\ldots,n} NEF = f(t) \sum_{i=1,\ldots,n} NMF \tag{3}$$

Thus, in a simple manner, it represents how the Earth system self-regulated during the entire pre-Industrial Revolution period. How can the Earth system tend towards the equilibrium in the current phase, where there is an additional factor in the equation? Following the same reasoning, Equation (1) can be rewritten for the post-Industrial Revolution period, as shown in Equation (4):

$$\sum_{i=1,\ldots,n} NEF + \sum_{i=1,\ldots,n} AEF = \sum_{i=1,\ldots,n} NMF \tag{4}$$

The variable *AEF* represents the anthropogenic emission factor for greenhouse gases. It is evident that when Equation (4) is expressed as a function of time, the process towards reaching equilibrium will take longer and result in a greater number of fluctuations between warmer and cooler periods. However, in reality, the *AEF* is not composed of sporadic processes, as is the case with the *NEF*, which although they can reach large proportions, are limited in duration and the quantity of gases emitted. The *AEF*, since its inception during the Industrial Revolution, has been characterized by its cumulative growth in both type and quantity. In other words, the result of Equation (4) surpasses the natural mitigation capacity of the Earth system, as illustrated in Figure 6.

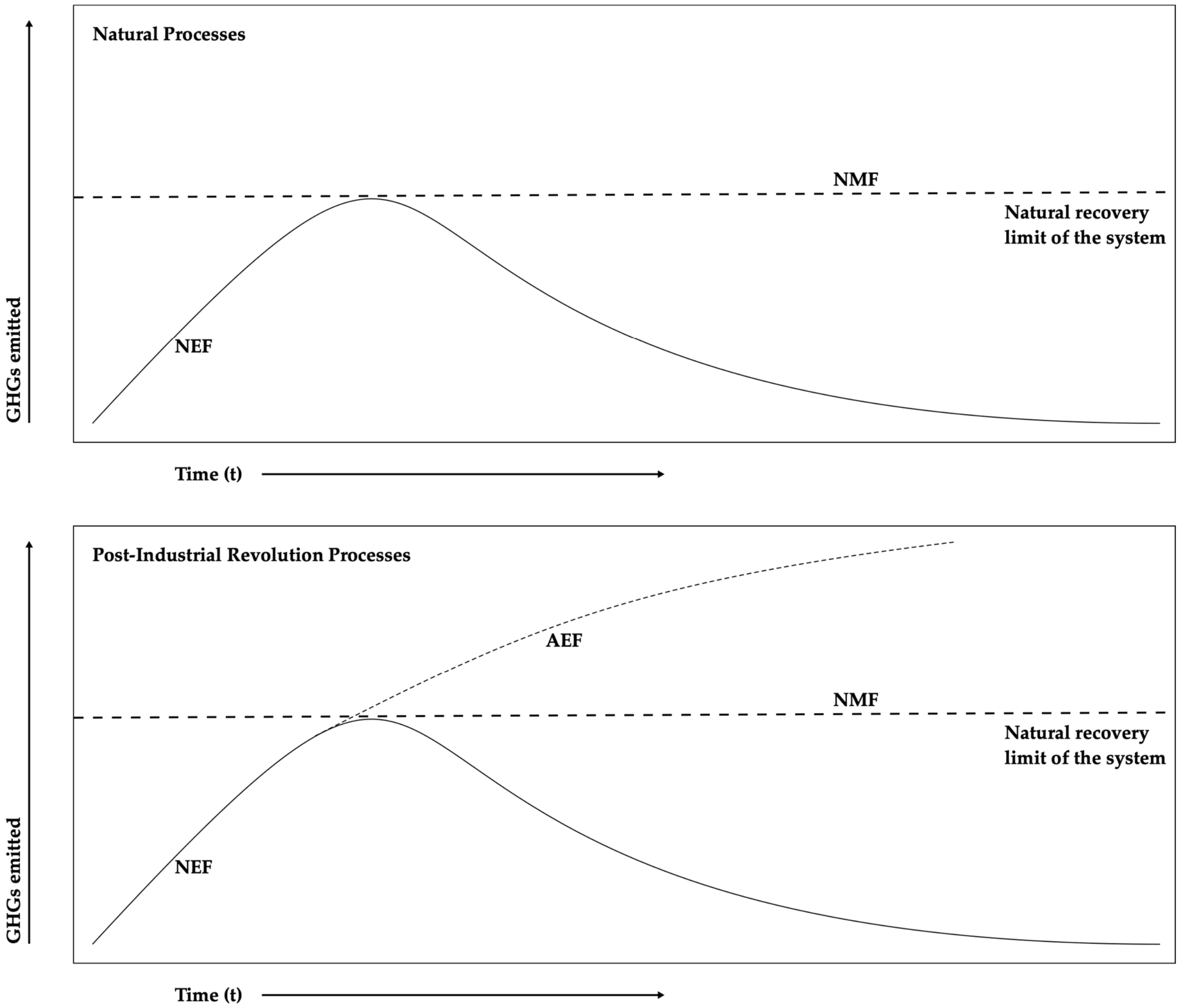

Figure 6. Evolution of the relationship between NEF and AEF with the natural capacity of the Earth system to counteract and neutralize the emission factors (NEF—Natural Greenhouse Gases Emission Factors; NMF—Natural Greenhouse Gases Mitigation Factors; AEF—Anthropogenic Greenhouse Gases Emission Factors).

