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Assessment of Climate Change Factors and Impacts Using the Pythagorean Fuzzy AHP Approach

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Abstract − Today, climate change has become a global crisis threatening not only the environment but also economic, social, and political systems worldwide. This situation necessitates the systematic analysis of both the drivers contributing to climate change and the areas affected by it. Given the high level of uncertainty in environmental decision-making processes, the use of fuzzy logic-based multi-criteria decision-making approaches has become essential. In this study, the Pythagorean Fuzzy Analytic Hierarchy Process (AHP), developed by utilizing Pythagorean fuzzy sets, is applied to prioritize the factors influencing climate change and the elements impacted by it. Accordingly, the relevant factors and elements were identified through literature review and expert opinions, and the methodological steps were followed to assign their respective weights. The results of the study indicate that among the factors contributing to climate change, fossil fuel use and carbon emissions was identified as the most critical factor. This was followed by animals and industrialization, while tourism activities and the health sector received the lowest priority levels. On the other hand, among the elements affected by climate change, biodiversity emerged as the most critical domain, with natural disasters and insects also assigned high importance levels. In contrast, destruction of cultural and historical sites and economy and socio-politics were ranked lower due to their more indirect effects. This study is the first to examine climate change drivers and impacts, ranking them under uncertainty. The findings provide decision-makers with a roadmap to identify strategic focal points in combating climate change.

Keywords − *Climate change, fuzzy sets, multi-criteria decision making, Pythagorean fuzzy AHP, sustainability*

1. Introduction

Climate is defined as a combination that includes the average characteristics of all weather conditions observed or occurring over a long period of time in any region of the Earth, along with the temporal distribution of their frequency, extreme values, severe weather events, and all forms of variability [1]. Climate is a critical element that determines various features and distributions of both managed and natural systems, including hydrology and water resources, cryology, marine and freshwater ecosystems, terrestrial ecosystems, forestry, and agriculture [2]. Climate change refers to unusual climatic events resulting from human activities disrupting the balance of the atmosphere [3]. According to the United Nations Framework Convention on Climate Change (UNFCCC), climate change is defined as a change in climate that is attributed directly or indirectly to human activities altering the composition of the global atmosphere, in addition to natural climate variability observed over comparable time periods [4]. Since the mid-20th century, changes in extreme weather and climate events have been observed. Most of these changes, associated with anthropogenic effects, include decreases in extreme cold temperatures, increases in the occurrence of extreme heat, accelerated rates of sea level rise, and

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increased frequency of heavy precipitation events in many regions. Rising temperatures, elevated CO_2 and other greenhouse gases (GHGs), along with altered precipitation patterns, have resulted in extreme climatic conditions and climate change [2]. It is essential to accurately identify the key factors influencing the climate and their potential consequences. Research in this field has revealed that influencing factors and their outcomes often trigger one another. Human activities, including maritime transport, forestry, agriculture, and livestock—primarily driven by the growing demand for energy—are among these contributing factors. At the same time, these sectors are also among the areas most affected by climate change [5]. Climate change is a multidimensional global problem influenced by numerous factors, such as rising temperatures, wildfires, urbanization, increasing pollution, biodiversity loss, and lifestyle changes. The main drivers of climate change include greenhouse gas emissions from human activities such as fossil fuel combustion, deforestation, industrial processes, and agricultural practices. On the other hand, climate change manifests itself through altered weather patterns, with increasingly frequent and intense hurricanes, droughts, and floods. Therefore, analyzing these factors and their impacts is of critical importance for developing strategies to reduce greenhouse gas emissions.

In this study, the Pythagorean Fuzzy Analytic Hierarchy Process (AHP) method is employed to rank, by order of importance, the factors contributing to climate change and the elements affected by it. This research is the first of its kind to examine both the causes of climate change and the affected elements using a fuzzy multi-criteria decision-making approach. The factors and elements identified in the study can provide guidance to both researchers and public institutions in the development and dissemination of strategies for climate change mitigation.

2. Climate Change

Global warming is a process that affects all living organisms and causes significant changes in the environment. Due to the accumulation of greenhouse gases in the atmosphere, solar radiation cannot be adequately reflected into space, leading to heat being trapped in the lower atmospheric layers and causing a rise in temperature. The amount of greenhouse gases has particularly increased since the Industrial Revolution, which began in the 1750s, with carbon dioxide levels rising by 40%, from 280 ppm to 394 ppm. This increase has paved the way for various changes in the climate system [6]. At the core of climate change lies global warming, largely driven by the burning of fossil fuels (coal, oil, natural gas), which release carbon dioxide and other greenhouse gases into the atmosphere [7].

The use of fossil fuels, industrialization, population density, urbanization, agricultural and livestock activities, deforestation, cement production, and increasing waste generation have all contributed to the concentration of human-induced gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in the atmosphere. In other words, the intensification of the natural greenhouse effect leads to rising global temperatures. This trend, which became particularly noticeable in the late 19th century, accelerated after the 1980s, and in recent years, new global temperature records have been recorded annually [4]. Rapid rises in atmospheric and sea levels further highlight the seriousness of the situation. The primary causes of global warming are emissions of carbon dioxide, methane, and nitrous oxide linked to fossil fuel consumption and land-use changes [2, 8]. According to various climate models, global temperatures are expected to rise by between 1.4°C and 5.8°C over the next century [2].

The rapid pace of technological development over the last three centuries has strained the atmosphere's natural regenerative capacity. Since the Industrial Revolution, environmental damage has far exceeded that of previous periods. According to the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report, it is 95–100% likely that the observed increase in temperatures between 1951 and 2010 was caused by human activities [9]. Historically, various approaches have been developed to explain climate change. French mathematician Joseph Alphonse Adhémar (1797–1862) argued that the wobbling of the Earth's rotational axis could lead to climate changes, supporting his view with evidence of cooling trends in Antarctica. Scottish scientist James Croll, in his 1864 publication, linked climate variations to changes in the Earth's position relative to the Sun. Building on this, Serbian astronomer Milutin Milankovitch (1879–1958) explained past climate changes through orbital parameters (eccentricity, axial tilt, and precession), which later became known as the Milankovitch Cycles. These astronomical factors are regarded as key natural drivers of climate variability, as they determine the amount and distribution of solar energy reaching the Earth [10].

2.1. Factors Contributing to Climate Change

2.1.1. Fossil Fuel Consumption and Industrialization

The rapid increase in global population and technological advances has significantly raised energy demand, while fossil fuels, despite being unsustainable, continue to dominate the energy sector [11]. Carbon dioxide is one of the most critical greenhouse gases, trapping infrared radiation and contributing to rising temperatures. The CO_2 concentration, which was 280 ppm in the pre-industrial era, has reached 416 ppm today and is projected to double by 2100. According to the World Meteorological Organization, global temperatures have increased by 1°C compared to pre-industrial levels, and IPCC reports indicate that the last three decades have been the warmest on record. Greenhouse gas emissions caused by human activities have been responsible for 1.1°C of global warming since 1850 [2]. In addition, oceans have absorbed excess CO_2, becoming more acidic, with pH levels decreasing by 25% compared to pre-industrial times [12]. The United Nations' Climate Action goal emphasizes the necessity of transitioning from fossil fuels to renewable sources. In this context, there has been a global shift toward sustainable energy sources such as wind, solar, and hydropower [8]. On the other hand, the transportation sector accounts for 24% of global CO_2 emissions, underscoring the urgency of phasing out internal combustion engines, reducing private vehicle use, and promoting alternatives such as public transportation and cycling [13]. Moreover, individual responsibility plays a critical role. As Stanisław Jerzy Lec aptly remarked, many people tend to ignore their role in the climate crisis; however, individual-level actions can significantly contribute to managing the process. The reduce, reuse, recycle approach—combined with energy conservation, the use of decarbonized electricity, reduced meat consumption, minimizing food waste, and adopting conscious consumption habits—offers an effective roadmap to combating climate change [12].

2.1.2. Agricultural Activities and Deforestation

Climate change directly affects plant nutrition, soil fertility, and carbon sequestration through changes in temperature, precipitation, and CO_2 levels. Rising temperatures alter growing seasons, while irregular precipitation increases the vulnerability of production systems [14]. Agricultural practices play a significant role in greenhouse gas emissions. N_2O emissions from fertilizer use and CH_4 emissions from livestock and rice cultivation are the primary sources. Since methane has 32 times the greenhouse effect of CO_2, improving irrigation, fertilization, and drainage practices is essential for its reduction [3]. The impacts of climate change on agricultural production are multidimensional: higher temperatures reduce seed germination and yields; drought leads to water scarcity; sudden rainfall increases risks of floods and erosion. Seasonal shifts disrupt sowing–harvesting calendars, while the spread of pests and diseases increases the use of chemical pesticides. Declining water resources intensify sectoral competition, forcing farmers to adopt new techniques and climate-resilient crops. Yield losses reduce farmers' incomes, diminish food supply, and trigger price increases [7]. In arid and semi-arid regions, soils become more prone to erosion, while rising temperatures and decreasing precipitation cause yield fluctuations [14]. Since 1900, 770 severe droughts have been recorded, resulting in 38 million deaths [13]. The reduction of water resources increases salinization and land degradation, while excessive use of fertilizers and pesticides worsens environmental pollution [15]. Therefore, enhancing carbon sequestration, adopting sustainable farming practices, improving water management, and developing climate-resilient crop varieties are considered priority solutions [7, 14].

