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Anomalous Responses of Rice Yield and Quality in Extreme Climate to Predict and Escape Future Damages

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Abstract:

Extreme climatic exposure due to global warming and climate change has direct or indirect consequences on rice yield and quality. The burgeoning population and socioeconomic progress are stimulating the growing demand for good-quality rice worldwide. Climate change research on rice always emphasizes yield, while more could be learned about quality. Thorough research about extreme high and low temperatures effects on rice at crucial growth stages remains mostly unknown and results in limited attempts to explicate the underlying concept. Climatic factors often pose a threat to the vegetative and reproductive development of rice and might play a vital role in grain quality change but a lack of thorough research has been done yet. Rice is one of the major agricultural commodities that provide more calorie and nutritional benefits compared to other cereals. Frequent climate change causes certain alterations in rice quality, while temperature and light intensity are the major challenges. Thus, it is important to quantify how rice grain quality will respond to climate change in the future. Rapid economic development coinciding with serious pollution results in severe solar dimming and discrete temperature increases in divergent rice-cultivating countries. Fluctuation in rice ecology – temperature, solar radiation, CO_2 and O_3 – has a domino effect to hamper grain quality traits. Responses of rice grain quality traits – appearance, cooking, flavor, and nutrition – to extreme climatic factors enable us to clarify the insights of changes. If we are to escape the destructive impacts of extreme temperatures, need to identify the most sensitive periods, patterns of yield losses and underlying mechanisms of mutable rice quality. We used books, previous field or phytotron research and review articles to create a comprehensive sole literature. We find that the extreme temperature influence on rice coinciding with impending global warming simulation is methodically understated. The demonstration of evidence allows case studies corresponding with typical spatiotemporal temperature in neoteric and intensive forms of analysis on rice yield and quality, combined with morpho-physiology and molecular research. This review will be associated with the enhancement of agricultural sustainability in future climate change.

Keywords: Climate change, extreme temperatures, light, elevated CO_2, ozone, rice grain quality

Introduction

Rice (*Oryza sativa* L.) is the staple food for several Asian countries and accounts for more than 12% of global cropland area, thus its production and quality are crucial for food security among half of the world population (Elert, 2014; FAOSTAT, 2010). Due to ever-increasing demand for food, population growth and improved living standards rice production needs to be increased by 25-30% to fulfill the demand in 2050 (Jamal et al., 2023). The prerequisite to meet the loads of crop calories and protein will increase by 11% and 7% respectively from 2005 to 2050 (Tilman et al., 2011). The challenge of meeting this demand for rice has advanced the productivity during last century through the introduction of semi-dwarf varieties and hybrid rice. However, the subsequent grain yield is increasing and the next major leap in rice production is to combine higher yield with superior quality (Qian et al., 2016). Innovative and powerful strategies are required to meet the future demand for novel elite rice varieties with high yields and superior quality (Zeng et al., 2017).

Climate change impacts all aspects of agriculture including production, distribution, access to food and food prices and poses a continuous risk to global food security in the future (IPCC, 2014; Tai, et al. 2014). Previous research suggested that climate change continuously happens through internal changes in the earth, human activities, biotic processes, variations in solar radiation, plate tectonics, volcanic eruptions, etc. and results in global warming (America's Climate Choices, 2010; Gillis, 2015). Crop growth and development are strictly regulated by the surrounding environment through hormone signaling networks during chilling and high temperatures or any other stresses (Patel & Franklin, 2009). However, climatic fluctuations from optimum growth conditions often influence rice yield and quality, while becoming more severe during their susceptible growth stages such as flowering and early grain filling (Welch et al., 2010).

