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Review Article

Impact of Climate Change on Coffee Quality and Yield

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Abstract: Agriculture and its products are being negatively impacted by climate change, which is concerning the entire world. The production of coffee is heavily reliant on a predictable series of meteorological conditions. Coffee quality and productivity levels are directly impacted by changes in temperature, precipitation patterns, storms, strong winds, and other extreme weather occurrences. This study evaluated coffee production, growth requirements, climate change factors, and the effects of climate change on coffee yields and quality. There is also discussion of potential ways to lessen the impact of climate change on coffee quality and productivity.
Keywords: Climate Change, Coffee Quality, Coffee Yield, Mitigation.

1. INTRODUCTION

One of the most popular drinks in the world, coffee contributes significantly to the foreign exchange earnings of several nations. Coffee products provide a direct or indirect source of income for about 125 million people in coffee-growing regions across the world [28-35]. More than nine million tons of green beans are produced each year, and they have produced several million employment in the nations that produce and consume them, making them the second most important commodity in international trade after oil [18]. Brazil is the world's top producer and exporter of coffee, with Vietnam, Colombia, Indonesia, and Ethiopia following closely behind [18]. Although there are over 124 species in the genus Coffea that have been identified, the two most commercially significant species are Coffea arabica L. and Coffea canephora P [8-13]. Caniphora (Robusta) accounts for around 30% of the world's coffee production, whereas Arabica accounts for 70% [7, 8]. In order to achieve high yields and quality, both species' productivity and output are heavily reliant on the climate [25].

One of humanity's most pressing problems is the impact of climate change on natural systems [22]. There are numerous indications that weather change is occurring at a significantly faster rate than previously, resulting in permanent alterations to important earth systems and ecosystems [19]. The burning of more fossil fuels, changes in land use, and the continued release of greenhouse gases into the atmosphere are all significant contributors to climate change. The amount of heat from the sun that is retained in the Earth's atmosphere and would otherwise be radiated back into space can be increased by the rising levels of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrogen dioxide (N_2O) in the atmosphere [44]. The two most common greenhouse gases that affect the global climate through emissions are carbon dioxide (CO_2) and methane (CH_4) [34]. Ecosystems are changing at an unprecedented rate and scale due to climate change. Increases in the average global temperature (global warming); modifications to cloud cover and precipitation, especially over land; melting of ice caps and glaciers and decreased snow cover; and an increase in ocean temperatures and acidity as a result of seawater absorbing heat and carbon dioxide from the atmosphere are the primary features of climate change [16].

One of the biggest risks to the world's coffee industry is the changing climate and rising global temperatures. As stated by [25], state that climate adaptability, particularly air temperature and precipitation, has a significant impact on the productivity and quality of Arabica and Robusta coffee. Although heat and water stressors from climate change may have a direct effect on plant output, fertilizer supplies, diseases, and pests may also be impacted indirectly [36]. Most scientists concur that global warming cannot be stopped

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in the short term and that long-term mitigation and reversal of environmental harm will require global policy changes and sustainable agriculture practices. This review's main goal is to evaluate how climate change affects coffee production's yields and quality.

2. Production of Coffee

2.1 Production of Coffee Worldwide

Coffee output and consumption have increased significantly during the last 50 years [12]. Nowadays, coffee is produced in more than 70 nations, with just three countries Brazil, Vietnam, and Colombia supplying more than half of the world's supply (Fig 2). A large crop in one year is often followed by a lesser crop the following year, indicating significant instability in the dynamics of global coffee production [17]. For Asia, Oceania, Africa, North America, and South America, the corresponding changes in global coffee production by region from 1961 to 2022 were 1649%, 680%, 118%, 74%, and 51%, respectively (Fig 1). The globe produced 168.20 million bags of coffee in the 2022–23 crop year, the most ever. All coffee-growing regions saw a consistent increase in production over the period, with the exception of Africa [17].