In essence, Figure 6 indicates that once the natural self-regulation capacity of the system is exceeded, the levels of greenhouse gases in the atmosphere will continue to increase indefinitely, resulting in significant changes in the system and the intensification of its effects and characteristics. For instance, the greenhouse effect, which is a natural process crucial for the existence of life on Earth, is intensified by the increase in greenhouse gas concentrations, leading to an acceleration of the global warming process. This, in turn, results in alterations in the processes of evaporation, evapotranspiration, and air and water mass circulation, causing a rise in extreme meteorological events and potentially catastrophic changes in the planetary climate. To address this issue, Equation (4) must be revisited and an additional factor, which represents the set of anthropogenic mitigation measures to reduce greenhouse gas emissions, must be added to increase the system's regulatory capacity. Equation (5) shows the inclusion of the anthropogenic mitigation factors (*AMF*), and Figure 7 illustrates the functioning of the system with the inclusion of this anthropogenic mitigation component.

$$\sum\nolimits_{i=1,\ldots,n} NEF + \sum\nolimits_{i=1,\ldots,n} AEF = \sum\nolimits_{i=1,\ldots,n} NMF + \sum\nolimits_{i=1,\ldots,n} AMF \quad (5)$$

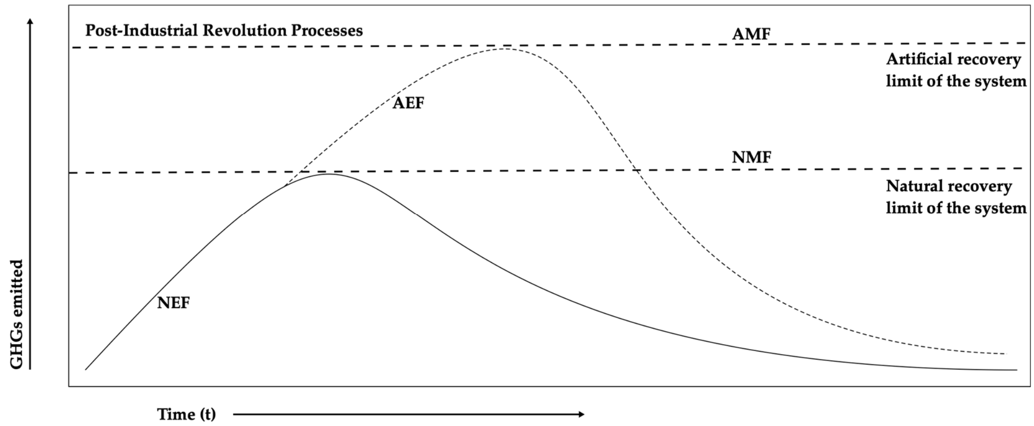

Figure 7. Resilience of the Earth system with the inclusion of anthropogenic (artificial) measures to mitigate greenhouse gas emissions (NEF—Natural GHGs Emission Factors; NMF—Natural GHGs Mitigation Factors; AEF—Anthropogenic GHGs Emission Factors; AMF—Anthropogenic GHGs Mitigation Factors).

