Climate Change on Tea

Subjects: Agronomy
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Even though climate change is having an increasing impact on tea plants, systematic reviews on the impact of climate change on the tea system are scarce. This study was undertaken to assess and synthesize the knowledge around the impacts of current and future climate on yield, quality, and climate suitability for tea; the historical roots and the most influential papers on the aforementioned topics; and the key adaptation and mitigation strategies that are practiced in tea fields.

Keywords: climate change ; climatic factors ; climate suitability ; tea ; quality ; yield

1. Introduction

Plants of *Camellia sinensis* are the botanical source for the world's most-consumed nonalcoholic beverage—tea. The tea plant originated in south-western China around 5000 years ago and is now grown in over 58 countries with an estimated area of 4.37 million ha of land [1]. China, India, Kenya, and Sri Lanka are the leading tea producers in the world. Tea is being manifested as a vital part of the economy, rural development, food security, and poverty alleviation in many developing nations while quenching the thirst of 4.5 billion consumers around the globe [2]. The tea industry is anticipated to grow at a compound annual growth rate (CAGR) of about 4% to 5.5% from 2017 to 2024 [1][2]. The retail value of the world tea market was estimated at around USD 50 billion in 2017 and is projected to grow to over USD 73 billion by 2024 [2]. Therefore, a concerted effort should be made to harness the optimal benefits of the tea sector and downstream production lines in the future, even with the expected global challenges.

Climate change, triggered by global warming, has been identified as a major challenge across the globe. In this context, the entire globe has experienced a striking surge in changing climate that is projected to increase at a significant pace in the future, with an unforeseen influence on agriculture, including that of tea. Climate change is defined as a change in the statistical properties, including averages, variability, and extremes, of the climate system that persists for several decades or longer [3]. The future climate will lead to an increase in adverse impacts across the globe. The changes in the global average temperatures by 2100 are predicted to be within the range of 1.1 to 5.4 °C. The amount and intensity of precipitation will differ considerably by region, with an exponential rise in some areas and a decline in others [4]. The level of carbon dioxide (CO_2) has gradually risen from 280 parts per million (ppm) in the preindustrial period to 408 ppm currently and is projected to further increase up to approximately 800 ppm by 2100. Furthermore, wind and precipitation associated with tropical storms are likely to increase in intensity [4].

As tea plants have a long life span, the literature highlights the numerous decadal impacts of climate change, including stresses such as severe drought, uneven and heavy precipitation, increased temperatures, elevated CO_2 concentrations, and other extreme weather events, including floods, frosts, and storms [5][6]. Moreover, climate change-related biotic (i.e., pests and diseases) and abiotic stressors (i.e., UV irradiation, nutrient deficiency, and ozone depletion) affect the sustainability of climate-smart tea systems [7][8]. In tea-producing areas, agrometeorological conditions are experiencing variability with climate change. Uncertain and less predictable climate scenarios may no longer satisfy the ecophysiological requirements of tea, thus posing risks, threats and limitations, as well as advantages in some locations for the tea sector.

The impacts of climate change on the tea yield have already been broadly investigated and include irreversible yield losses, impacts on regional economies, and the threatening of millions of livelihoods of humans in many nations [9][10]. However, studies related to the impact of the current and future climate on the tea yield have only recently been published, so there are few pieces of scientific literature in the popular databases on this topic compared to other crops. Moreover, tea accounts for 35%–50% of secondary metabolites on a dry weight basis; these metabolites are also vulnerable to climatic variables altering phytochemical and organoleptic (texture, color, taste visual appeal, aroma) properties, which has divergent impacts on market prices, consumer demand, and the psychological implications of tea consumers across nations [11]. Considerable research has recently been conducted to cover this research topic, but the reviews are limited and still emerging. A systematic review was undertaken by Ahmed et al. [11], seeking the impact of environmental variables on tea quality previously, but that review did not look at the impact of future climate on tea quality. Overall, no previous studies include both the impacts of environmental variables on tea quality at present and how this quality may change under future climate.

In line with the altered climate and its related consequences, shifting and changing (i.e., gain/loss) suitable habitats have also been noted. Species distribution models (SDMs) are used to evaluate relationships between climate and species occurrences to predict possible changes in ecosystems [12][13]. In certain areas, climate change will be advantageous for tea plants, whilst in others it may not be desirable. Even though there is ample scientific literature addressing the effects of climate change on the tea yield or quality, the literature regarding the effect of climate change on the climate suitability for tea has been largely neglected.