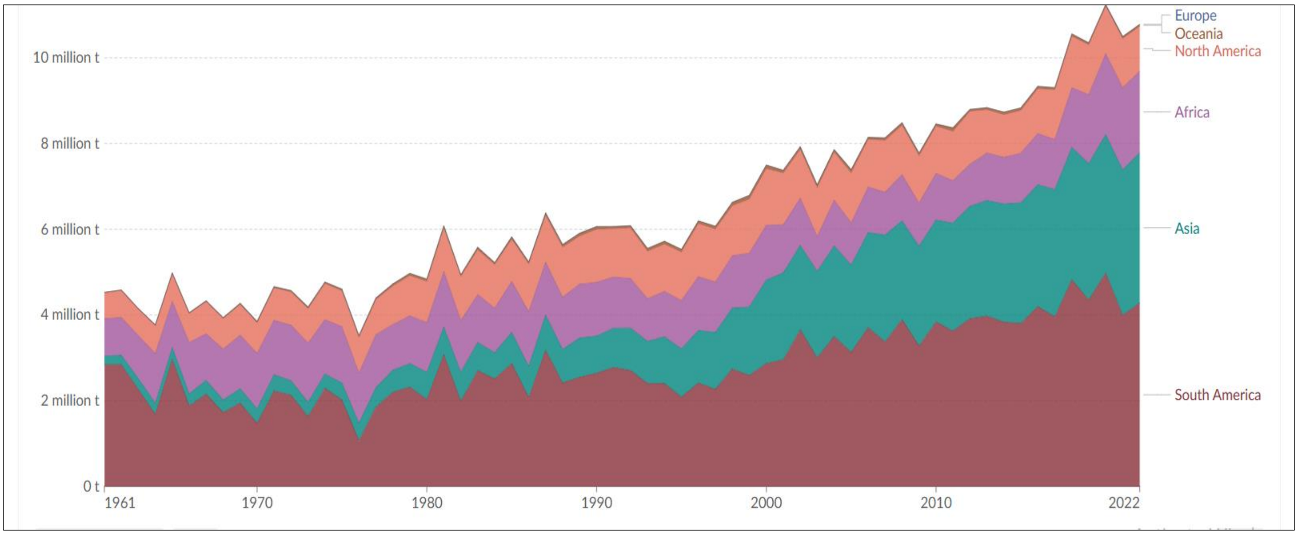

Figure 1: ***World coffee production by region (1961 - 2022)***
Source: *International coffee organization*