2.1.3. Urban Development

The interaction between human activities and climate change has reached a critical level, with cities expected to experience the most pronounced impacts. The physical effects of climate change on urban areas include the formation of urban heat islands, drought, sea-level rise, floods caused by sudden rainfall, and storms. In addition, socio-economic issues such as rapid urbanization and poverty are exacerbated by climate change. Urban contributions to climate change are primarily linked to CO_2 and other greenhouse gas emissions arising from increased energy consumption in transportation, construction, and industrial sectors, as well as rising surface temperatures. Thus, cities are both vulnerable to the impacts of climate change and significant contributors to the process [16].

2.1.4. Wastewater Management and Carbon Emissions

Climate change directly affects wastewater treatment plants, which in turn contribute to the process through greenhouse gas emissions. Climatic variables such as precipitation regimes, sea-level rise, storms, floods, temperature fluctuations, and icing determine the operation of facilities. A 2–5 °C temperature increase is projected by 2050, with biological process-based facilities being the most affected, as bacterial populations function within limited temperature ranges. The growing number of facilities necessitates examining environmental impacts and emission sources. Temperature fluctuations reduce efficiency in processes such as sedimentation, aeration, sludge treatment, stabilization, and chlorination. Hence, process models should be supported by automation and optimization, and emergency plans should be developed for coastal facilities facing sea-level rise. The main emissions are CO_2, CH_4, and N_2O, requiring identification of sources and reduction measures [17]. Companies also face uncertainties regarding the magnitude and timing of climate change. In Canada, for instance, the oil and gas sector accounts for 22% of total greenhouse gas emissions, and carbon-intensive industries face pressure to transform their processes. Shifting to low-carbon materials and products, developing new technologies, and improving industrial processes are among the key approaches [18]. Enhancing the efficiency of existing technologies and transitioning to renewable energy sources are priorities for reducing emissions. Expanding the use of solar, wind, geothermal, and wave energy reduces fossil fuel dependency, while the development of carbon capture technologies is also seen as critical [11, 13].

2.1.5. Animals

Climate change directly affects the livestock sector, particularly through reduced feed and water availability. These two factors are interlinked, acting as both cause and consequence. Livestock is a major source of greenhouse gas emissions—especially methane and nitrous oxide—while climate change, through rising temperatures and water scarcity, reduces feed production and negatively impacts animal nutrition. Droughts and yield losses can lead to severe consequences, including animal deaths. For example, in 2013, extreme heat in Australia caused significant cattle losses, clearly illustrating the impact of climate change on livestock [19]. Livestock accounts for 14.5% of total anthropogenic greenhouse gas emissions. Direct sources include enteric fermentation, manure, and energy consumption, while indirect sources encompass production, land use, and associated changes. Land-use changes contribute 9.2% of total livestock emissions, while fossil fuel-related CO_2 emissions from feed and animal transport, as well as fertilizer production, also play a significant role [20]. Climate change further accelerates the spread of diseases in livestock and increases heat stress, threatening animal health. In tropical and warm regions, the proliferation of parasite- and bacteria-related diseases reduces milk and animal production. Studies indicate that global warming will exacerbate animal diseases, leading to negative impacts on production [19].

2.1.6. Health Sector

The health sector, while providing services for disease prevention, diagnosis, and treatment, generates significant environmental and economic impacts due to its high consumption of energy, water, and materials, as well as the generation of waste [21]. Currently, the sector accounts for 4–5% of global carbon emissions, making it a notable contributor to climate change [22]. Emission sources include electricity consumption, medical supplies, heating and cooling, anesthetic gases, and waste disposal [23]. In the UK, NHS data indicate that 62% of emissions come from the supply chain, 24% from care delivery, 10% from staff and patient travel, and 4% from private healthcare services [22]. In Turkey, the sector consumes 10 billion kWh of electricity and 1.5 billion m^3 of water annually, while generating 1.5 million tons of waste and 6 million tons of carbon emissions, placing a heavy burden on resource efficiency [24]. Globally, the sector is responsible for 4.4% of emissions, with the United States having the highest share at 8.5%. Therefore, it is essential for healthcare professionals to contribute to climate change mitigation and adaptation policies, and to be trained to prepare health systems for a green transition [12].

2.2. Elements Affected by Climate Change

2.2.1. Ecosystems and Biodiversity

Biodiversity refers to the dynamic systems formed by living organisms and their ecological environments. Ecosystem diversity emerges from the interaction of biotic (plants, animals, microorganisms) and abiotic (soil, water, air, minerals) components [25]. The approximate 1.5°C rise in global temperatures is directly linked to anthropogenic greenhouse gas emissions. This increase has triggered consequences such as glacier melting, sea-level rise, extreme climate events, and biodiversity loss [7]. Unsustainable development practices in the past century have led to severe degradation of biodiversity and ecosystems [25]. Climate change reduces species diversity in agricultural production, threatening food security; while rapidly adapting species may proliferate, slow-adapting species face decline and extinction risks [7]. Observed impacts include productivity losses, shifts in reproductive cycles, disruptions in food chains, and changes in soil structures, which create cascading effects on both biodiversity and ecological balance [25]. Preserving biodiversity plays a critical role in enhancing resilience against climate change and ensuring the continuity of ecosystem services. Recent analyses highlight that protecting 30–50% of terrestrial, freshwater, and marine ecosystems effectively and equitably is necessary for sustaining planetary resilience [26]. Although full species recovery may not be possible, sustainable policies can stabilize the current situation [25].

2.2.2. Water Resources and the Hydrological Cycle

The hydrological cycle refers to the continuous circulation of water across oceans, the atmosphere, and land, forming the hydrosphere. Of the Earth's total 1.36 billion km^3 of water, 97.2% is in oceans, 2.15% in glaciers, and less than 1% in freshwater resources [26]. Water is indispensable and strategic for life, and one of the most critical impacts of climate change is the reduction of water resources. Rising temperatures trigger droughts, disruptions in the hydrological cycle, sea-level rise, glacier melting, evaporation, and changes in precipitation patterns. Climate change alters atmospheric conditions, causing spatial and temporal shifts in rainfall, evapotranspiration, and runoff processes, while increasing the frequency of extreme events. River flow regimes are changing, drought and flood risks are rising, and groundwater reserves are particularly threatened in arid regions. Sea-level rise leads to saltwater intrusion in coastal aquifers, while declining rainfall reduces freshwater availability. Climate change affects not only the quantity but also the quality of water. Reduced precipitation and higher temperatures increase pollutant concentration and decrease dissolved oxygen levels, leading to severe water quality issues. Flooding events further transport contaminants to dams, escalating treatment needs and economic burdens [27]. Today, drought, industrialization, and population growth are rapidly increasing water demand, making the protection of water resources critical not only for humans but also for sustaining biodiversity [28].

2.2.3. Agricultural Production and Food Security

Soil is the largest carbon sink, playing a key role in the global carbon and nutrient cycle. Carbon sequestration in soils helps mitigate the adverse impacts of climate change [14]. Climate change restricts geographical areas for cultivation, crop diversity, and productivity, while floods, droughts, and changing rainfall regimes negatively affect crop production [3, 13]. This threatens livelihoods, food security, and international political balances [26]. Rising temperatures and irregular rainfall harm water quality and resources, while floods, droughts, and agricultural issues threaten freshwater supplies. Declining water quality and reduced dissolved oxygen levels increase risks of waterborne diseases [29]. Climate-driven harmful algal blooms (HABs) cause toxin accumulation in shellfish, posing serious health threats [12]. Globally, the food sector is heavily affected, with North Africa, the Middle East, India, and South America identified as the most vulnerable regions. Hunger risk is projected to rise by 18% by 2050. In Turkey, agricultural production is largely dependent on rainfall. Climate change is projected to reduce maize, barley, wheat, and sugar beet yields, with losses of up to 10% for maize and 5% for sugar beet by 2050. Yield reductions could drive food prices up by as much as 250%, posing a critical food security threat [30].

2.2.4. Impacts on Human Health and Psychology

Climate change is one of the most significant health risks of the 21st century. It exacerbates existing health issues, introduces new threats, and directly impacts public health. Ecosystem degradation, biodiversity loss, and increasing natural disasters lead to rising respiratory and cardiovascular diseases, injuries, and fatalities during disasters, food- and waterborne illnesses, and shifts in the distribution of infectious agents [29]. Air pollution and climate change also trigger asthma and chronic respiratory conditions. Higher temperatures cause vasodilation, sweating, oxidative stress, inflammation, and clotting disorders. Heatwaves elevate suicide risks in individuals with pre-existing psychological conditions and increase cases of depression and anxiety [12]. Between 2000 and 2019, 9.43% of global deaths (about 5 million) were attributed to low temperatures, while heat-related deaths are expected to rise significantly by the 2050s. Hot days also increase emergency visits for cardiovascular, respiratory, and metabolic diseases [13]. Fossil fuel subsidies worsen air pollution and climate impacts, aggravating respiratory and cardiovascular illnesses and causing millions of deaths annually [4].