The thematic content of publications can be visualized using keywords/items of the related topics, and co-occurrence item density maps are becoming popular in systematic reviews that mirror the density of the items in the bibliography [14]. The historical context, as well as the influential reference of a particular topic, can be detected by Reference Publication Year Spectroscopy (RPYS) based on the cited reference in the bibliography [7]. All-inclusive systematic reviews showcase landmarks of the specific fields of research that aid researchers in understanding the contribution of other authors to a similar topic, as well as the evaluation and progress of a particular topic over time.

There has been a large upsurge in climate change across the world, and this will continue even more dramatically in the decades ahead [15], and tea systems are not exempt from these escalating adverse effects. This systematic review showcases current and future climate impacts on the yield, quality, and climate suitability for tea, while reporting the historical basis, the most influential research papers related to the above aspects, and the adaptation and mitigation strategies which other researchers have addressed, together in the same review.

Given this trend, across disciplines, we found that the impact of the current and future climate presents both advantages and disadvantages for tea, having multidimensional and multifaceted consequences. It is important to note that a lower number of studies have been conducted to address climate suitability for tea, as well as the impact of the future climate on the tea yield and quality (Table S2) (supplementary could be found in https://www.mdpi.com/2073-4395/11/4/619/htm). The thematic maps with keywords (Figure 1) and Reference Publication Year Spectroscopy (RPYS) (Figure 2) have recently been largely exploited by researchers in systematic reviews. As per Figure 2, historical foundations linked with the study topics were investigated, and three pronounced reference peaks were found in RPYS that represent the most significant papers by Wijeratne [16], Ahmed et al. [17], and Adhikari et al. [18] linked to the yield, quality, and climate suitability for tea, respectively. Within the corresponding citation network, the reference counts (N-CR) are comparatively small (Figure 2); as all citations included in the WoS database were considered, this may be due to the fact that the research questions addressed here are only starting to be researched.

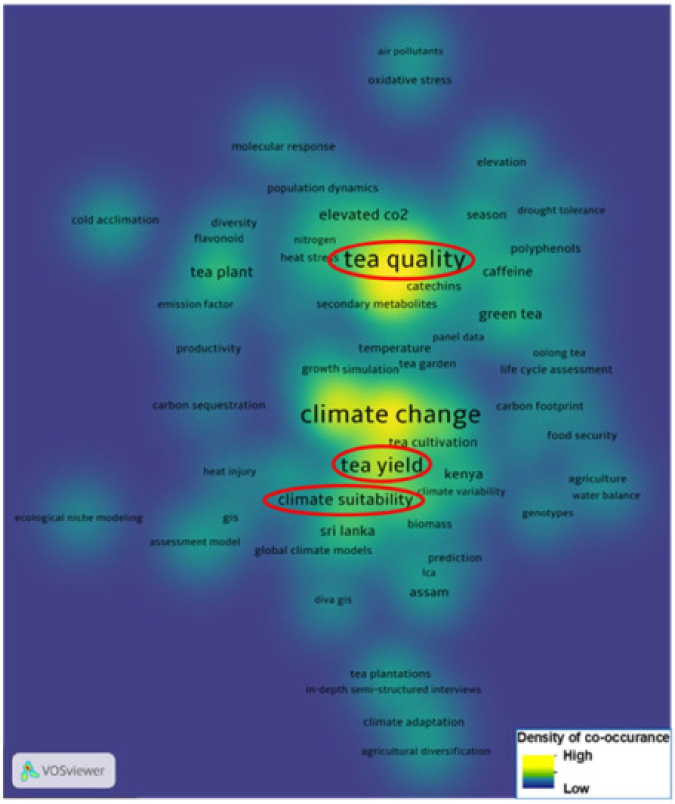

Figure 1. Visualization of the co-occurrence density of keywords from 762 papers on climate change and tea (*Camellia sinensis*). Note: As a threshold level, two nodes were taken.