According to the Paris Climate Deal 2015, the United Nations Framework Convention on Climate Change (UNFCCC) agreed to limit global warming to less than 2°C but climate change has already become a vital factor behind the fluctuation in rice growth, yield and quality since 1980 (IPCC, 2015). To the Special Report on Emissions Scenarios (SRES), global mean surface temperatures are projected to increase by 1.8°C to 4.0°C by 2100 and carbon dioxide (CO_2) concentration is projected to increase from ≈379 ppm now to more than 550 to 800 ppm by 2100 (IPCC, 2000; IPCC, 2007). Previous research shows that feeding the growing population in a fluctuating climate poses an urgent challenge to global agriculture (Ray et al. 2015). Hence, climate change and extreme weather events will bring more instability in yield, food supplies and higher risks of food insecurity (IPCC, 2012). For instance, high temperatures during the rice growing season have dramatic impacts on agricultural productivity, farm incomes and eventually food security (Xu et al., 2021). Therefore, the climate change effect of rice is needed to be quantified.

Rice grain quality is usually evaluated through appearance, texture, physiochemical traits, ease of cooking, swelling capacity and eventually taste quality (Liu et al., 2013). Consumer acceptability is influenced by multiple texture attributes, hardness and stickiness of rice (Juliano et al., 1981). Global warming and climate change coinciding with more weather extremes will potentially affect the rice quality through altering milling, cooking, eating, nutritional quality and also the market value (Lee et al., 2013). Global climate change, temperature, light, CO_2, and O_3 stresses are becoming major areas of concern for researchers worldwide. The responses of plants to these stresses are complex and may alter plant metabolism, cellular homeostasis, physiological, and biochemical processes. To understand changes in rice grain quality with constant climatic change or weather extremes more advanced research is required. This review will bring new insights into the rice quality changes in divergent climatic conditions and provide basic information about the focus of adaptation in future climate change.

Discussion

Impacts of Temperature on Rice Grain Quality

Among all the factors, temperature (cold or heat) is the most important consequence of fluctuating environmental conditions and has overwhelming impacts on plant growth and metabolism (Suzuki et al., 2012; Bita & Gerats, 2013). In recent years, among all the extreme events, temperature has been the most common phenomenon in various locations of the world. High temperature (HT) stress at the heading stage is now an important focus in agricultural research (Bamagoos et al., 2021). Therefore, it is obligatory to assess the impact of climate change on the altered responses of rice as morpho-physiology, grain yield, and quality of grain. Most researchers believe that high or low temperatures during grain filling may lower the crop quality of rice as it depends upon the rice grain's physical, milling, and physiochemical traits.

IPCC (2013) has also stated that the mean global temperatures are predicted to increase in frequency and cause extreme heat events. The high temperature affects the yield, appearance quality, and physicochemical traits of rice, and the critical period of temperature effect is usually 0-15 days after heading (Wu et al., 2016). Fertilization rate, early grain filling, duration of grain filling, grain mass, endosperm structure, the content and ratios of free polyamines, phytohormones, and the conversion efficiency of sucrose into starch are in declining trend in HT (Cao et al., 2016). It is also suggested that high night and day temperature reduces grain yield, number of panicles, pollen viability, spikelet fertility, grain weight panicle-1, grain width, amylose content, gel consistency and increase grain chalkiness, which hamper the grain appearance and quality traits in rice (Mohammed et al., 2013; Coast et al., 2015; Fahad et al., 2016a; Zhang et al., 2023). HT shortens the grain filling period and high filling rate, raising the percentage of immature and chalky grains (Zhang et al., 2023). (Tashiro & Wardlaw, 1991) also stated that the formation of chalky grains was most sensitive to high temperatures during 12–16 days after heading. Spikelet sterility becomes a major factor, although the other growth components are sufficient at less than 20 ◦C and above 32 ◦C. Heat-induced spikelet sterility in rice occurs due to climate change (Krishnan et al., 2011). It is also reported that HT would inhibit dehiscence and germination of pollen grain and pollen production (Rativa et al., 2020). The germination percentage of pollen grain and spikelet fertility would be reduced by HNT (high night temperature) or daily minimum temperatures (Mohammed & Tarpley, 2010). Plants are subjected to high temperatures (35 ◦C ± 2), which severely reduce the photosynthesis, stomatal conductance, and water use efficiency and increase the leaf water potential of rice cultivars (Fahad et al., 2016b). The systematic analysis of HNT response at the physiological and molecular levels significantly reduces yield and quality (Shi et al., 2013). HNT stimulates the rice respiration rate at night and reduces photosynthesis, sink strength, and sucrose synthase, which impact starch accumulation in the developing grain, thereby changing the grain yield and quality at the physiological maturity of rice (Bahuguna et al., 2015).