Thus, the greater and more effective the (anthropogenic) mitigation measures that are added to the natural regeneration capacity, the greater the resilience of the system will be [97]. However, given the current state of the system in which the effects of climate change are already taking place, the implementation of mitigation measures should most likely be viewed not only as a means of offsetting current emissions, but rather as a means of capturing and storing greenhouse gases in order to offset the emissions produced over the entire post-Industrial Revolution period [98]. Simply compensating for current emissions will slow down the processes related to climate change, but it will be challenging to reverse the situation and stabilize the system within the parameters observed during the pre-Industrial Revolution period, especially within a timeframe that could be considered reasonable [99]. It should be noted that the timeframe for any measure to have a measurable effect should correspond to several generations [100]. For example, the analyses and scenarios presented for the end of the 21st century will impact, for better or for worse, and depending on the type and scope of the measures implemented, both people who are born now and more intensely their children and grandchildren [101]. In other words, what is decided now should be implemented by the current generation, with the continuation of their children, in order to guarantee a safer future for their grandchildren [102]. The word "safer" is used here to set the tone for the objectives of this work. In fact, climate change does not represent the only problem. Indeed, all other problems may also be considered as indirect causes of harm, such as conflicts arising from the need for access to resources such as drinking water, fertile soil, forests, energy resources, or vital space for the sustenance of populations [103]. It can be concluded that in the same way in which the processes causing climate change take effect over an extended period of time, the impacts of the measures aimed at mitigating and reversing the situation will also only become apparent after an equally long period. It is also evident that global-scale efforts require agreements between countries, such as those facilitated by the United Nations (UN), which can often leave citizens without a full understanding of these measures and their effects [104]. In this context, the examination of climate change must encompass more than just an examination of the physics of the atmosphere or the transfer of mass and energy [105]. It must also encompass an evaluation of the components related to the natural processes of greenhouse gas emissions, such as volcanic activity, an analysis of past events and their evolution, and an assessment of the system's capacity for recovery [106]. This will facilitate the identification of the most effective mitigation measures and enable an understanding of their potential consequences [107]. Additionally, it is crucial to study the impacts that past events have had on populations and societies, as this will provide insight into behaviors that can be applied to the present [108].

4. The Challenge of Climate Change

As a starting point to the discussion, the key challenges concerning climate change can be listed, as presented in Table 2.

Table 2. Key challenges concerning the discussion about climate change.

	Key Challenges
1.	A complex and multi-faceted issue that requires cooperation from multiple countries and sectors.
2.	Economic interests, lack of political consensus, and difficulty of behavioral change pose significant obstacles to effective mitigation efforts.
3.	Controversy surrounding the existence of climate change and influence of special interest groups exacerbate the situation.
4.	Urgent and concerted efforts are necessary to reduce greenhouse gas emissions and limit the impacts of climate change.
5.	Consequences of anthropogenic climate change are already evident, affecting biodiversity, food and water security, human health, and the global economy.
6.	Rapid and ambitious action is essential to ensure a more sustainable future for all people.

Climate change is a complex and multi-faceted issue that requires cooperation from multiple countries and sectors. However, economic interests, lack of political consensus, and difficulty of behavioral change pose significant obstacles to effective mitigation efforts. Similarly, controversy surrounding the existence of climate change and influence of special interest groups exacerbate the situation. Urgent and concerted efforts are therefore necessary to reduce greenhouse gas emissions and limit the impacts of climate change, as the consequences of anthropogenic climate change are already evident, affecting biodiversity, food and water security, human health, and the global economy. Ultimately, rapid and ambitious action is essential to ensure a more sustainable future for all people.

Several initiatives are under way to mitigate climate change, the most well-known and comprehensive of which is the Paris Agreement on Climate, also known as the Paris Agreement, signed in 2015 at the United Nations Climate Change Conference (COP21) [109]. This agreement aims to limit the increase in global temperature to less than 2 degrees Celsius above pre-industrial levels and to strive to limit the increase to 1.5 degrees Celsius [110]. To achieve these goals, signatory countries agreed to establish greenhouse gas emission reduction targets and to periodically review their progress [111]. Other important agreements include the 1997 Kyoto Protocol, which established emission reduction targets for industrialized countries, and the 2010 Cancun Agreement, which established measures to support the development of renewable energy and increase the resilience of the most vulnerable countries to climate change [112]. The parties that have signed international climate accords, such as the Paris Agreement, have pledged to implement effective strategies aimed at reducing the emission of greenhouse gases and controlling the increase in global temperatures [113]. To achieve this, these countries have agreed to adopt various measures, including the promotion of renewable energy sources, the enhancement of energy efficiency, the implementation of responsible land management practices, and the deployment of carbon capture and storage technologies [114]. Additionally, the signatory countries have agreed to periodically evaluate their emissions reduction targets and commitments to confirm that they are effectively addressing the challenges posed by climate change [115]. These actions are vital in preserving the health of the planet and securing a sustainable future for future generations [116].