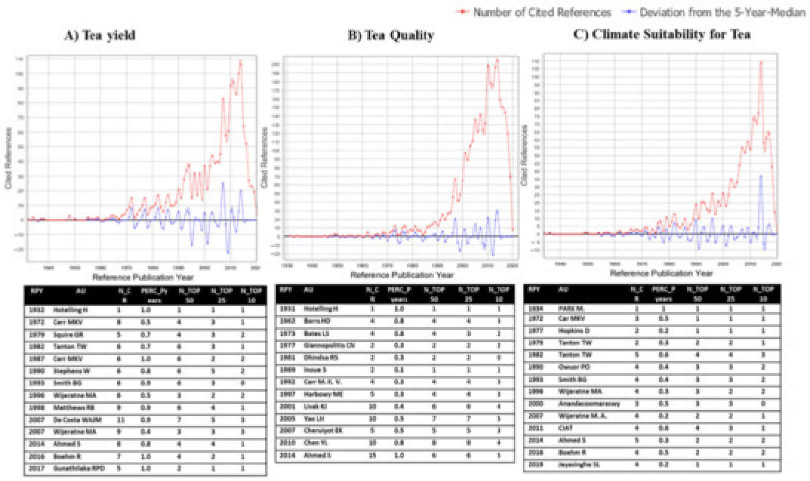

Figure 2. The Reference Publication Year Spectroscopy (RPYS) spectrograms and the distribution by reference publication year for 1930–2020 of the main references cited, based on the subjects' entitled effect of climate change on the (**A**) yield (**B**) quality and (**C**) climate suitability for tea, with the historical roots of the relevant topics. Note: Highly cited papers included in the spectrogram, RPY: Reference publication year, N_CR: Number of cited references, PERC_Pyear: Percent in year, N_top 50: Top 50% cited reference, N_TOP 25: Top 25% cited reference, N_TOP 10: Top 10% cited reference.

2. Tea Yield

According to the previous evidence gathered from our search (42 studies) (Table S4), climate change poses both pros and cons for the growth and development of tea and is anticipated to have a considerable impact on the tea yield (Figure S2). As a C3 crop, tea plants receive advantages of an increment of CO_2, temperature, and rainfall amount, while also receiving an adverse impact from the decrease in sunny days, rainy days, and relative humidity, and increased extreme climatic events, such as drought, floods, and excessively warm and cold weather. Five studies have clearly indicated a biomass increment of tea leaves with an increasing CO_2 concentration. As a C3 plant, tea leaves improve photosynthesis with elevated CO_2, which is due to an improved maximum rate of carboxylation (RuBisCO) and, RuBP generation, stimulating the biomass production of a tea bush via increased photosynthesis and respiration [19]. An increment of the tea yield with elevated CO_2 was further amplified by a rising temperature at high elevations, while the yield increment with elevated CO_2 was decreased at low elevations, since the rising temperature pushed the already high temperature into the ceiling temperature range, which is undesirable for physiological processes linked to the tea yield [20]. In addition, the photosynthesis would acclimatize to high CO_2 levels, limiting growth factors such as a shortage of nitrogen and other micronutrients, so the increase of the tea yield would not be as great as anticipated [6].

About 50% (22 out of 42) of the reviewed studies for this topic focused on the impact of temperature fluctuations on the tea yield. Many tea-producing countries reported that increasing temperatures tend to reduce tea yields while reporting beneficial impacts in some tea-growing regions in cooler countries [20][21][22]. Atmospheric temperatures beyond the limit of 12 °C and 30 °C are less favorable for tea bushes, which reduces tea shoot growth as tea growth is highly temperature-dependent [23][24]. The maximum photosynthetic rate of tea is recorded at optimum average ambient temperatures of between 18 °C and 20 °C [25]. With an increase in temperature, the evapotranspiration will increase in the tea fields and alter the surface and microclimate around the tea bush, subsequently reducing the tea yield [9]. The quantity and variability of rainfall are crucial, and 17 studies showed that rainfall and seasonal changes will affect tea production. Five studies postulated that a high, low, and uneven distribution of rainfall reduces the tea yield. Rainfall is a major factor that influences the photosynthesis, metabolism, growth, and development of tea bushes. Generally, for successful cultivation, a tea plant requires a minimum annual rainfall of between 1150 mm and 1400 mm and an optimum annual rainfall of 2500 mm–3000 mm [25][26]. Global warming directly impacts the hydrological cycle and creates ramifications of high rainfall intensities, rainfall variability, floods, and soil erosion in tea fields [27].