2.2.5. Economic and Socio-Political Consequences

Climate change threatens livelihoods by degrading resources and intensifying extreme weather events, while driving rapid economic losses. Even wealthy nations face escalating costs from floods, droughts, heatwaves, storms, and surges. However, the poorest communities, those contributing the least to climate change, suffer the earliest and most severe impacts. According to the Swiss Re Institute, climate change could reduce global GDP by 11–14%. Achieving the Paris Agreement targets could lower this loss to 4.2%, while a 3.2°C rise by mid-century could shrink the global economy by 18% [26]. Climate change drives not only economic but also socio-cultural transformations. Social values, cultural heritage, well-being, inequalities, migration, and displacement are directly tied to climate impacts. Extreme events destroy agricultural and residential areas, forcing migration and causing social and cultural disruption. Nordhaus [31] highlighted how rising greenhouse gas emissions exacerbate economic damage and intensify crises. Climate migration is emerging as an adaptation strategy to environmental stress. Vulnerability varies across regions due to socioeconomic development, inequality, governance, and unsustainable land use. Approximately 3.3–3.6 billion people live under high climate vulnerability. The interdependence of people and ecosystems further amplifies risks through unsustainable development models [26]. Projections indicate that Turkey, as a developing country, will be among the nations most adversely affected by climate change [4].

2.2.6. Insects

Agricultural crops and their associated pests are both directly and indirectly impacted by climate change [13]. Due to their poikilothermic nature, insect development, reproduction, behavior, and distribution are directly dependent on temperature. Rising atmospheric CO_2, higher temperatures, and declining soil moisture alter insect population dynamics, significantly increasing crop losses. Insects also act as vectors of plant pathogens, including viruses, phytoplasmas, and bacteria. Climate-driven global warming facilitates the geographic expansion and intensification of these vectors, spreading plant diseases more easily. The estimated annual economic loss from such diseases exceeds $30 billion [2]. Recent studies suggest vector-borne disease outbreaks will rise in the coming decades. By 2050, climate change could cause an additional 33,000 deaths—97% of which will occur in Sub-Saharan Africa and South Asia. By 2080, about 6.1 billion people, nearly 60% of the global population, could be at risk of mosquito-borne dengue fever [13].

2.2.7. Natural Disasters

Rising global temperatures break new records annually, driving the frequency and intensity of wildfires, storms, droughts, floods, and other climate-related disasters [29]. According to UN data, 7,348 disasters occurred between 2000 and 2019, killing 1.23 million people and affecting 4.2 billion. Over the last two decades, climate-related disasters accounted for 91% of all disasters. Wildfires have become more frequent and intense, with low rainfall and high heat prolonging fire seasons and causing severe health (burns, injuries, psychological impacts) and ecological losses [12, 13]. Drought, exacerbated by reduced rainfall and increased evaporation, drives water insecurity, food shortages, and dust storms. Extreme rainfall events have increased by 30%, heightening flash floods and urban flooding risks. Between 1900 and 2015, floods and storms displaced nearly 90 million people and caused millions of deaths. Post-flood contaminant transport threatens drinking water and farmland. Heatwave records between 2015 and 2020 doubled the 1951–1980 average. Nearly 46% of floods, 34% of storms, 31% of droughts, and 32% of wildfires since 1900 occurred in just the last 15 years. Sea surface temperatures have risen by 0.06°C per decade since 1880, accelerating glacier melting and thermal expansion, contributing to faster sea-level rise. Sea levels rose by 1.7 mm per year between 1971 and 2010, doubling since 1993. Increased rainfall also exacerbates soil erosion, with a 1% rise in rainfall linked to a 1.5–2% increase in erosion [14]. Projections suggest global monsoon rainfall will increase by 1.7–2.4% between 2021 and 2040 under high climate scenarios [13].

A review of the literature highlights numerous studies addressing climate change. Olabi and Abdelkareem [11] examined the positive impacts of renewable energy developments on climate change, Zhao et al. [13] investigated mitigation and adaptation strategies benefiting human health, Cheng et al. [20] analyzed strategies to limit the impacts of livestock, Elbasiouny et al. [14] explored the role of soil carbon sequestration on plant nutrition, Hu et al. [32] studied the effects of habitat and environmental changes on communities, and Badrzadeh et al. [33] identified pollution-sensitive areas along rivers to develop water management strategies. Overall, literature reveals that climate change stems from multiple factors and affects a wide range of elements. Therefore, analyzing contributing factors alongside impacted elements is essential to determine effective measures and policies. In this study, such factors and elements are systematically prioritized based on their significance. Considering the uncertainties in climate change assessments, reducing subjectivity and ensuring reliable multi-criteria evaluations are vital. Accordingly, the Pythagorean Fuzzy AHP method—capable of modeling uncertainties—was employed.

3. Methods

In daily life, individuals are required to make various decisions in different fields. A decision refers to a choice among available alternatives, while decision-making denotes the process leading to that choice [34]. The decision-making process is realized through the analysis of multiple alternatives and the selection of the most appropriate one. At this point, Multi-Criteria Decision-Making (MCDM) methods provide decision-makers with systematic and rational solutions [35]. MCDM represents a set of algorithms aimed at evaluating, ranking, and identifying the most suitable option among existing alternatives. While classical MCDM techniques are employed when information is clear and precise, fuzzy MCDM approaches are preferred in cases where uncertainties prevail. However, the selection of the most appropriate method in decision-making problems depends on the structural characteristics of the problem and the dynamics of the decision-making process. MCDM methods are widely applied to problems involving numerous criteria and alternatives, and the variety of these methods continues to expand. Nevertheless, it cannot be argued that a single MCDM method always yields the best result for every type of problem, as different methods may produce different outcomes for the same problem. Therefore, selecting the appropriate method in the decision-making process is of critical importance. A proper understanding of the characteristics of these methods provides decision-makers with the opportunity to choose the most suitable method or a combination of methods [35]. Among these, one of the most used approaches is the AHP [36].

3.1. Analytic Hierarchy Process

The Analytic Hierarchy Process is a widely used and effective decision-support method that evaluates both qualitative and quantitative criteria in a hierarchical structure, incorporating the judgments of multiple decision-makers [37]. The method decomposes a complex problem into goal–criteria–subcriteria–alternative layers, derives priority vectors through pairwise comparisons, and ensures the reliability of judgments via consistency analysis [38]. Historically, the approach was first introduced by Myers and Alpert in 1968 and later systematized and popularized within operations research by Saaty in 1977 [39]. AHP has enabled the rational ranking of alternatives under multiple criteria and subcriteria, standing out for its ability to quantify subjective judgments alongside objective data [38]. Nevertheless, classical AHP has limitations in fully representing uncertainty in human judgments. To address this, fuzzy set theory has been integrated into AHP, allowing more flexible modeling of linguistic judgments. In particular, the Pythagorean fuzzy set structure—capable of simultaneously considering membership and non-membership degrees—has been preferred.

3.2. Pythagorean Fuzzy AHP

Although AHP is one of the most frequently employed methods in MCDM problems, it has been criticized for its inability to adequately capture uncertainty and hesitation during pairwise comparisons. In classical AHP, decision-makers are compelled to provide precise numerical evaluations, which can increase inconsistencies stemming from subjective judgments and reduce the reliability of the decision-making process. Consequently, reaching robust solutions in complex problems becomes difficult. To overcome these shortcomings, an extended version of AHP—known as the Fuzzy Analytic Hierarchy Process (FAHP)—was developed. FAHP was first introduced to the literature by Van Laarhoven and Pedrycz, employing triangular fuzzy numbers to represent uncertainty in a more flexible and meaningful way. This approach enables decision-makers to use linguistic expressions in addition to deterministic values, thereby better reflecting the uncertainties of real-world conditions in the decision-making process. Particularly in problems involving a large number of criteria, FAHP provides distinct advantages by surpassing the rigid boundaries of classical AHP and generating more reliable and effective results. Fuzzy AHP is thus a powerful method developed to enhance reliability and consistency in solving MCDM problems. It allows decision-makers to use fuzzy expressions—including intermediate values—rather than relying solely on crisp numbers, thereby modeling uncertainty more realistically. In FAHP, pairwise comparisons among main and sub-criteria are expressed through fuzzy numbers derived from decision-makers' linguistic evaluations. This reduces errors arising from subjective judgments and makes the process more adaptable and robust. The identification of factors influencing climate change and elements affected by it is often based on subjective assessments. In such problems, it is not feasible to classify outcomes in strictly binary terms, such as affects or does not affect. In reality, effects appear in varying degrees—sometimes high, sometimes low, or uncertain. This necessitates approaches capable of modeling uncertainty in complex and multidimensional problems such as climate change. At this point, fuzzy set theory, which incorporates interval values, becomes a crucial tool [40].