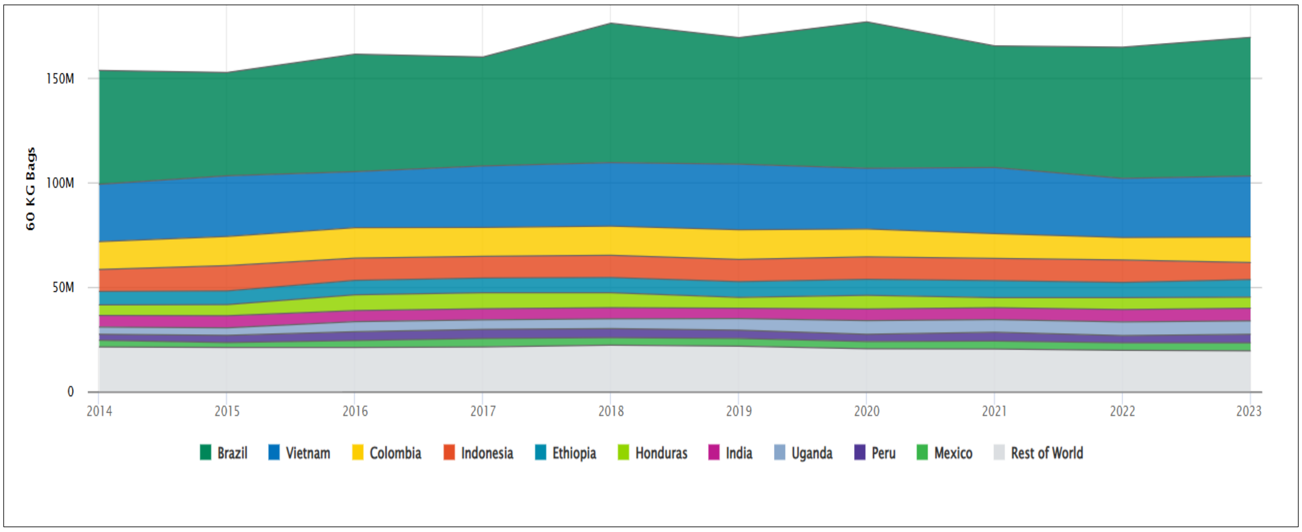

Figure 2: ***Production quantities of top 10 coffee producers 2014–2022***
Source: USDA Foreign Agricultural service.gov

Global coffee production has increased by an average of 144,400 t yr-1 during the last 25 years, following the breakdown of the ICO-policed quota system (Figure 3, left). According to USDA data, only nine of the top 25 coffee-producing nations over the previous 25 years Brazil, Ethiopia, Honduras, Indonesia, India, Malaysia, Nicaragua, Peru, and Vietnam have experienced notable increase [40].

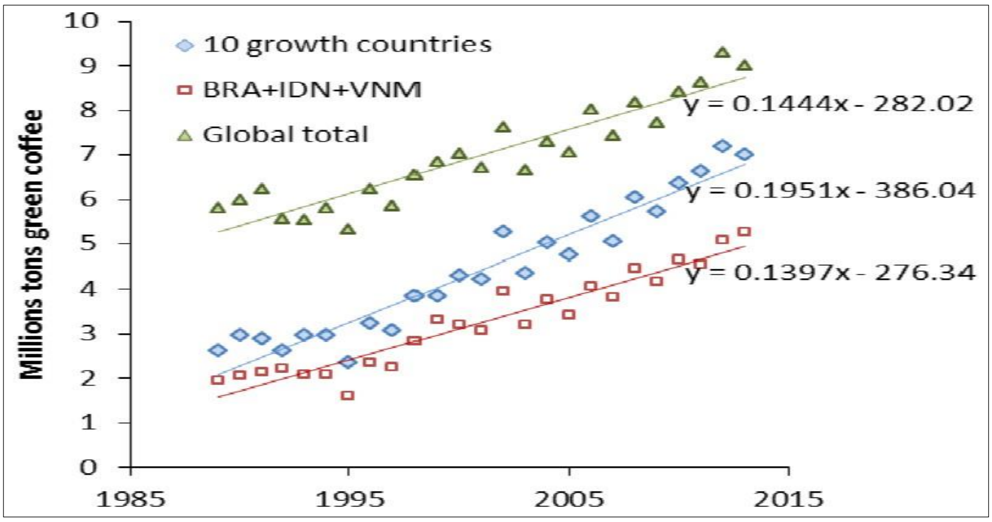

Figure 3: ***Left: world coffee production of all countries (triangles), ten growth countries (diamonds) and Brazil+Indonesia+Vietnam (squares) since 1989***

2.2 Production, Use, and Market of Coffee in 2020–2021 and 2021–2022

In comparison to the previous coffee year, which saw 170.83 million bags produced, the predicted total production for the 2021–2022 coffee year was 167.2 million bags, a 2.1% decline. Approximately 93.97 million bags of Arabica were produced, compared to 73.2 million bags of Robusta. Around 51.4 million bags were produced in Asia and Oceania, a 7.1% increase. Nevertheless, it was found that South America's production had decreased by 7.6% to 77.5 million bags. For the coffee year 2021–2022, production in Mexico and Central America decreased by about 3.5% to 19.0 million bags, while production in Africa decreased by 0.3 percentage points to 19.27 million bags [46].

Around 170.3 million bags of coffee were consumed worldwide in 2021–2022, a 3.3% rise. In the coffee year 2021–2022, the United States and Canada consumed 31.9 million bags of coffee, a 5.4% increase, while Europe consumed about 54.2 million bags. The consumption of coffee in Asia and Oceania increased from 39.66 million bags in the 2020–21 coffee year to over 40.8 million bags. With 5.4 million and 26.72 million bags of coffee drunk, respectively, the growth rates for coffee consumption in Mexico & Central America and South America were assessed to be 0.3% and 0.5%, respectively. For the 2021–2022 coffee year, 11.7 million bags were consumed in Africa [46].