It has been reported that a considerable yield reduction results from drought stress [28][29], influencing tea growth, and tends to increase the number of dormant/unproductive buds and eventually reduces the yield [16]. For achieving the optimum tea yield, a radiation intensity from 0.3 cal/cm^2/min to 0.8 cal/cm^2/min, humidity between 70% and 90%, and prolonged photoperiods are necessary [30]. There is a reliable source of evidence demonstrating that the amount of solar radiation reaching the Earth has become unstable with climate change over the years [31]. A reduction in sunlight hours resulting from fewer rainy days and more cloudy days with a low light intensity would benefit tea production, as tea is the maximum function of the photosynthetic apparatus adapted to shade conditions. The light quality is also important, affecting tea growth as shorter wavelengths inhibit tea plant growth, and long wavelengths stimulate growth [32].

3. Tea Quality

Previous studies provide contradictory evidence on how climate change can alter biochemicals present in tea leaves. It is presumed that the chemical composition of tea leaves is a result of multiple genes and hormones, and their interactions mediate biotic and abiotic stressors. The impact of ambient and increased CO_2 levels on tea quality is clearly described in 14 recent studies (Table S5). It was found that elevated CO_2 significantly increased soluble sugar, theanine, polyphenol, jasmonic acid, and salicylic acid while decreasing caffeine and free amino acids in the tea leaves. However, the literature indicates that elevated CO_2 aggravates the susceptibility of tea plants to certain insects and pathogens, posing a serious threat to potential tea production systems.

Ten out of 14 studies (71%) showed a decrease in phenolic compound concentrations with a seasonal change from spring to other seasons. Vivid fluctuations of phenolic compounds, catechins, and amino acids found with drought, but not the extent of drought periods, reduced the levels of biochemicals. Munivenkatappa et al. [33] showed that drought tea varieties accumulate higher levels of biochemicals. Generally, *Camellia sinensis* var. *assamica* (e.g., Assam or Indian tea) is more tolerant to drought than *C. sinensis* var. *sinensis* grown in Japan, China, Iran, and Turkey [34]. The supplementation of K+, Kaolin, abscisic acid (ABA), and methyl jasmonate (MeJA) can protect tea plants from drought stress [35].

Previous studies show that there is an inverse association between tea quality and temperature, as the concentrations of catechins, phenols, caffeine, and antioxidants were found to be higher at higher elevations with a cooler temperature [36][37][38]. Hence, in the context of climate change, increasing temperatures can deteriorate the quality of tea as a result of warming, particularly at lower altitudes. Nevertheless, one study suggested that a rise in temperature can lead to increased catechin concentrations in tea [39]. Ahmed et al. [11] found that high precipitation is inversely correlated with concentrations of biochemicals having a negative impact on tea quality, diluting the concentration levels of biochemicals. Other climate extremes, such as frost, cyclones, late spring, cold spells, hail, and floods, will also lead to a deterioration in tea quality [40].

High intensity prolonged sunlight causes photoinhibition in tea plants and alters the chemicals present in tea leaves. There is a negative relationship between amino acid levels in tea shoots and sunlight hours, while the amount of amino acid is positively correlated with the relative humidity [41][42]. Multiple genes and hormones mediate tea biochemicals over abiotic factors, and their relationship remains largely unknown [43]. Considering all of the above complex interactions between climatic factors and tea quality, the concentrations and types of certain biochemicals are highly variable, depending on abiotic stresses (Figure S2), reflecting the uncertain nature of tea quality and thus welcoming future research to address this knowledge gap.

From a consumption perspective, the organoleptic parameters of the taste, color, brightness, and flavor of the final tea are governed by secondary metabolites. It is apparent that some secondary metabolites will be enhanced with altered climatic conditions, especially with elevated CO_2 and an increase in temperature in cooler regions. Generally, increases in the concentrations of biochemicals are accompanied by an increased tea quality until a specific threshold for consumer demand and consumption. Higher levels of free amino acids (AA) with a certain threshold of total polyphenol (TPC) indicate a better quality of green tea, but these thresholds of amino acids and polyphenols are significantly influenced by climate change. Moreover, the theaflavins and thearubigins are responsible for delivering better quality black tea, and these polyphenol levels are highly climate-dependent. However, high levels of specific phenolics are associated with a bitter taste that is typically less preferred by consumers [44]. An array of complicated biochemical and physiological adaptations have progressed in tea plants to allow them to adapt and endure climate change, leaving the quality of tea in the future in jeopardy. Given these alarming circumstances, researchers, concessioners, and related parties should further investigate the dynamics of tea chemicals in the face of climate change, targeting the maintenance of a desirable quality of tea in the future.