In this study, the Pythagorean Fuzzy Analytic Hierarchy Process (PFAHP) was applied as an advanced fuzzy logic-based MCDM approach. Pythagorean fuzzy sets, introduced by Yager in [41], extend Atanassov's [42] intuitionistic fuzzy sets. While intuitionistic fuzzy sets constrain the sum of membership (μ) and non-membership (ν) degrees to be less than or equal to 1, Pythagorean fuzzy sets expand this condition by requiring that the sum of their squares not exceed 1. In other words, for intuitionistic sets, $x + y \leq 1$, whereas for Pythagorean sets, the condition is $x^2 + y^2 \leq 1$. This distinction makes Pythagorean fuzzy sets more flexible and powerful. Decision-makers can express uncertainty and hesitation within a broader domain, enabling more realistic results. Situations frequently encountered in daily life—such as a condition being simultaneously close to both true and false to varying degrees—can be more effectively modeled through Pythagorean fuzzy sets. For example, even if a criterion is considered to have a high impact on climate change, the degree of uncertainty in this judgment can also be mathematically represented [43]. PFAHP retains the hierarchical structure of classical AHP, but pairwise comparisons are performed using Pythagorean fuzzy values instead of crisp numbers. By incorporating the dimension of uncertainty into the decision-making process, this method enables the simultaneous and flexible evaluation of multiple criteria and alternatives. Decision-makers can represent their hesitation through Pythagorean fuzzy values, achieving more consistent and reliable outcomes. Thus, the method provides a strong theoretical framework and a highly applicable tool for practical problems characterized by uncertainty. The prominence of Pythagorean fuzzy sets in decision-making stems primarily from their ability to reduce subjectivity and manage uncertainty more effectively. In classical AHP, decision-makers are constrained to precise values, which is inadequate for multidimensional problems such as climate change. In contrast, PFAHP allows decision-makers to articulate their judgments more accurately and flexibly, resulting in more reliable weight calculations. Consequently, factors contributing to climate change and elements most affected by it can be ranked more objectively compared to traditional methods. Studies in the literature demonstrate that Pythagorean fuzzy sets are successfully applied not only in the context of climate change but also across fields such as engineering, healthcare, environmental management, supply chains, and sustainability [43, 44]. This method facilitates the integration of multiple expert opinions and the effective processing of uncertain data. Furthermore, by striking a balance between computational simplicity and flexibility, it achieves high applicability in both theoretical and practical studies.

In conclusion, Pythagorean fuzzy sets transcend classical fuzzy logic by offering decision-makers greater representational power. The PFAHP employed in this study provides a reliable, innovative, and practical approach for determining the relative importance of factors influencing climate change and elements affected by it. Some fundamental concepts and definitions that contribute to the understanding of Pythagorean fuzzy sets are presented below [45].

Definition 1. Let *X* be a fixed set. A Pythagorean fuzzy set $\tilde{P}$ is an object having the form Yager [41]:

$$\tilde{P} \cong \{\langle x, \mu_{\tilde{P}}(x), \nu_P(x);\ \rangle x \in X\} \tag{3.1}$$

where $\mu_p(x)$: x ↦ [0,1] and $\nu_p(x)$:x ↦ [0,1] represent the membership and non-membership degrees of $x \in X$, respectively. The sum of their squares must not exceed 1, as shown in (3.2):

$$0 \le \mu_p^2(x) + v_p^2(x) \le 1 \quad |x \in X \tag{3.2}$$

In PFS, each element is characterized by a membership degree (μ) and a non-membership degree (v), where the condition $\mu^2 + v^2 \le 1$ must hold. The part of uncertainty that cannot be explained by membership or non-membership is called the hesitation degree. It reflects the level of indeterminacy or hesitation associated with the evaluation of the decision-maker. The hesitation degree is calculated using (3.3):

$$\mu_p(x) = \sqrt{1 - \mu_p^2(x) - v_p^2(x)} \tag{3.3}$$

. Let a PFN be defined with a membership degree $\mu = of$ 0.6 and a non-membership degree $v = 0.7$. The hesitation degree is then calculated as:

$$\mu_p(x) = \sqrt{1 - 0{,}6^2 - 0{,}7^2} = \sqrt{0{,}15} \approx 0{,}387$$

This result indicates the extent of uncertainty in the expert's assessment that is not captured by membership or non-membership values. To effectively employ Pythagorean fuzzy sets in decision-making processes, some fundamental operations are introduced below.

Definition 2. Let $\beta_1 = \mathrm{P}(\mu_{\beta_1}, v_{\beta_1,})$ and $\beta_2 = \mathrm{P}(\mu_{\beta_2,} v_{\beta_2,})$ be two Pythagorean fuzzy numbers (PFNs). The main operations are defined as follows:

$$\beta_1 \oplus \beta_2 = \mathrm{P}\left(\sqrt{\mu_{\beta_1}^2 + \mu_{\beta_2}^2 - \mu_{\beta_1}^2 \mu_{\beta_2}^2}, v_{\beta_1,} v_{\beta_2}\right) \tag{3.4}$$

$$\beta_1 \otimes \beta_2 = \mathrm{P}\left(u_{\beta_1,} u v_{\beta_2} \sqrt{v_{\beta_1}^2 + v_{\beta_2}^2 - v_{\beta_1}^2 v_{\beta_2}^2}\right) \tag{3.5}$$

$$\lambda \beta_1 = \mathrm{P}\left(\sqrt{1 - \left(1 - \mu_{\beta_1}^2\right)^{\lambda}} v_{\beta_1}^{\lambda},\right) \tag{3.6}$$

$$\beta_1{}^{\lambda} = P\left(\mu_{\beta_1}^{\lambda}, \sqrt{1 - \left(1 - v_{\beta_1}^2\right)^{\lambda}}\right) \tag{3.7}$$

Definition 3. The distance between two PFNs is defined by (3.8):

$$(\beta_1, \beta_2) = \frac{1}{2}\left(\left|\mu_{\beta_1}^2 - \mu_{\beta_2}^2\right| + \left|v_{\beta_1}^2 - v_{\beta_2}^2\right| + \left|\pi_{\beta_1}^2 - \pi_{\beta_2}^2\right|\right) \tag{3.8}$$

Definition 4. When multiple decision makers (DMs) are involved in evaluating criteria, interval-valued PFNs (IVPFNs) can be aggregated using the interval-valued PF weighted geometric (IVPFWG) operator. This operator extends the weighted geometric mean to interval-valued Pythagorean fuzzy numbers, ensuring that both membership and non-membership information are incorporated in a balanced manner. It enables the integration of expert opinions with different weights, thus providing a collective evaluation. If $\beta_i = \mathrm{P}([\mu_i^L, \mu_i^U], [v_i^L, v_i^U])$ is an IVPFN and $w_j = (w_1, w_2, w_3, \ldots, w_n)^T$ is the weight vector, $\sum_{i=1}^n w_i = 1$ then the IVPFWG operator is given as in (3.9):

$$\mathrm{IVPFWG}(\beta_1, \beta_2, \beta_3, \ldots, \beta_n) = \left(\left[\prod_{j=1}^n \mu_{\alpha_J}^L{}^{w_j}, \prod_{j=1}^n \mu_{\alpha_J}^U{}^{w_j}\right], \left[\prod_{j=1}^n v_{\alpha_J}^L{}^{w_j}, \prod_{j=1}^n v_{\alpha_J}^U{}^{w_j}\right]\right) \tag{3.9}$$

The linguistic scale corresponding to the Pythagorean fuzzy numbers used by decision makers to evaluate alternatives and criteria is presented in Table 1 [45].

Table 1. Linguistic variables and Pythagorean fuzzy numbers

Linguistic Variables	Pythagorean fuzzy numbers			
	The lower value of the membership degree (μL)	The upper value of the membership degree (μU)	The lower value of the non-membership degree (vL)	The upper value of the non-membership degree (vU)
Certainly Low Importance (CLI)	0	0	0.9	1
Very Low Importance (VLI)	0.1	0.2	0.8	0.9
Low Importance (LI)	0.2	0.35	0.65	0.8
Below Average Importance (BAI)	0.35	0.45	0.55	0.65
Average Importance (AI)	0.45	0.55	0.45	0.55
Above Average Importance (AAI)	0.55	0.65	0.35	0.45
High Importance (HI)	0.65	0.8	0.2	0.35
Very High Importance (VHI)	0.8	0.9	0.1	0.2
Certainly High Importance (CHI)	0.9	1	0	0
Exactly Equal (EE)	0.1965	0.1965	0.1965	0.1965

The steps of the Pythagorean Fuzzy AHP method are presented below [45].

Step 1: Based on the scale provided in Table 1, decision makers perform pairwise comparisons of criteria or alternatives and construct the corresponding pairwise comparison matrix.