The effectiveness of measures implemented globally to reduce greenhouse gas emissions is a widely debated issue [117]. While there is evidence that some measures have been effective in reducing emissions in certain countries and sectors, much remains to be done to achieve the global goals set by international climate agreements, such as the Paris Agreement [118]. In many countries, emissions continue to increase due to a lack of adequate policies and investments in the transition to renewable energy sources and energy efficiency improvements [119]. Furthermore, the lack of international cooperation and the lack of commitment by some countries to reduce their emissions are also significant obstacles to the success of these measures [120]. The reduction of greenhouse gas emissions is a pressing global issue, and countries have implemented various measures to address it [121]. Among the most effective measures are transitioning to renewable energy sources, replacing fossil fuels with wind and solar energy, and improving energy efficiency, such as upgrading buildings and using more fuel-efficient vehicles [122]. Another measure is carbon capture and storage technology, which captures and stores CO_2 emissions before they are released into the atmosphere [123]. Responsible forest management practices, such as protecting existing forests and restoring degraded areas, can also contribute to reducing greenhouse gas emissions and increasing carbon sequestration capacity [124]. Some countries are also implementing fiscal policies and incentives to encourage the adoption of green technologies and more sustainable behaviors [125]. These measures can help mitigate the negative effects of climate change and promote sustainable development [126].

These measures have been shown to be effective in reducing greenhouse gas emissions in specific countries and sectors, but there is still much to be done to achieve the global goals set by international climate agreements [127]. However, the effectiveness of these measures can be impacted globally, as not all countries implement the measures simultaneously or in the same way [128]. The lack of international cooperation and disregard of some countries in adopting effective measures to reduce their greenhouse gas emissions are significant obstacles to the success of these measures on a global scale [121]. Furthermore, disparities in financial and technological capabilities among countries can also influence the effectiveness of the implemented measures [129]. It is essential that countries work together and collaborate to ensure that actions are effective in combating climate change [130]. International cooperation and the commitment of all countries are crucial for the success of measures to reduce greenhouse gas emissions and protect the planet for future generations [131].

In addition to the aforementioned measures, several additional actions can boost the mitigation of climate change [132]. The development of green technologies, such as renewable energy storage battery technology, can help accelerate the transition to renewable energy sources [133]. Investment in research and development of green technologies can help find solutions to the challenges related to climate change [134]. Education and awareness about climate change are important to help people understand the significance of taking measures to mitigate greenhouse gas emissions [135]. Stricter policies and regulations to limit greenhouse gas emissions can be important to ensure that the implemented measures are truly effective [124]. International cooperation is therefore essential to ensure that all countries work together towards a common goal of mitigating climate change [136]. These additional measures can help boost ongoing efforts to mitigate climate change and protect the planet for future generations [137]. Implementing measures to mitigate climate change is a challenging task due to various factors [138]; one such factor is the complexity of the issue. Climate change is a complex global issue that involves various economic sectors such as energy, transportation, agriculture, and forests [137]. Additionally, solutions to climate change require cooperation from multiple countries and sectors, which can be challenging [139].

Another factor is economic interests [140]; many countries and companies are heavily invested in fossil fuel sources such as oil, gas, and coal, and may resist changes to renewable energy sources [141]. Additionally, shifts to more sustainable practices may have a short-term negative economic impact, which may discourage the implementation of mitigation measures [18]. Lack of political consensus is another factor that makes implementing mitigation measures difficult [142]. The issue of climate change is highly political and can be divided in terms of opinions and ideologies [143]. This can make it difficult to implement mitigation measures, especially at international levels [144]. Difficulty of behavioral changes is another challenge [145]. Climate change requires significant changes in individual and collective behavior, including changes in energy, transportation, and lifestyle choices [146]. This can be difficult to achieve, especially in highly consumerist societies [147].