The low temperatures also have anomalies that impact the grain quality of rice, like high temperatures. The extreme minimum temperature, especially chilling in cereal crops, is one of the major factors that affect growth and yield (Hasanuzzaman et al., 2013). In some cases, low temperatures through the seeding stage can also indirectly affect the grain-filling period and the quality of rice. Low temperature or cold stress includes both chilling (<20 ◦C) and freezing stress (<0 ◦C) that impacts most significantly on agricultural crops (Lang et al., 2005; Thakur et al., 2010). In the chilling temperature, the cellular respiration, chlorophyll content, leaf water content, and accumulation of storage proteins, minerals, and amino acids are significantly inhibited, resulting in a short grain-filling rate and period (Nayyar et al., 2005). At extreme low temperature, the enzymatic activities in endosperm development decrease all except the granule-bound starch synthase (GBSS) (Ahmed et al., 2008). Some researchers consider the low temperature as the main reason for chalkyness. Moreover, cold induces flower abortion, pollen-ovule infertility, fertilization, seed filling, low seed set and high sterility rate of rice grains (Thakur et al., 2010; Qiuju et al., 2015). Low temperatures at the seedling stage indirectly decrease the grain-filling time, grain weight, brown-milled rice (%), gelatinization temperature (GT), gel consistency (GC) and increase the chalkiness and protein content in rice (Huang et al., 2013). In addition, the grain protein and almost all amino acid contents negatively correlate with the difference in maximum and minimum temperature (Liu et al., 2015).

On the other hand, warming might benefit crop growth by allowing higher yield, mitigating low temperature or chill injury, and relieving heat stress by shifting the post-anthesis phase to more favorable temperature conditions (Porter & Gawith, 1999). However, in extreme temperature conditions, even if there is sufficient growth in other plant components, it may still reduce the quality of rice grain. Therefore, daily maximum and minimum temperatures both play essential roles in grain quality. At the molecular level, various reports, including our previous studies, have shown that high and low temperatures could change physiology and genetic activities affecting amylose and storage protein accumulation, further reducing the rice grain quality. So, further research is required on grain quality in specific locations to face the challenge of fluctuating temperatures in the face of future climatic change.

Impacts of elevated CO_2 on Rice Grain Quality

The productivity and the quality of crops are greatly affected by environmental conditions, and carbon dioxide (CO_2) is one of the important components and chiefly responsible for global warming. The CO_2 is essential for plant photosynthesis. The increase in atmospheric CO_2 concentration has the potential to enhance the growth and yield of rice (*Oryza sativa* L.), but little is known regarding the impact of elevated CO_2 on the grain quality of rice, especially under different climatic scenes. The atmospheric concentration of CO_2 is the most important feature of global climate change and is increasing along with temperature from pre-industrial times (280 μmolmol^{-1}) to present (400 μmolmol^{-1}) and consistent with future estimation (936 μmolmol^{-1}) by the end of the century (IPCC, 2013). The atmospheric CO_2 is rising, accompanied by global warming, and affecting rice grain quality. The elevated CO_2 increases grain length, width, chalkiness, and starch pasting properties with a decrease in protein concentration, which indicates the improvement in the palatability of rice by the taste analysis of cooked rice (Jing et al., 2016).

The aboveground plant biomass, root biomass, grain yield, leaf area index, and net carbon assimilation rates of the plants growing under elevated CO_2 conditions show a significant increase and result in higher starch amylose content, carbon, and nitrogen grain yields compared with control conditions (Roy et al., 2015). The elevated CO_2 greatly accelerates grain growth and development, which causes excessive filling during the early grain-filling stage and incomplete filling during the late grain-filling stage, which raises chalkiness (Yang et al., 2007). The appearance quality of rice grain is largely affected by higher elevated CO_2 through decreased undamaged grain (UDG) and increased percentage of chalky or white-base grains (WBSG), which are negatively correlated with grain protein content (Usui et al., 2016).