Step 2: Using (3.10) and (3.11), the difference matrix between the lower and upper bounds of the membership and non-membership functions is calculated. The difference matrix between the lower and upper bounds of the membership and non-membership functions is used to measure the degree of uncertainty in interval-valued Pythagorean fuzzy sets. By calculating the differences between the upper and lower bounds, this matrix quantifies the spread of expert opinions: small differences indicate strong consensus and stability, while larger differences reveal higher uncertainty or inconsistency. Thus, the difference matrix plays a key role in assessing the reliability of expert evaluations and the robustness of the decision-making process.

$$d_{ik_l} = \mu_{ik_l}^2 - v_{ik_u}^2 \quad (3.10)$$

$$d_{ik_u} = \mu_{ik_u}^2 - v_{ik_l}^2 \quad (3.11)$$

Step 3: The multiplicative matrix is obtained using (3.12) and (3.13). A multiplicative matrix is a type of pairwise comparison matrix used in decision-making methods to represent the relative importance of criteria. It provides a consistent structure for comparisons and serves as the basis for deriving weights and evaluating the reliability of judgments, even under uncertainty.

$$s_{ik_l} = \sqrt{1000^{d_l}} \quad (3.12)$$

$$s_{ik_u} = \sqrt{1000^{d_u}} \quad (3.13)$$

Following the approach proposed by Karasan et al. [45], we set the base value to 1000, as this value provides the clearest representation of the relationships among the matrix elements without compromising consistency. The appropriateness of 1000 was confirmed by comparing the criterion relations in both the defuzzified and interval multiplicative matrices.

Step 4: The degree of certainty for each criterion is calculated using (3.14). The degree of certainty for each criterion represents the level of confidence or clarity in the experts' evaluations. A higher value indicates stronger agreement and less ambiguity among the experts, while a lower value reflects greater hesitation or uncertainty. This measure is useful for assessing the reliability of the criteria weights and enhancing the robustness of the decision-making process.

$$\tau_{ik} = 1 - (\mu_{ik_u}^2 - \mu_{ik_l}^2) - (v_{ik_u}^2 - v_{ik_l}^2) \quad (3.14)$$

Step 5: Preliminary weights are determined by combining the certainty degrees and the multiplicative matrix, as expressed in (3.15).

$$t_{ik} = \left(\frac{s_{ik_l} + s_{ik_u}}{2}\right) \tau_{ik} \quad (3.15)$$

Step 6: The normalized importance weights are calculated using (3.16).

$$w_i = \frac{\sum_{k=1}^{m} t_{ik}}{\sum_{i=1}^{m} \sum_{k=1}^{m} t_{ik}} \quad (3.16)$$

Numerous studies in the literature have applied the Pythagorean Fuzzy AHP method. Some of the studies conducted over the last five years are presented in Table 2.

Table 2. Selected studies applying the Pythagorean fuzzy AHP method (last five years)

Author(s)	Objective	Method Used
Gürsoy [46]	To determine target market selection criteria for automotive foreign trade companies and evaluate their relative importance.	Pythagorean Fuzzy AHP
Ülker and Özçelik [40]	To integrate sustainability criteria into the supplier evaluation and selection process, making it more objective and aligned with dynamic conditions.	Fuzzy AHP, Fuzzy EDAS, Fuzzy VIKOR
Tezcan [44]	To determine the most suitable aircraft type for airline companies under various criteria.	Pythagorean Fuzzy AHP
Tezcan et al. [47]	To identify risky forest areas and contribute to wildfire management through strategic planning.	Pythagorean Fuzzy AHP, Fuzzy TOPSIS
Nebati [37]	To analyze the crew pairing process of Turkish Airlines, addressing uncertainties and constraints, and to develop a decision support model.	Pythagorean Fuzzy AHP, Fuzzy WASPAS
Yazar et al. [48]	To design and select the most suitable ergonomic kiosk system for university students and visitors, minimizing cost while improving ergonomics.	Pythagorean Fuzzy AHP, Fuzzy TOPSIS
Salari et al. [49]	To evaluate health risks in nanomaterial production by integrating Pythagorean Fuzzy AHP with Fuzzy Inference System (FIS) and a Health Risk Assessment (HRD) model.	Pythagorean Fuzzy AHP, Fuzzy Inference System
Ma et al. [50]	To develop a decision support model for concept design of new products by handling uncertainty and subjectivity through big data with Pythagorean fuzzy sets.	Pythagorean Fuzzy AHP, Fuzzy TOPSIS
Farooq [51]	To evaluate and prioritize factors influencing pedestrian crossing behavior in Budapest using the Pythagorean Fuzzy AHP method.	Pythagorean Fuzzy AHP
Lahana et al. [52]	To analyze barriers to green supply chain management and evaluate interrelations among these barriers.	Pythagorean Fuzzy AHP, Fuzzy DEMATEL
Milošević et al. [53]	To assess the smartness levels of public buildings by evaluating green building indicators and applying multiple criteria decision-making methods.	Pythagorean Fuzzy AHP
Shute et al. [54]	To identify and prioritize sustainability-oriented performance factors in higher education institutions using Pythagorean Fuzzy AHP.	Pythagorean Fuzzy AHP
Çelik and Yıldız [43]	To determine and rank the factors affecting renewable energy efficiency using the Pythagorean Fuzzy AHP method.	Pythagorean Fuzzy AHP

4. Results

In this study, the Pythagorean Fuzzy AHP method is employed to rank the factors contributing to climate change and the elements affected by climate change according to their level of importance. In this context, the selection of the factors influencing climate change and the elements affected by it was grounded in an extensive literature review, including international reports such as the IPCC assessments and related academic studies. Furthermore, the factor list was validated through consultation with two industrial engineers and one environmental and sustainability specialist. This integrated approach ensured that the chosen parameters are both theoretically well-founded and practically relevant to the scope of this study, as summarized in Table 3.

Table 3. Factors contributing to climate change and elements affected by climate change

Factor No	Factors Contributing to Climate Change	Element No	Elements Affected by Climate Change
FCC-1	Fossil Fuel Use and Carbon Emissions	ECC-1	Biodiversity
FCC-2	Industrialization	ECC-2	Agricultural Production
FCC-3	Agricultural Activities	ECC-3	Food Security
FCC-4	Deforestation	ECC-4	Human Health and Psychology
FCC-5	Natural Disasters	ECC-5	Economy and Socio-Politics
FCC-6	Urban Development	ECC-6	Natural Disasters
FCC-7	Wastewater Management	ECC-7	Insects
FCC-8	Health Sector	ECC-8	Climate Migration
FCC-9	Animals	ECC-9	Destruction of Cultural and Historical Sites
FCC-10	Consumption Habits and Waste Generation	ECC-10	Air Quality
FCC-11	Tourism Activities	ECC-11	Soil Pollution
FCC-12	Population Growth		

4.1. Evaluation of Factors Contributing to Climate Change

Step 1: The factors listed in Table 3 were evaluated based on the scale provided in Table 1, through a consensus of one expert specializing in environment and sustainability and two industrial engineers. As a result of this evaluation, the pairwise comparison matrix presented in Table 4 was obtained.

Table 4. Pairwise comparison matrix of factors contributing to climate change

	Factors contributing to climate change											
	FCC-1	FCC-2	FCC-3	FCC-4	FCC-5	FCC-6	FCC-7	FCC-8	FCC-9	FCC-10	FCC-11	FCC-12
FCC-1	EE	AI	VHI	VHI	HI	HI	VHI	CHI	AI	HI	VHI	HI
FCC-2	AI	EE	AI	HI	HI	AAI	HI	VHI	AI	AAI	CHI	HI
FCC-3	VLI	AI	EE	BAI	AI	AI	BAI	AAI	BAI	BAI	HI	HI
FCC-4	VLI	LI	AAI	EE	HI	AI	HI	VHI	AI	AAI	VHI	AAI
FCC-5	LI	LI	AI	LI	EE	BAI	AAI	AAI	VLI	BAI	BAI	BAI
FCC-6	LI	BAI	AI	AI	AAI	EE	AAI	HI	LI	AI	AAI	AI
FCC-7	VLI	LI	AAI	LI	BAI	BAI	EE	HI	LI	BAI	LI	AI
FCC-8	CLI	VHI	BAI	VLI	BAI	LI	LI	EE	VLI	LI	AAI	AI
FCC-9	AI	AI	AAI	AI	VHI	HI	HI	VHI	EE	CHI	HI	AAI
FCC-10	LI	BAI	AAI	BAI	AAI	AI	AAI	HI	CLI	EE	AAI	AAI
FCC-11	VLI	CLI	LI	VLI	AAI	BAI	HI	BAI	LI	BAI	EE	BAI
FCC-12	LI	LI	LI	BAI	AAI	AI	AI	AI	BAI	BAI	AAI	EE

The linguistic evaluations presented in Table 4 were converted into the corresponding triangular fuzzy numbers provided in Table 1, and the subsequent steps were carried out.

Step 2: The difference matrices between the lower and upper bounds of the membership and non-membership functions were calculated using (3.10) and (3.11). The results are presented in Tables 5 and 6.