For coffee, 2021–2022 was a year of recovery. After the global population left the COVID-19 pandemic, the world economy recovered from a 3.0% contraction in 2020 to an almost record 6.0% expansion in 2021. Global coffee consumption in 2020–2021 was expected to have increased by 3.3% to 170.3 million 60-kg bags from 164.9 million bags in the same year. It is estimated that the supply has dropped by 2.1%, from 170.7 million bags to 167.2 million bags. The ICO Composite Indicator Price (I-CIP), which rose from 130.45 US cents/lb for coffee year 2020–21 to 197.91 US cents/lb for coffee year 2021–2022, benefited from the improving economy [46].

3. COFFEE ECOLOGY

Arabica coffee requires an elevation of more than 1000 meters above sea level (masl). It lacks the quality that the global market demands at low elevations [32]. Rainfall between 1200 and 1500 mm annually is ideal for Arabica coffee. The distribution pattern and the overall amount are both significant. Rainfall should be evenly distributed throughout the seven to nine months of the year. For coffee to flower uniformly, it requires a dry, stressful time with little to no rain. In the absence of a stress phase, flowering could last for several months, making harvesting more challenging [32]. However, extended water stress limits the process of photosynthesis since it causes the stomata to close and other physiological functions of the plant to decrease [2]. Although it may withstand temperatures far below or above these limits for brief periods of time, the ideal average temperature is between 15 and 24℃ [45].

Arabica is far more tolerant to lower temperatures than robusta. Fruits and foliage cannot tolerate prolonged exposure to 15°C or temperatures below 6°C. Robusta coffee may be grown between sea level and 800 meters, while Arabica coffee thrives at higher elevations and in regions with yearly mean temperatures between 22°C and 26°C [2].

4. CHANGE IN CLIMATE

A statistically significant change in the mean state of the climate or in its variability that lasts for a long time (usually decades or more) is referred to as climate change. A shift in the long-term weather patterns that define different parts of the world is known as global climate change [41]. The atmospheric concentration of greenhouse gases (GHGs) has increased significantly due to human activities since the start of the Industrial

Revolution approximately 150 years ago. The Inter-Governmental Panel on Climate Change's Third Assessment Report from 2001 states that between 1750 and 2000, the atmospheric concentrations of carbon dioxide, methane, and nitrous oxide increased by roughly 31%, 151%, and 17%, respectively. Additionally, the Food and Agriculture Organization (FAO) has observed a sharp increase in climate change events, such as drought, floods, high temperatures, storms, etc., as illustrated in Figure 4 the phenomena known as climate change could result from increased warmth caused by rising GHG levels, which could then affect global temperatures. Figures 5 and 6 illustrate the rising trend of CO2 emissions, sea level, and world surface temperature, respectively.