The controversy surrounding the existence of climate change, including the belief that it is a natural process, still exists for several reasons [148]. One of the main reasons is the lack of complete scientific understanding about the Earth's climate and the processes that drive it [149]. Some people may argue that the changes observed in the climate can be attributed to natural causes, such as variations in the Earth's orbit or solar activity [150]. Another reason is the influence of special interest groups, who have a vested interest in denying the reality of climate change [151]. These groups often finance and promote scientific studies that support their positions and cast doubt on the scientific consensus on climate change [152]. The issue of climate change can be politically polarizing, with some ideologies viewing government action to address climate change as an infringement on individual freedoms and the economy [153]. The consequences of climate change are often not immediately visible, and the full impact may only be felt in the future [154]. This can make it difficult for some people to fully grasp the urgency of the situation and act [155]. Economic factors tend to be one of the main obstacles in the fight against climate change [143]. The dependence on fossil fuel sources and resistance to the transition to renewable energy sources by countries and businesses, as well as the negative economic impact that transitioning to more sustainable practices may have in the short term, are examples of how economic interests can be a barrier to the implementation of climate change mitigation measures [156]. The pursuit of short-term economic growth may lead to resistance to change towards more sustainable practices, even if they are necessary to protect the future of the planet [157].

The assertion that climate change is a natural phenomenon is a hypothesis that has been disputed by researchers worldwide [105]. Despite instances of natural climate changes in the past, the scientific community is in consensus that human activities are the primary cause of contemporary climate change [158]. Various investigations have revealed that the combustion of fossil fuels, deforestation, and other anthropogenic activities have released substantial volumes of greenhouse gases into the atmosphere, which have triggered rapid global warming and consequent climatic changes that have global implications [159]. The consequences of anthropogenic climate change are undeniable and encompass a rise in average global temperatures, an increase in sea levels, acidification of oceans, melting of glaciers, and more frequent and intense extreme weather occurrences such as heatwaves, storms, hurricanes, and flooding [160]. These impacts are causing adverse effects on biodiversity, food and water security, human health, and the global economy [161]. Therefore, governments, businesses, and civil society must undertake urgent and concerted efforts to limit the impacts of climate change by reducing greenhouse gas emissions [162].

A review of the Earth's climate history shows that the climate has undergone significant changes throughout time [163]. These changes have been driven by various natural factors, including changes in the Earth's position relative to the sun, variations in volcanic activity, and changes in the composition of the atmosphere [164]. Some of the most notable episodes of climate change include the mass extinctions that occurred throughout the Earth's history [165]. These extinctions resulted from climate change and environmental changes, such as the End-Ordovician Extinction, which occurred about 443 million years ago, the Late Devonian Extinction, which occurred about 375 million years ago, the Permian-Triassic Extinction, which is the largest mass extinction event in Earth's history, the Triassic-Jurassic Extinction, and the Cretaceous-Paleogene Extinction, which resulted in the loss of the dinosaurs [166]. Another significant period of climate change was the Ice Age, which occurred approximately 2.6 million years ago and lasted until about 11,700 years ago [167]. During this period, global temperatures significantly decreased, causing the expansion of glaciers and a change in the global climate [168]. In contrast, the Medieval Warm Period was a period of warming that occurred between the 11th and 14th centuries and was characterized by temperatures warmer than those of today [169]. This warming was attributed to various factors, including variations in solar activity, changes in the Earth's position relative to the sun, and changes in the composition of the atmosphere [170]. The Little Ice Age, which occurred between the 15th and 19th centuries, was a period of weakened climate characterized by colder and drier conditions, with more severe winters and shorter summers [171]. This period had implications for agriculture, fishing, and other economic sectors [172]. The causes of the Little Ice Age are still a matter of debate, but it is believed to have been influenced by natural factors such as variations in solar activity, changes in volcanic activity, and variations in the configuration of the Gulf Stream [173]. Additionally, human activities such as deforestation and intensive agriculture may have contributed to the climate changes during this period [174].