Table 5. Difference matrix between the lower points of membership and non-membership functions

	Factors contributing to climate change											
	FCC-1	FCC-2	FCC-3	FCC-4	FCC-5	FCC-6	FCC-7	FCC-8	FCC-9	FCC-10	FCC-11	FCC-12
FCC-1	0,00	-0,10	0,60	0,60	0,10	0,10	0,60	0,81	-0,10	0,10	0,60	0,10
FCC-2	-0,10	0,00	-0,10	0,10	0,10	0,10	0,10	0,60	-0,10	0,10	0,81	0,10

FCC-3	-0,80	-0,10	0,00	-0,30	-0,10	-0,10	-0,30	0,10	-0,30	-0,30	0,10	0,10
FCC-4	-0,80	-0,60	0,10	0,00	0,10	-0,10	0,10	0,60	-0,10	0,10	0,60	0,10
FCC-5	-0,60	-0,60	-0,10	-0,60	-0,10	-0,30	0,10	0,10	-0,80	-0,30	-0,30	-0,30
FCC-6	-0,60	-0,30	-0,10	-0,10	0,10	0,00	0,10	0,10	-0,60	-0,10	0,10	-0,10
FCC-7	-0,80	-0,60	0,10	-0,60	-0,30	-0,30	0,00	0,10	-0,60	-0,30	-0,60	-0,10
FCC-8	-1,00	-0,80	-0,30	-0,80	-0,30	-0,60	-0,60	0,00	-0,80	-0,38	0,10	-0,10
FCC-9	-0,10	-0,10	0,10	-0,10	0,60	0,10	0,10	0,60	0,00	0,81	0,10	0,10
FCC-10	-0,60	-0,30	0,10	-0,30	0,10	-0,10	0,10	0,10	-1,00	0,00	0,10	0,10
FCC-11	-0,80	-1,00	-0,60	-0,80	0,10	-0,30	0,10	-0,30	-0,60	-0,30	0,00	-0,30
FCC-12	-0,60	-0,60	-0,60	-0,30	0,10	-0,10	-0,10	-0,10	-0,30	-0,30	0,10	0,00

Table 6. Difference matrix between the upper points of membership and non-membership functions

	Factors contributing to climate change											
	FCC-1	FCC-2	FCC-3	FCC-4	FCC-5	FCC-6	FCC-7	FCC-8	FCC-9	FCC-10	FCC-11	FCC-12
FCC-1	0,00	0,10	0,80	0,80	0,30	0,30	0,80	1,00	0,10	0,30	0,80	0,30
FCC-2	0,10	0,00	0,10	0,30	0,30	0,30	0,30	0,80	0,10	0,30	1,00	0,30
FCC-3	-0,60	0,10	0,00	-0,10	0,10	0,10	-0,10	0,30	-0,10	-0,10	0,30	0,30
FCC-4	-0,60	-0,30	0,30	0,00	0,30	0,10	0,30	0,80	0,10	0,30	0,80	0,30
FCC-5	-0,30	-0,30	0,10	-0,30	0,10	-0,10	0,30	0,30	-0,60	-0,10	-0,10	-0,10
FCC-6	-0,30	-0,10	0,10	0,10	0,30	0,00	0,30	0,30	-0,30	0,10	0,30	0,10
FCC-7	-0,60	-0,30	0,30	-0,30	-0,10	-0,10	0,00	0,30	-0,30	-0,10	-0,30	0,10
FCC-8	-0,81	-0,60	-0,10	-0,60	-0,10	-0,30	-0,30	0,00	-0,60	-0,08	0,30	0,10
FCC-9	0,10	0,10	0,30	0,10	0,80	0,30	0,30	0,80	0,00	1,00	0,30	0,30
FCC-10	-0,30	-0,10	0,30	-0,10	0,30	0,10	0,30	0,30	-0,81	0,00	0,30	0,30
FCC-11	-0,60	-0,81	-0,30	-0,60	0,30	-0,10	0,30	-0,10	-0,30	-0,10	0,00	-0,10
FCC-12	-0,30	-0,30	-0,30	-0,10	0,30	0,10	0,10	0,10	-0,10	-0,10	0,30	0,00

Step 3: The multiplicative matrices were calculated using (3.12) and (3.13), and the results are presented in Tables 7 and 8.

Table 7. The multiplicative matrix of the lower points

	Factors contributing to climate change											
	FCC-1	FCC-2	FCC-3	FCC-4	FCC-5	FCC-6	FCC-7	FCC-8	FCC-9	FCC-10	FCC-11	FCC-12
FCC-1	1,00	0,71	7,94	7,94	1,41	1,41	7,94	16,41	0,71	1,41	7,94	1,41
FCC-2	0,71	1,00	0,71	1,41	1,41	1,41	1,41	7,94	0,71	1,41	16,41	1,41
FCC-3	0,06	0,71	1,00	0,35	0,71	0,71	0,35	1,41	0,35	0,35	1,41	1,41
FCC-4	0,06	0,13	1,41	1,00	1,41	0,71	1,41	7,94	0,71	1,41	7,94	1,41
FCC-5	0,13	0,13	0,71	0,13	0,71	0,35	1,41	1,41	0,06	0,35	0,35	0,35
FCC-6	0,13	0,35	0,71	0,71	1,41	1,00	1,41	1,41	0,13	0,71	1,41	0,71
FCC-7	0,06	0,13	1,41	0,13	0,35	0,35	1,00	1,41	0,13	0,35	0,13	0,71
FCC-8	0,03	0,06	0,35	0,06	0,35	0,13	0,13	1,00	0,06	0,27	1,41	0,71
FCC-9	0,71	0,71	1,41	0,71	7,94	1,41	1,41	7,94	1,00	16,41	1,41	1,41
FCC-10	0,13	0,35	1,41	0,35	1,41	0,71	1,41	1,41	0,03	1,00	1,41	1,41
FCC-11	0,06	0,03	0,13	0,06	1,41	0,35	1,41	0,35	0,13	0,35	1,00	0,35
FCC-12	0,13	0,13	0,13	0,35	1,41	0,71	0,71	0,71	0,35	0,35	1,41	1,00

Table 8. Multiplicative matrix of the upper points

	Factors contributing to climate change											
	FCC-1	FCC-2	FCC-3	FCC-4	FCC-5	FCC-6	FCC-7	FCC-8	FCC-9	FCC-10	FCC-11	FCC-12
FCC-1	1,00	1,41	15,85	15,85	2,82	2,82	15,85	31,62	1,41	2,82	15,85	2,82
FCC-2	1,41	1,00	1,41	2,82	2,82	2,82	2,82	15,85	1,41	2,82	31,62	2,82
FCC-3	0,13	1,41	1,00	0,71	1,41	1,41	0,71	2,82	0,71	0,71	2,82	2,82
FCC-4	0,13	0,35	2,82	1,00	2,82	1,41	2,82	15,85	1,41	2,82	15,85	2,82
FCC-5	0,35	0,35	1,41	0,35	1,41	0,71	2,82	2,82	0,13	0,71	0,71	0,71
FCC-6	0,35	0,71	1,41	1,41	2,82	1,00	2,82	2,82	0,35	1,41	2,82	1,41

FCC-7	0,13	0,35	2,82	0,35	0,71	0,71	1,00	2,82	0,35	0,71	0,35	1,41
FCC-8	0,06	0,13	0,71	0,13	0,71	0,35	0,35	1,00	0,13	0,75	2,82	1,41
FCC-9	1,41	1,41	2,82	1,41	15,85	2,82	2,82	15,85	1,00	31,62	2,82	2,82
FCC-10	0,35	0,71	2,82	0,71	2,82	1,41	2,82	2,82	0,06	1,00	2,82	2,82
FCC-11	0,13	0,06	0,35	0,13	2,82	0,71	2,82	0,71	0,35	0,71	1,00	0,71
FCC-12	0,35	0,35	0,35	0,71	2,82	1,41	1,41	1,41	0,71	0,71	2,82	1,00

Step 4: The degrees of determinacy for each factor, calculated using (3.14), are presented in Table 9.

Table 9. Determinacy degrees of the factors

	Factors contributing to climate change											
	FCC-1	FCC-2	FCC-3	FCC-4	FCC-5	FCC-6	FCC-7	FCC-8	FCC-9	FCC-10	FCC-11	FCC-12
FCC-1	1,00	0,80	0,80	0,80	0,80	0,80	0,80	0,81	0,80	0,80	0,80	0,80
FCC-2	0,80	1,00	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,81	0,80
FCC-3	0,80	0,80	1,00	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80
FCC-4	0,80	0,70	0,80	1,00	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80
FCC-5	0,70	0,70	0,80	0,70	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80
FCC-6	0,70	0,80	0,80	0,80	0,80	1,00	0,80	0,80	0,70	0,80	0,80	0,80
FCC-7	0,80	0,70	0,80	0,70	0,80	0,80	1,00	0,80	0,70	0,80	0,70	0,80
FCC-8	0,81	0,80	0,80	0,80	0,80	0,70	0,70	1,00	0,80	0,70	0,80	0,80
FCC-9	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	1,00	0,81	0,80	0,80
FCC-10	0,70	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,81	1,00	0,80	0,80
FCC-11	0,80	0,81	0,70	0,80	0,80	0,80	0,80	0,80	0,70	0,80	1,00	0,80
FCC-12	0,70	0,70	0,70	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	1,00

Step 5: The pre-normalized weights were calculated using (3.15) and are presented in Table 10.