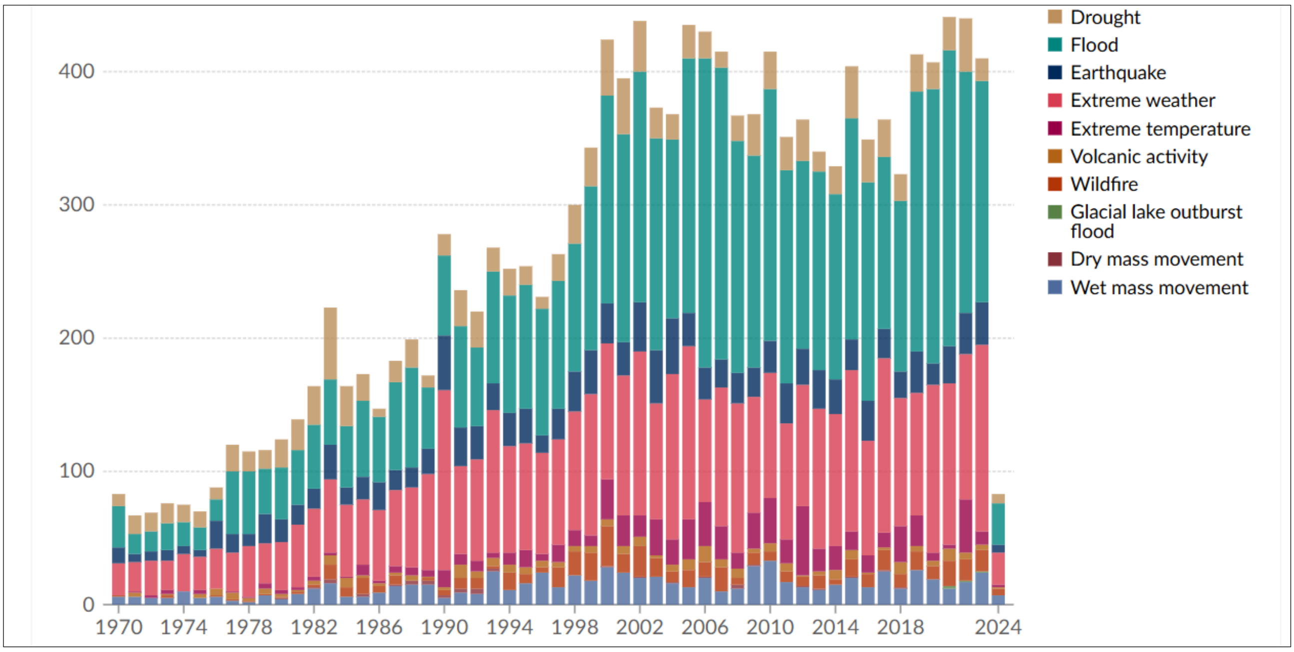

Figure 4: ***Increasing number of extreme climate-related events occurred during 1970–2024***
Source: *Food and Agriculture Organization (FAO) based on data from Emergency Events Database (EM-DAT)*