The current climate change differs significantly from those that occurred in the Earth's history primarily because of human activities [149]. While the past climate changes were largely attributed to natural factors, such as changes in the Earth's position relative to the sun, volcanic activity, and atmospheric composition, the current ones are mainly caused by human activities [175]. The burning of fossil fuels, deforestation, and intensive agriculture are examples of human activities that are releasing large amounts of greenhouse gases into the atmosphere, which are accelerating global warming and causing climate change at a faster pace than those observed in the past [176]. For example, agriculture and food production contribute to the release of methane in several ways [177]. One significant source is enteric fermentation in livestock, which refers to the digestive process that occurs in the stomachs of ruminant animals like cows and sheep [178]. During this process, methane is produced and released as a byproduct, which is then emitted into the atmosphere through belching [179]. Another source is manure management, which involves the storage and treatment of animal waste. When manure is stored or treated in anaerobic conditions (such as in lagoons or pits), it can produce methane as a byproduct, which is then emitted into the atmosphere [180]. Rice cultivation is also a significant source of methane emissions [181]. When rice paddies are flooded for cultivation, anaerobic conditions are created in the soil, which can lead to the production of methane [182]. Furthermore, the use of synthetic fertilizers in agriculture can also contribute to the release of methane [183]. When synthetic fertilizers are applied to soil, they can stimulate the growth of methanogenic bacteria, which can produce and release methane as a byproduct [184].

The significant increase in greenhouse gas concentrations in the atmosphere, particularly carbon dioxide, methane, and nitrous oxide, is contributing to global warming, causing sea levels to rise, and causing severe weather events such as heatwaves, droughts, and intense storms [185]. The current climate change's scale and speed are unprecedented in the Earth's recent history [8]. In the past, climate changes occurred gradually over thousands of years, giving ecosystems and species enough time to adapt to the new conditions [186]. However, the current climate change is happening at an unprecedented rate, making it difficult for ecosystems and species to adapt quickly enough [187]. This has led to the extinction of several plant and animal species and significant biodiversity loss [188]. Furthermore, the current climate change is also affecting human societies by threatening food security, causing economic losses, and increasing the risk of conflicts and migration due to displacement [189]. While past climate changes were attributed to natural factors, the current climate change is largely caused by human activities, particularly the burning of fossil fuels [190]. The scale and speed of the current climate change are unparalleled in the Earth's recent history, making it difficult for ecosystems and species to adapt quickly enough, and thus they threaten the sustainability of human societies [191].

Will humanity be prepared to face a process of global-scale climate change? The answer to this question is controversial and depends on various factors. On one hand, humanity has access to advanced technologies and knowledge that can help mitigate and adapt to climate change, such as renewable energy sources, energy storage technologies, resilient infrastructures, and more sustainable agricultural practices. However, the implementation of these solutions is complex and requires international cooperation and strong political actions to be effective. Additionally, many countries still heavily rely on fossil fuel sources and there is little incentive to switch to renewable energy sources [192]. The use of a carbon tax is a policy mechanism that can contribute to mitigating climate change by creating economic incentives to reduce greenhouse gas emissions [193]. A carbon tax is a fee levied on the carbon content of fuels and products that emit carbon dioxide when burned, such as coal, oil, and gas [194]. The tax would increase the cost of these products, encouraging consumers and producers to use cleaner, low-carbon alternatives [195]. By making carbon-intensive products more expensive, a carbon tax provides an economic incentive for individuals and businesses to reduce their carbon footprint [196]. The revenue generated from a carbon tax could also be used to fund research and development of new technologies and alternative energy sources [197]. A carbon tax can help to level the playing field between carbon-intensive industries and those using low-carbon alternatives [198]. However, there are potential challenges associated with implementing a carbon tax, including political opposition and the potential for negative economic impacts on certain sectors [199].

Climate change is already causing increased negative impacts on the most vulnerable communities, including low-income populations, indigenous populations, and low-lying regions. Therefore, humanity may not be fully prepared to face a process of global-scale climate change, but it is important to note that there is still time to take action to improve resilience and minimize the negative impacts of climate change. Rapid and ambitious action is necessary to ensure a more sustainable future for all people.

5. Conclusions

International efforts to mitigate climate change have made significant progress with the signing of several climate agreements, including the Paris Agreement. However, there is still much work to be done to meet global goals. The effectiveness of implemented measures to reduce greenhouse gas emissions depends on the country and sector, and some nations' lack of cooperation and commitment hinders progress on a global scale. Further measures, including developing green technologies and stricter policies, can improve ongoing efforts. Climate change is a complex issue that requires cooperation from multiple sectors, and challenges such as economic interests and political consensus hinder mitigation efforts. Despite controversy, the scientific consensus is that human activities are the primary cause of contemporary climate change, which is already affecting the environment, human health, and the economy. Urgent and concerted efforts are necessary to reduce greenhouse gas emissions and limit the impacts of climate change, but there is still time to take action to improve resilience and minimize the negative impacts.

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