Table 10. Matrix of weights before normalization

	Factors contributing to climate change											
	FCC-1	FCC-2	FCC-3	FCC-4	FCC-5	FCC-6	FCC-7	FCC-8	FCC-9	FCC-10	FCC-11	FCC-12
FCC-1	1,00	0,85	9,52	9,52	1,69	1,69	9,52	19,45	0,85	1,69	9,52	1,69
FCC-2	0,85	1,00	0,85	1,69	1,69	1,69	1,69	9,52	0,85	1,69	19,45	1,69
FCC-3	0,08	0,85	1,00	0,43	0,85	0,85	0,43	1,69	0,43	0,43	1,69	1,69
FCC-4	0,08	0,17	1,69	1,00	1,69	0,85	1,69	9,52	0,85	1,69	9,52	1,69
FCC-5	0,17	0,17	0,85	0,17	0,85	0,43	1,69	1,69	0,08	0,43	0,43	0,43
FCC-6	0,17	0,43	0,85	0,85	1,69	1,00	1,69	1,69	0,17	0,85	1,69	0,85
FCC-7	0,08	0,17	1,69	0,17	0,43	0,43	1,00	1,69	0,17	0,43	0,17	0,85
FCC-8	0,04	0,08	0,43	0,08	0,43	0,17	0,17	1,00	0,08	0,36	1,69	0,85
FCC-9	0,85	0,85	1,69	0,85	9,52	1,69	1,69	9,52	1,00	19,45	1,69	1,69
FCC-10	0,17	0,43	1,69	0,43	1,69	0,85	1,69	1,69	0,04	1,00	1,69	1,69
FCC-11	0,08	0,04	0,17	0,08	1,69	0,43	1,69	0,43	0,17	0,43	1,00	0,43
FCC-12	0,17	0,17	0,17	0,43	1,69	0,85	0,85	0,85	0,43	0,43	1,69	1,00

Step 6: The importance weights for each factor were calculated using (3.16) and are presented in Table 11.

Table 11. Importance weight and ranking of the factors

Factors		Before normalization importance weights	Normalized importance weights	Ranking
FCC-1	Fossil Fuel Use and Carbon Emissions	66,99	0,2564	1
FCC-2	Industrialization	42,67	0,1633	3
FCC-3	Agricultural Activities	10,40	0,0398	7
FCC-4	Deforestation	30,44	0,1165	4
FCC-5	Natural Disasters	7,36	0,0282	9
FCC-6	Urban Development	11,92	0,0456	6
FCC-7	Wastewater Management	7,26	0,0278	10
FCC-8	Health Sector	5,35	0,0205	12
FCC-9	Animals	50,49	0,1933	2
FCC-10	Consumption Habits and Waste Generation	13,06	0,0500	5
FCC-11	Tourism Activities	6,61	0,0253	11
FCC-12	Population Growth	8,71	0,0333	8

An examination of Table 11 reveals that Fossil fuel use and carbon emissions are the most significant factors influencing climate change, with an importance weight of 0,2564. Animals emerged as the second most important criterion, followed by industrialization in third place. Conversely, tourism activities and the health sector were identified as the two least influential factors.

Then, sensitivity analysis was conducted to examine the robustness of the results obtained from the Pythagorean fuzzy AHP method. By testing different scenarios of factor weights (Table 12), the analysis aimed to determine whether the ranking of factors would change, thereby assessing the stability and reliability of the decisions. The results of the sensitivity analysis conducted with a total of 13 scenarios are given in Figure 1.

Table 12. Combinations of scenarios with different factor weights

Scenarios	Combinations
Scenario 1	Current
Scenario 2	FCC-1 CLI, The Rest current
Scenario 3	FCC -2 CLI, The Rest current
Scenario 4	FCC-3 CLI, The Rest current
Scenario 5	FCC-4 CLI, The Rest current
Scenario 6	FCC-5 CLI, The Rest current
Scenario 7	FCC-6 CLI, The Rest current
Scenario 8	FCC-7 CLI, The Rest current
Scenario 9	FCC-8 CLI, The Rest current
Scenario 10	FCC-9 CLI, The Rest current
Scenario 11	FCC-10 CLI, The Rest current
Scenario 12	FCC-11 CLI, The Rest current
Scenario 13	FCC-12 CLI, The Rest current

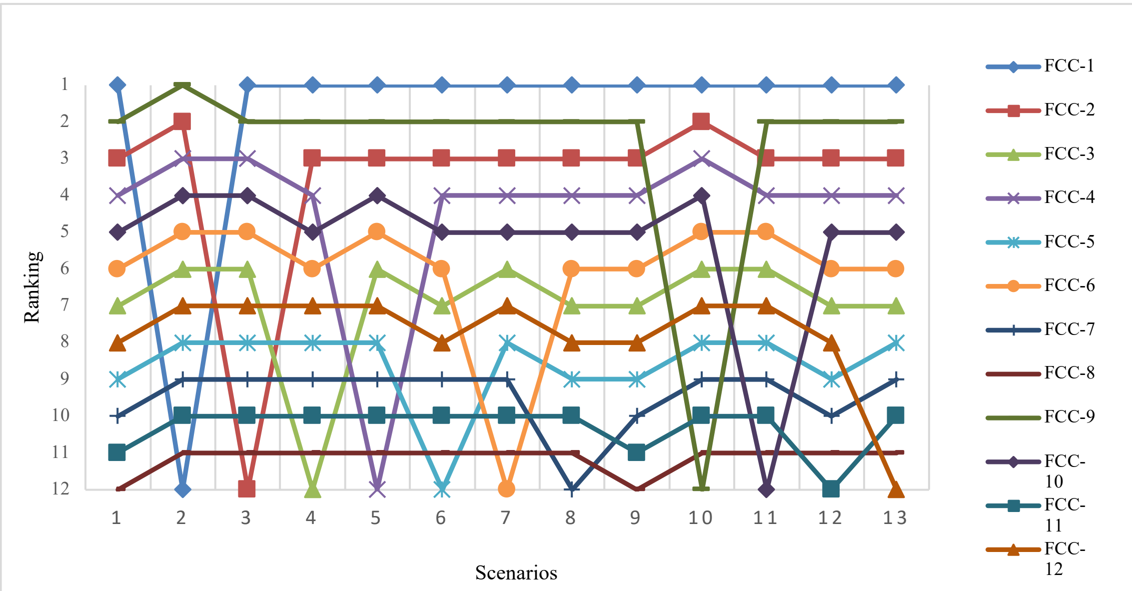

Figure 1. Changes in sensitivity analysis results

Considering Table 11 and Figure 1 together, fossil fuel use and carbon emissions (FCC-1) emerged as the most influential factor on climate change, followed by animals (FCC-9) and industrialization (FCC-2) in the second and third positions, respectively. The sensitivity analysis results (Figure 1) show that despite variations in the factor weights under different scenarios, the top-ranked factors largely maintained their positions, while only the lower-ranked criteria exhibited some fluctuations. This indicates that the results obtained through the Pythagorean Fuzzy AHP method are stable and reliable, with the most critical factors consistently preserving their importance across different conditions.

4.2. Evaluation of the Elements Affected by Climate Change

The steps applied in the evaluation of the factors influencing climate change were also followed for the prioritization of the elements affected by climate change. In this section, some tables derived from certain steps are omitted.

Step 1: The elements listed in Table 3 were evaluated by an environmental and sustainability expert together with two industrial engineers, based on the scale provided in Table 1. As a result, the pairwise comparison matrix presented in Table 13 was obtained.

Table 13. Pairwise comparison of the elements affected by climate change

	Elements affected by climate change										
	ECC-1	ECC-2	ECC-3	ECC-4	ECC-5	ECC-6	ECC-7	ECC-8	ECC-9	ECC-10	ECC-11
ECC-1	EE	HI	VHI	VHI	VHI	AAI	AI	HI	HI	AI	AI
ECC-2	LI	AI	AAI	AI	HI	AI	LI	AAI	AAI	AAI	AI
ECC-3	VLI	BAI	AI	AAI	AAI	BAI	LI	BAI	HI	AI	BAI
ECC-4	VLI	AI	BAI	EE	AAI	LI	AI	HI	AAI	AAI	BAI
ECC-5	VLI	LI	BAI	BAI	EE	VLI	BAI	AI	BAI	LI	BAI
ECC-6	BAI	AI	AAI	HI	VHI	EE	AI	AI	BAI	AI	AAI
ECC-7	AI	HI	HI	AI	AAI	AI	EE	HI	HI	AAI	AAI
ECC-8	LI	BAI	AAI	LI	AI	AI	LI	EE	AAI	LI	AI
ECC-9	LI	BAI	LI	BAI	AAI	AAI	LI	BAI	EE	BAI	BAI
ECC-10	AI	BAI	AI	BAI	HI	AI	BAI	HI	AAI	EE	AI
ECC-11	AI	AI	AAI	AAI	AAI	BAI	BAI	AI	AAI	AI	EE

The linguistic evaluations presented in Table 12 were converted into the corresponding triangular fuzzy numbers provided in Table 1, and the subsequent steps of the method were applied.