4.1 Emission of Carbon Dioxide

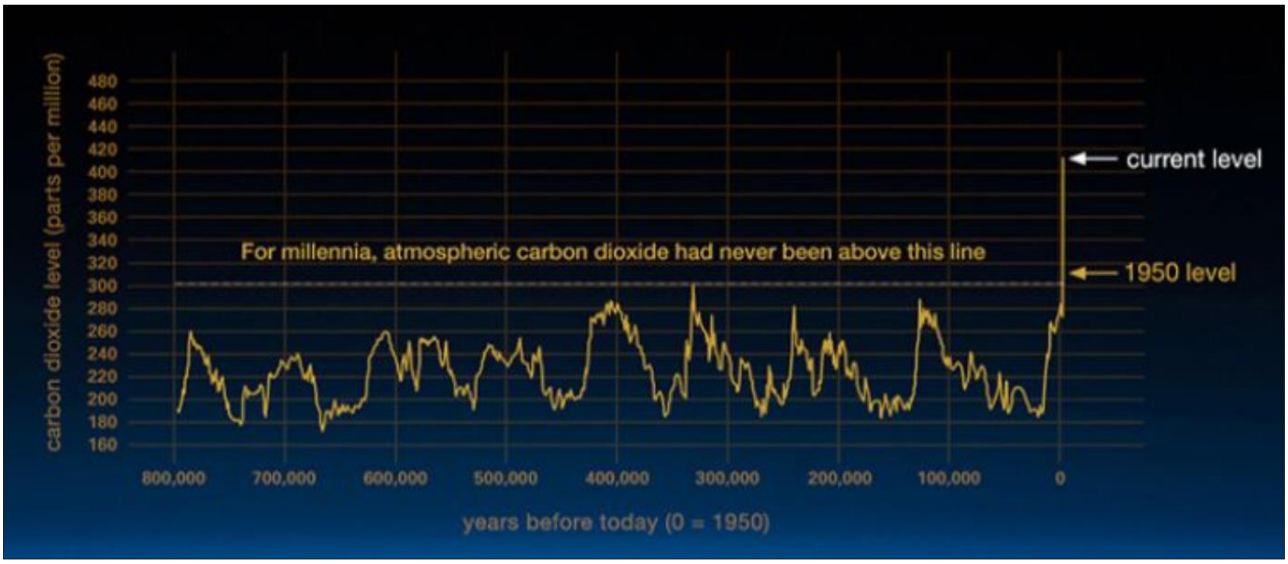

Figure 5: ***CO2 (ppm) trend over years***
Source: *NASA satellite data*

4.2 Temperature of the Earth's Surface

Index of global land-ocean temperatures

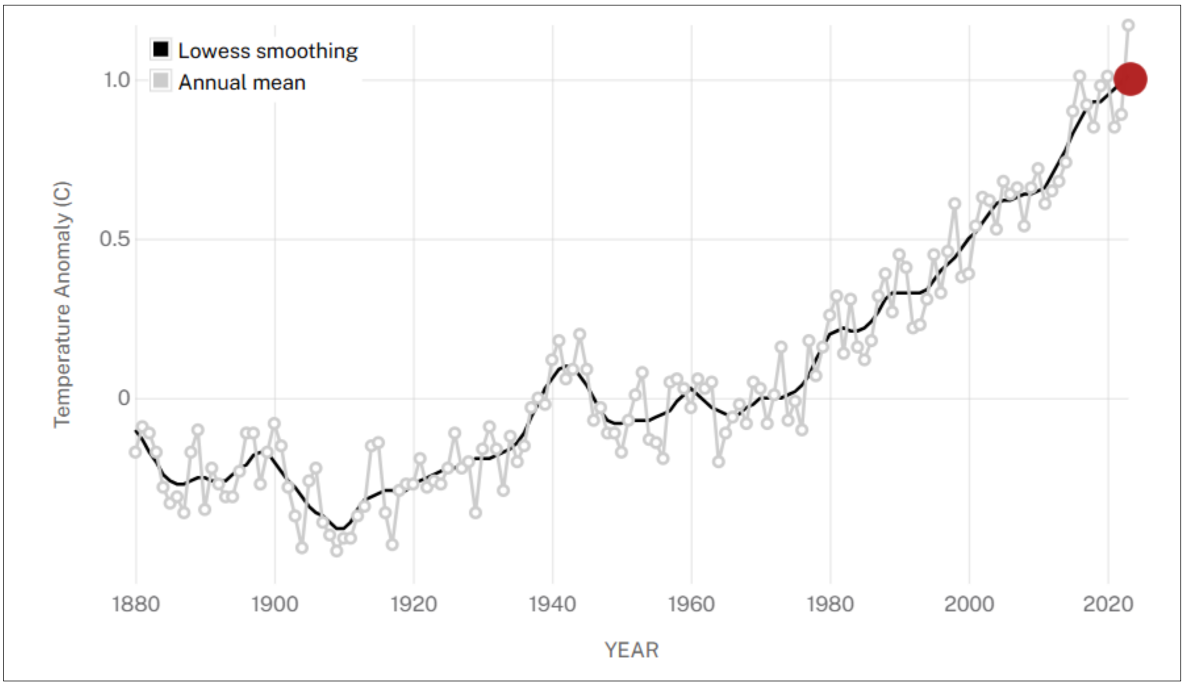

Figure 6: ***Global temperature variation***
Source: *NASA satellite data*

5. HOW CLIMATE CHANGE AFFECTS COFFEE YIELD

Temperature increases exceeding 30°C can affect physiological functions, particularly in dry air. Arabica coffee is typically grown in hilly regions and performs better at higher elevations [3-45]. However, physiological issues brought on by temperature decreases can very readily impact coffee development and fruiting, especially at higher elevations. Additionally, water stress reduces photosynthesis by affecting the Arabica plant's physiological activity [15].