Although the CO_2 enrichment in the field consistently raises biomass and yield, if the concentration is more than 450 ppm, that will perhaps cause deleterious effects on grain quality (Erda et al., 2005). Free air CO_2 enhancement (FACE) prominently increases rough, brown, and milled rice while markedly reducing head rice, appearance, and nutritive value of grains due to a reduction in protein and Copper (Cu) content in milled rice. Better eating or cooking quality has resulted in FACE (amylose −3.8%; peak viscosity +4.5%, breakdown +2.9%, setback −27.5%), and all these changes in grain quality revealed that hardness of grain decreases with elevated CO_2, while cohesiveness and resilience increased when cooked (Yang et al., 2007). Moreover, elevated CO_2 causes lower mineral, crude protein, nitrogen uptake, assimilation and translocation with high carbohydrate (starch) induced dilution (Fernando et al., 2012; Johnson, 2013; Högy et al., 2010). Previously, Zhang et al. (1999) mentioned that the nutritional quality was significantly reduced by the decline of total amino acid amount greatly at elevated CO_2 and also found no modification in cooking quality (amylose content, gel consistency, and alkali spreading value). The meta-analysis of 125 studies together, the results suggest that rising CO_2 and warming accompanied by low N supply are unlikely to stimulate rice production, especially with the current trajectory of emissions scenarios (Wang et al., 2013). The physiological mechanism underlying CO_2 toxicity is not well known yet, but elevated CO_2 (0.1-1%) does not reduce vegetative growth but increases ethylene synthesis and inhibits seed set and, thus, yield (Bugbee et al., 1994).

However, the interactive effects of elevated CO_2 and temperature on the grain quality of rice have not been studied well. So, as an important component of the environment, more research is required to evaluate mitigation techniques to maintain the rice grain quality in high elevated CO_2 with other climate factors in the future.

Impacts of light on Rice Grain Quality

Solar radiation, along with temperature, significantly impacts radiation use efficiency (RUE) at the leaf level, among all other climatic parameters (Zhu et al., 2008). At high solar radiation, RUE can be reduced because of the increase in photosynthesis, with further increases in light diminishing, and excess energy will engage photo-protective mechanisms (Ort, 2001). The rapid decline of photosynthesis occurs under high light stress (Zhou et al., 2007). Among all the environmental factors, light intensity is one of the most important and determines the basic characteristics of rice development. Low light stress often creates severe climatic disasters in some rice-growing regions and significant loss in yield and quality due to continuously cloudy weather or rainfall, especially during the grain-filling stage (Liu et al., 2014).

In 2015, Liang et al. (2015) reported that low light markedly impacts the appearance, cooking, and nutritional qualities of rice by increasing major protein, amino acids, and chalkiness rate, whereas reducing brown rice, milled rice, 1000-grain, weight, and amylose content. The rice grain yield and quality are determined by light intensity (Yao et al., 2000), and low light severely constrains yield in some rice-growing regions of the world, especially in Southeast Asia and China (Ren et al., 2002). Due to the insufficient supply of assimilates and decreased activity of a soluble starch branching enzyme involved in starch synthesis results in poor appearance and milling qualities, high chalkiness, and reduced head yield in low light conditions after the heading stage (Ren et al., 2003; Ren et al., 2003; Kim et al., 2014). Shading after the heading stage causes a reduction of the net photosynthetic rate, dry matter accumulation, and sink capacity in rice, which significantly reduces the number of filled grains and weight (Deng et al., 2009; Liu et al., 2009). It’s also found by Ding et al. (2003) that shading after heading prolongs the rice growth period and reduces chlorophyll, malondialdehyde, and photosynthesis, which results in lower grain filling than that under strong light. In the case of aromatic rice (Jasmine or Basmati) production, a significant change in the yield and quality traits under shading and an increase in 2-acetyl-1-proline, which is the major compound responsible for the aromatic character of fragrant rice. The continuous shading (15 days before harvest) significantly increases the protein content in grains and the aroma of aromatic rice, but a significant reduction is observed in grain filling rate and yield (Tang et al., 2015). These indicate that shading could have a selective effect on the metabolism of these volatile compounds (Mo et al., 2015). Wang et al. (2013) have indicated that shading impacts starch synthase and related enzyme activities during grain filling in rice. Shading impacts rice quality differently amongst genotypes, increases protein content and chalkiness, and declines amylose content (Zhang et al., 2007). A significant decrease in peak, trough, and final breakdown viscosities of rice flour, though increased pasting temperature, setback viscosity, and other physiochemical quality traits in shading (55%) state (Kim et al., 2014). So, light intensity is another important requirement for plant development and determines morpho-physiological traits, yield, and physical and physiochemical qualities of rice grain.