Step 2: Like the prioritization of the factors influencing climate change, the matrices of differences between the lower bounds of the membership and non-membership functions, the multlicative matrix of the lower values, the certainty degrees of the elements, and the pre-normalization weight matrix were obtained by following the procedural steps of the method.

Step 3: Using (3.16), the importance weights of each element were calculated, and the results are presented in Table 14.

Table 14. Importance weights and ranking of the elements

Elements		Before normalization importance weights	Normalized importance weights	Ranking
ECC-1	Biodiversity	38,86	0,2624	1
ECC-2	Agricultural Production	12,34	0,0833	4
ECC-3	Food Security	8,87	0,0599	8
ECC-4	Human Health and Psychology	10,56	0,0713	7
ECC-5	Economy and Socio-Politics	4,46	0,0301	11
ECC-6	Natural Disasters	19,84	0,1339	2
ECC-7	Insects	15,39	0,1039	3
ECC-8	Climate Migration	8,03	0,0542	9
ECC-9	Destruction of Cultural and Historical Sites	7,01	0,0474	10
ECC-10	Air Quality	10,75	0,0725	6
ECC-11	Soil Pollution	12,01	0,0811	5

An examination of Table 14 reveals that biodiversity, with an importance weight of 0.2624, emerges as the most critical element affected by climate change. Natural disasters rank second, followed by insects as the third most significant criterion. In contrast, degradation of cultural and historical sites, economy, and socio-politics are identified as the least influential elements within the ranking.

In this section, a sensitivity analysis was also conducted for the elements affected by climate change. The scenarios constructed for this purpose are presented in Table 15, and the results obtained are illustrated in Figure 2.

Table 15. Combinations of scenarios with different element weights

Scenarios	Combinations
Scenario 1	Current
Scenario 2	ECC-1 CLI, The Rest current
Scenario 3	ECC -2 CLI, The Rest current
Scenario 4	ECC-3 CLI, The Rest current
Scenario 5	ECC-4 CLI, The Rest current
Scenario 6	ECC-5 CLI, The Rest current
Scenario 7	ECC-6 CLI, The Rest current
Scenario 8	ECC-7 CLI, The Rest current
Scenario 9	ECC-8 CLI, The Rest current
Scenario 10	ECC-9 CLI, The Rest current
Scenario 11	ECC-10 CLI, The Rest current
Scenario 12	ECC-11 CLI, The Rest current

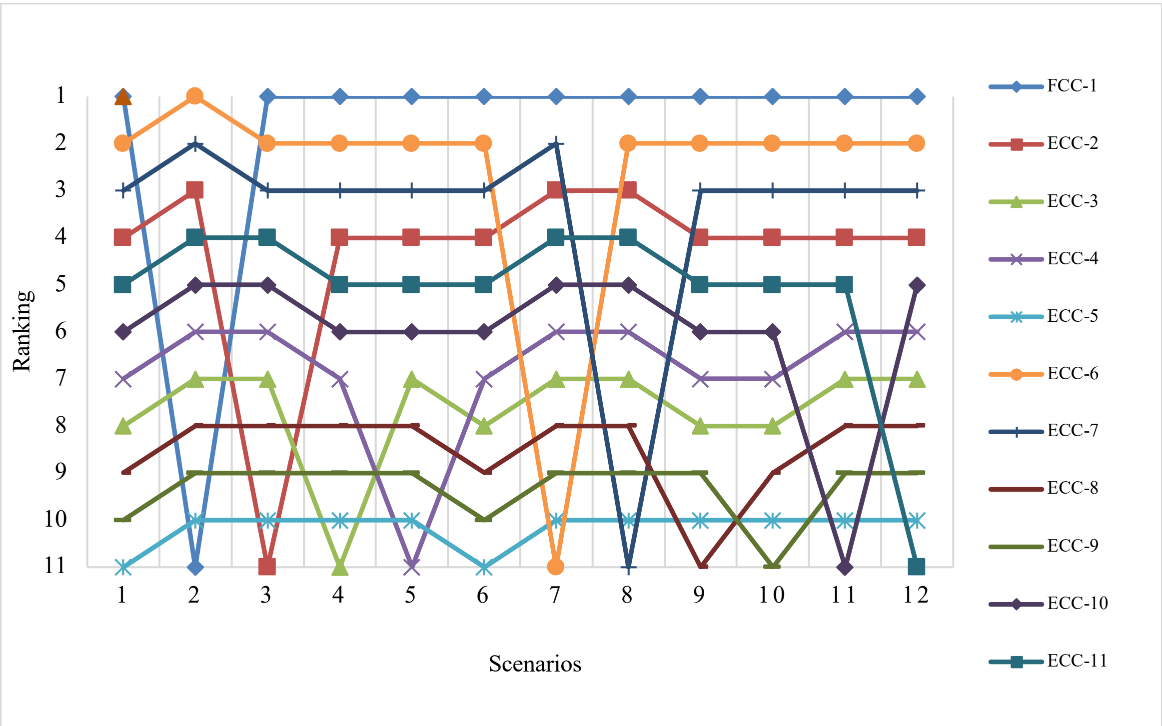

Figure 2. Changes in sensitivity analysis results

When the importance weights and rankings obtained in Table 14 are compared with the sensitivity analysis results presented in Table 15 and Figure 2, it is observed that the overall ranking remains largely preserved even when factor weights are varied across different scenarios. The stability of the top-ranked elements in particular supports the reliability of the results obtained in Table 14. On the other hand, some fluctuations observed among the middle- and lower-ranked elements indicate that certain factors are more sensitive to changes in weights. Therefore, the sensitivity analysis demonstrates that the prioritization results in Table 14 are largely robust and consistent, with variations occurring only in the relative positions of less significant elements.

5. Conclusion

Today, climate change has become a critical issue that affects not only the environment but also the economic, social, and political dimensions of the entire world. Identifying the underlying causes of this global problem and prioritizing the areas most affected are essential steps that directly shape the measures to be taken. In this context, the present study applied the PFAHP method with the aim of ranking both the factors contributing to climate change and the elements affected by it, according to their relative importance. The objective was to introduce a quantitative and systematic perspective into environmental decision-making processes characterized by uncertainty.

The findings reveal that among the factors influencing climate change, Fossil Fuel Consumption and Carbon Emissions emerged as the most critical, with the highest weight. This can be attributed to the heavy reliance on fossil fuels in core sectors such as energy production, industry, and transportation, and to the resulting accumulation of greenhouse gases in the atmosphere, which directly drives global warming. The persistence of this factor reflects the limited progress in energy transition and the insufficient adoption of renewable resources, emphasizing the urgency of mitigation. Ranked second, Animals highlight how anthropogenic drivers disrupt ecosystems through habitat reduction, methane emissions from livestock, and the breakdown of natural cycles. Industrialization follows in third place as a major trigger of carbon emissions due to its intensive energy and resource use. By contrast, Tourism Activities and the Health Sector ranked lowest, as their direct impacts are relatively limited. However, their placement at the bottom does not imply irrelevance but rather a comparatively weaker influence compared to other factors.

About the elements most affected by climate change, Biodiversity was identified as the most critical. Climate change directly threatens species' habitats, leading to extinction or migration due to rising temperatures, droughts, wildfires, and sea-level rise. The destabilization of ecosystems threatens ecological chains and, consequently, agricultural systems, water resources, and environmental sustainability. Protecting biodiversity is therefore vital, not only for environmental resilience but also for the continuity of economic and social systems. Natural Disasters ranked second, while Insects ranked third. Increasing climatic imbalances, including rising temperatures, droughts, and heavy rainfall, intensify the frequency and severity of natural disasters, threatening human life and agricultural sustainability. Meanwhile, changes in insect populations can result in more harmful species, higher risks of disease transmission, and significant agricultural losses.

Conversely, degradation of cultural and historical sites, economy, and socio-politics ranked lower, given their more indirect and long-term impacts. Although the loss of cultural heritage sites may not appear as urgent as environmental or biological threats, it has the potential to undermine historical identity and tourism income in the long run. Similarly, the economic and socio-political consequences vary significantly across regions and are shaped by complex interdependencies, which explains their lower relative weight.

This study represents the first attempt to simultaneously evaluate and rank both the drivers of climate change and its affected elements under conditions of uncertainty, using the PFAHP method. In this respect, it provides an original methodological and conceptual contribution to literature. Ultimately, the research offers a prioritized set of factors and elements that can guide policymakers in tackling climate change. The findings highlight the importance of focusing particularly on reducing fossil fuel consumption, limiting carbon emissions, and protecting ecosystems. Equally, safeguarding biodiversity and mitigating natural disaster risks should be prioritized in adaptation and resilience strategies. Future research should broaden the scope by considering sector-specific analyses, interactions among factors, and the integration of economic cost–benefit and feasibility assessments, thereby enhancing the effectiveness of decision-support systems and contributing to more comprehensive climate policies.

Author Contributions

All the authors equally contributed to this work. They all read and approved the final version of the paper.

Conflict of Interest

The author declares no conflict of interest.

Ethical Review and Approval

No approval from the Board of Ethics is required.

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