4. Climate Suitability for Tea

Tea's ideal growing conditions are at high risk and expected to change significantly under the altered climate (Figure S2). Given the importance of the ecophysiological requirements for tea plants, their potential distribution and their relationship with climate variables are vital. To date, detailed appraisals of the impacts of the future climate on the suitability of habitats for tea crops are rare. We only found limited studies (Table S6) assessing the climate suitability and spatial distribution of tea crops. Multiple studies demonstrate three possible impacts of climate change on suitability habitats of tea: s shifting climate suitability of existing tea-growing areas resulting in gains (+) or losses (−) and generating new areas with climate suitability for tea.

Previous studies have demonstrated how climate change may cause a shift the climate suitability of current tea-growing areas. For example, suitable areas for tea will shift up the altitudinal gradient: those retaining some suitability will see declines of between 20% to 40%, compared with today's suitability of 60%–80% in Uganda [45]. The major tea-growing counties in China could gradually shift from south to north, and the optimum tea-producing zone in Kenya is projected to move to a higher altitude by 2050, compared to the current climate. Temperature- and precipitation-linked climate changes are the prime factors that impact the potential shift in tea cultivation [46][47]. The rise in the average temperature with global warming could be advantageous for tea plantations located at higher-elevations, as cooler regions would become warmer, but would have a negative effect on lowlands.

Furthermore, increasing minimum temperatures creates possible conditions to grow tea that has traditionally been incompatible with colder climates, whereas existing, well-known cultivation regions could become undesirable in the future as the temperature gradually becomes too hot [48]. For example, by 2075, the suitability of existing tea-growing regions in Kenya is projected to decrease by 22.5% [49]. Generally, the reduction in suitable areas for *Camellia sinensis* var. *sinensis* was greater than that for *Camellia sinensis* var. *assamica* due to its different sensitivity to temperature increases, and *Camellia sinensis* var *assamica* is originally native to dry and warmer climate [50].

In addition, some improved tea varieties developed for specific regions could be adopted for cultivation elsewhere, where they would face the same abiotic and biotic stresses. For example, Rivera-Parra and Peña-Loyola [47] identified areas in Ecuador using ecological niche modeling where it is possible to grow Ceylon and Nilgiris tea varieties that will sustain similar ecological niches in the future and have high agricultural potential. This can propel the development of new crop varieties/climate-smart /climate-ready clones, which can sustain the extreme region-specific ecological conditions.

However, it is difficult to expedite a comparative assessment on how climate suitability for tea varies with countries, as previous authors used different approaches, Representative Concentration Pathways (RCPs), and global climate models (GCMs) for their projections. Given the substantial disagreements between the various modeling approaches that are available in the literature, it is better to adopt "methodology ensemble" approaches that provide a much better ensemble projection [50] and overview of the uncertainties involved in such projections than the use of a single method. Efforts should also be made to project the climate suitability for tea by including all countries together, not on an individual country-by-country basis, so that the climatic requirements for tea can be derived more generally, which may allow better projections on future suitability than country-scale analyses. Early warning and monitoring systems should then be established according to the results of predictive models.

Overall, the adverse impacts of climate change on the yield, quality, and climate suitability for tea are greater than the positive impacts. Therefore, an increased understanding and awareness of how climatic factors interact with the tea system is required to identify appropriate adaptation and mitigation strategies, as mentioned in the results section. Compared to the large-scale tea growers, smallholder tea farmers are more susceptible to the adverse impacts of climate extremes such as drought, floods, storms, frost, and heavy rains [51]. In the given context, financial and technical aids should be given to smallholder tea growers while introducing risk management tools to deal with climate change. Importantly, smallholder tea farmers should be encouraged to utilize index-based insurances, mutual funds, microcredits, loans, and other subsidizing measures to cover the risk of economic losses caused by climate change. Farmers need to recognize climate risks and manage them to overcome anticipated consequences and reduce problems of protecting their livelihoods from climate change uncertainties. Some models (e.g., the Ricardian model) could be used to assess the effects of adaptation that describe what would happen to that farm area if it changed into different climate change conditions [52]. As tea farmers are amenable to adapting to climate change, the Ricardian analysis method can be applied to tea farms to estimate the value of adaptive responses of climate change. The inclusion of these evidence-based findings and tea farmers' participation in adaptation and mitigation efforts should be considered when formulating synergistic policies to combat the adverse effects of climate change on the tea sector.

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