Impacts of Ozone on rice grain quality

Another vital climatic factor, ozone (O_3), significantly influences rice grain quality. Due to anthropogenic activity, the O_3 concentration is believed to continually increase, which might severely affect grain crops' growth and grain quality. Several regions of the world suffer from O_3-induced crop yield loss, with economic costs reaching several billion dollars year^{-1} in some regions, such as the United States of America, the European Union, and East Asia (Sitch et al., 2007). Elevated O_3 reduces chlorophyll content, photosynthetic capacity, above-ground biomass, grain yield, harvest index, and mineral element concentrations, which led to a significant rise in crude protein concentration in rice grain (Li et al., 2016). Other researchers have also reported that ozone is damaging photosynthetic rate, chlorophyll content, carbon assimilation, stomatal conductance, plant growth and reducing the yield of crops (Biswas et al., 2008; Emberson et al., 2009). Ozone damages cell membranes, leading to cell death and leaf senescence, and it converts into reactive oxygen species (ROS) (Fiscus et al., 2005). The determinants of rice grain yield, including photosynthesis, biomass, leaf area index, grain number, and grain mass, are reduced by elevated O_3 (Ainsworth et al., 2008). The crop under O_3 stress owing to lower carbon fixation results in a reduction of starch concentration in grain (Mishra et al., 2013). So due to these morpho-physiological changes by O_3 stress must have an abundant impact on rice grain quality and it's highly necessary to do more innovative research on this topic to maintain the rice quality in the future.

Other climatic factors like available water, humidity, other GHGs, climatic hazards, etc., may also have a significant impact on rice grain quality all over the world and it is necessary to assess the effects as soon as possible to challenge the future uncertain of climate change in view of grain quality of agricultural crops.

Conclusion:

After going through the above references it’s clear that temperatures exceeding or down from the optimum either for the long term or suddenly for the short term have a great impact on rice grain yield and quality in particular stages. Meanwhile, the occurrence of extreme events will be enhanced in future global warming and climate changes. As the major crop rice is cultivated in various climatic locations and some areas are affected by extreme high or some by extreme low and other places are pretentious to both in different growth periods. However, existing research has inconsistent findings or similar data sets or stages not valued for rice quality and lack of precise information about the stage which may expose for a short period but can be pretentious to both yield and quality in the same cultivar focusing on physiology, yield, and appearance-physiochemical quality with molecular endorsement. The changes in yield or quality after harvest must need to be explained by gene, enzyme, and hormonal or other trait fluctuations during exposure, which has seldom been elucidated before. Therefore it's obligatory to assess the impact levels and involved mechanisms under the global warming simulated short-term extreme temperatures targeted to evaluate the most sensitive stages and insight molecular mechanism of yield and quality fluctuations to appeal a complete story to sustain crop. In addition, the research over the impending decades will seek to comprehend the numerous mechanisms that involve short-term extreme temperatures' impact on rice, with the hope that new techniques will evolve to mitigate or escape the most detrimental pathways of influence. Evolving such mechanisms might facilitate neoteric climate smart cropping systems or cultivars to precisely quantify extreme temperatures-induced variability and improve sustainability to ensure food security in future climate warming.

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