According to studies, coffee's net photosynthesis drastically drops at temperatures above 24°C, reaching zero at 34°C. This also prevents cherries from developing and ripening, and if it persists, it may lead to decreased growth or even yellowing and leaf loss [15-31]. It has also been discovered that the maintenance of high fruit set levels, maximum photosynthetic rates, and fruit size are all impacted by water availability. Accordingly, coffee phenology is susceptible to both the amount and timing of precipitation episodes [31].

Variability in climate is the most conducive to the growth of coffee pest diseases; production decline is estimated to be 13% worldwide [1]. Significant diseases brought on by climate change during coffee cultivation would raise the prevalence of pests and diseases and broaden the altitudinal zone where the coffee berry borer and the fungal disease coffee rust can thrive [27]. The two most important coffee pests that are becoming more prevalent and harmful due to climate change are the coffee berry borer (Hypothenemus hampei) and leaf rust (Hemileia vastatrix) [6]. Coffee Leaf Rust, which thrives in hot climates, spreads more quickly and damages coffee in high-altitude regions [29]. Additionally, excessive precipitation and low temperatures favor coffee berry disease (CBD), which is more severe than ever. Temperature changes will impact insect pest dynamics, causing minor pests, such thrips, to become big pests [29].

The loss of adequate area for growing coffee arabica is the other issue caused by climate change. Production may need to change as a result of rising temperatures making some production regions less or perhaps totally inappropriate for growing coffee [21]. According to [8], there will be 65% less area available for Arabica coffee cultivation as a result of climate change. Their best-case scenario prediction is this. At worst, they discovered that by 2080, climate change will cause all of the area that is suitable for growing Arabica coffee to vanish. According to [8], they found a negative correlation between the rise in global temperatures and the expansion of Arabica coffee, increasing susceptibility of the poor and landless, changes in patterns brought on by rising temperatures, a shift in climate and agricultural zones towards higher altitudes, and changes in productivity [29]. Since coffee is a highland species that is not acclimated to high temperatures, yield declines are all but guaranteed in a warming world [4].

6. HOW CLIMATE CHANGE AFFECTS THE QUALITY OF COFFEE

Given their capacity to impede the crop's phonological growth, temperature and rainfall conditions both affect the potential output and quality of coffee [14]. These effects, which ultimately lead to decreased coffee quantity and quality, include, for instance, interrupted flowering cycles and protracted drought spells [34]. As said by [25], state that climate adaptability, particularly air temperature and precipitation, has a significant impact on the productivity and quality of Arabica and Robusta coffee. Nonetheless, Arabica coffee is more susceptible to changes in the climate, particularly during the stages of fructification and flowering [14]. Because cooler temperatures at higher elevations cause ripening to be delayed, high elevation enhances bean and prospective cup quality by allowing the natural qualities of acidity, fragrance, and boldness to fully emerge [32]. Fruit development and ripening are accelerated beyond 23°C, resulting in a loss of quality; growth is slowed below 18°C [37].

Coffee quality and product viability decline as a result of insect and disease outbreaks. According to [21], climate change is expected to increase the incidence of pests, such as the berry borer, which will lower the quality of coffee beans and fruit. The bug most likely began as a predator of Coffea canephora, a less common coffee plant that thrives at lower elevations and higher temperatures than Coffea arabica, in Africa, according to studies [21]. According to [22], temperature rises have a direct and exponential impact on H. hampei population growth. The number of generations of the bug increases with rising temperatures. According to a research by [22], H. hampei would mature more quickly at temperatures between 1 and 2°C, producing more generations per fruiting season. They discovered that H. hampei would have to relocate to higher elevations if temperatures rose by more than 2°C. This accounts for the insects' migration from lower elevations, where Coffea canephora grows, to higher elevations, where Coffea arabica thrives.

Increased sunshine and drought can cause the beans to ripen too quickly, resulting in a significant loss in quality and yield [37]. It has also been discovered that the maintenance of high fruit set levels, maximum photosynthetic rates, and fruit size are all impacted by water availability. Accordingly, coffee phenology is susceptible to both the amount and timing of precipitation episodes [31].

7. POSSIBLE METHODS FOR PRODUCING MORE COFFEE

7.1. Mitigation of Climate Change

In order to improve sinks and lessen the severity of global warming, it is crucial to take steps to limit greenhouse gas emissions [15]. A significant management component of climate change mitigation initiatives, which include actions to decrease greenhouse gas sources or increase sinks, aims to conserve natural resources through better fertilizer use, water collection, and conservation methods. According to [33], these tactics are equally compatible with the idea of sustainability.

Reducing the amount of greenhouse gas emissions caused by coffee production, which is mostly determined by the carbon footprint of coffee production, and sequestering carbon in the shade trees or forest areas of coffee farms are the two main concepts of mitigation. At the moment, there is no acknowledged method for conserving existing trees, but planting new trees could be regarded as reducing other emissions [24]. According to [41], carbon sequestration is a crucial technology for maintaining the ideal CO_2 level in the atmosphere, which helps to mitigate climate change. About 40% of the carbon footprint of the entire coffee chain is attributed to on-farm emissions, specifically nitrogen fertilizer, according to studies on carbon footprints from coffee production [39].

7.2 Strategies for Adaptation

Initiatives and actions to lessen agro-ecosystems' susceptibility to anticipated climate change are referred to as adaptation strategies. These include altering cropping activities' timing or location, changing varieties, enhancing the efficiency of weed, disease, and pest management techniques, and better utilizing seasonal climate forecasts, among other things [33]. Reducing CO_2 is another benefit of climate change adaptation measure for coffee production. Increased water storage, local temperature regulation, and biodiversity preservation are further environmental advantages [30]. From changing crop cultivars to adapt to drought or temperature changes to drastic steps like completely shifting land use away from agricultural production, adaptation methods can take many different forms [42].

Many experts seem to agree that the best way to preserve Arabica coffee is to use shade trees [22]. Shade trees planted near coffee plants can block out the sun's impact on the plants, creating a lower temperature that is up to 4°C better suited for Arabica coffee plants. Good management practices that reduce soil erosion (e.g. cover crops and contour bunds) and increase water retention (mulching, shade) will further help farmers adapt to climate change and retain the more fertile topsoil [10-23].

It is crucial to develop new cultivars that are more productive, resistant to pests and diseases, suited to the local soil and climate, and have marketable qualities [11]. Ethiopia has a distinctive genetic diversity of wild, semi-wild, and farmed Arabica varieties with various disease-resistant traits, environmental adaptations, and quality attributes enabling future coffee variety breeding opportunities that are climate-adapted [30].

7.3 Cooperation in Mitigation and Adaptation

Both climate science and policy have recently turned their attention to the possibility of creating synergies between adaptation and mitigation of climate change. Additionally, there are growing calls for studies to determine the best combination of adaptation and mitigation [26]. The adaptation needs in important food-producing activities could be selected to provide mitigation at the same time by concentrating mitigation aims in key cost-effective sectors. In fact, a number of adaptation initiatives that boost rural incomes and system resilience may still have substantial mitigation value, producing win-win outcomes with no regrets. For instance, this would encompass all of the beneficial techniques that result in better preservation of soil and water resources [43].

8. CONCLUSION

This article provides an overview of coffee production, expanding demand, and climate change's effects on global coffee yields and quality. Techniques for climate adaptation and mitigation were offered as answers to these problems and difficulties brought on by global warming. Climate variability in the coffee-growing region led to lower yields and quality, more pest disease outbreaks, higher production costs, and a smaller production area. The problem's effects could have a detrimental effect on both producers and consumers in the coffee industry. A sustainable ecosystem and high-quality coffee production are guaranteed by the thorough implementation of all adaptation strategies. Generally speaking, future studies will concentrate on identifying realistic climate change adaptation techniques that smallholder farmers may utilize.

Author Contributions

The manuscript's authors are Meseret Degefa Regassa and Leta Ajema Gebisa. The final manuscript was read and approved by the authors.

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

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