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# Effect of Irrigating Cooler Water (ICWr) on The Canopy Temperature of Japonica Rice Cultivars Himenorin and Nikomaru

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## ABSTRACT

The canopy temperature of rice is a critical concern due to rising air temperatures and the increasing risk of heat damage. In this study, we investigated the canopy temperature difference (CTd) and canopy temperature depression (CTD) in the Japonica rice cultivars 'Himenorin' (HR) and 'Nikomaru' (NM). Additionally, we examined the effect of irrigating cooler water (ICWr) on canopy temperature, particularly its impact on CTD reduction, compared to a control plot. The results showed that CTd in HR was lower than in NM. Furthermore, CTD reached 2.23 °C in HR and 2.35 °C in NM under shallower ponding conditions. ICWr effectively reduced the canopy temperature in both cultivars and decreased CTD to a negative value. These findings highlight that ICWr can mitigate canopy temperature increases under more intense solar radiation and high air temperatures. Therefore, implementing ICWr in rice fields may serve as a potential countermeasure to reduce heat damage in rice by lowering canopy temperature. Further research is necessary to elucidate the underlying mechanisms and enhance strategies for mitigating heat exposure, ensuring rice resilience and sustainability in a changing climate.

## Introduction

High air temperature (Ta) during the grain-filling stage of rice (*Oryza sativa* L.), including the periods before heading, flowering, and the milky stage, affects both the yield quantity and quality. Additionally, global temperatures are projected to increase by 1.5 to 2.0 °C during the 21st century [1]. Furthermore, high temperatures impair rice growth and productivity by negatively affecting pollen viability, filled grain percentage, and 1,000-grain weight [2]. Wang et al. [3] reported that elevated temperatures reduce leaf photosynthesis by 1.7–16.6%. Moreover, warming decreases stomatal conductance during the milky and mature stages, leading to stomatal limitations in photosynthesis. Warmer temperatures are a key factor in yield reduction, primarily because of their adverse effects on spikelet fertility and number [4].

High Ta also influenced the canopy temperature of rice. Yoshimoto et al. [5] confirmed that canopy and panicle transpiration, along with the resulting evaporative cooling, significantly affect the temperature gap between ambient air and panicles. Furthermore, as panicle temperatures increase, the risk of heat-induced spikelet sterility increases [5]. Additionally, Korres et al. [6] reported that the combined effects of drought and heat stress during flowering reduced plant height, biomass, and yield. Similarly, low temperatures can negatively impact yield in the same way as high temperatures [7]. However, the interaction between temperature and rice growth largely depends on seasonal temperature variations [8].

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Several studies have examined the relationship between the canopy temperature and crop water management. Agronomically, Jiang et al. [9] reported that the canopy temperature did not significantly differ among nitrogen treatments between the milky and waxy stages. Additionally, canopy temperature is associated with plant traits, including shoot weight, plant water content, net photosynthesis, stomatal conductance, transpiration rate, and leaf stomatal area [9]. Furthermore, applying nitrogen fertilizer at the heading stage effectively mitigates the adverse effects of high temperatures by delaying significant physiological changes, thereby compensating for the deterioration of rice quality caused by elevated temperatures.

In terms of water management, Wang et al. [10] demonstrated that maintaining a 15 cm water depth can lower leaf and panicle temperatures in the Japonica rice cultivars 'Akitakomachi' and 'Nikomaru' under conditions of high solar radiation, elevated air temperature, and low relative humidity compared to conventional and shallower water-depth plots. Nishida et al. [11] investigated the effect of continuous irrigation with running water in rice fields and found that the cooling effect was most effective under weak wind conditions and at night. Similarly, Zang et al. [12] reported that alternate wetting and moderate soil drying increased the accumulation of non-structural carbohydrates in stems before heading, thereby enhancing grain filling. Shi et al. [13] compared two irrigation treatments: (i) below-ground water with a cooler temperature and (ii) pond water with a relatively higher water temperature. Their findings indicate that irrigation with cooler below-ground water did not significantly mitigate yield loss or improve grain quality.

Farmers typically irrigate the rice fields in the morning. However, under intense solar radiation, the temperature of ponded water in rice fields increases, thereby influencing the canopy temperature. In this study, we introduced irrigating cooler water (ICWr) in the afternoon as a novel countermeasure to reduce rice canopy temperature. Our findings highlight that afternoon ICWr can immediately lower the canopy temperature, mitigating heat stress in rice. Additionally, higher grain yields have been observed in genotypes with cooler canopies [14]. Furthermore, a lower canopy temperature relative to air temperature suggests that rice has a partial self-protection mechanism against heat damage [15].

In this study, we examined the effect of ICWr on the canopy temperature of Japonica rice cultivars 'Nikomaru' and 'Himenorin'. Previous research has shown that the stomatal conductance (gs) of 'Himenorin' is significantly higher than that of 'Nikomaru' [16], which may contribute to enhanced transpiration, thereby moderating canopy thermal conditions and supporting a higher photosynthetic rate. This study aimed (1) to analyze canopy temperature (Tc), canopy temperature depression (CTD) in both 'Himenorin' and 'Nikomaru', and the canopy temperature difference (CTd) between the two cultivars, and (2) to compare the differences in Tc and CTD between 'Himenorin' and 'Nikomaru' in irrigated plots versus control plots following ICWr application.

## Materials and Methods

The experiment was conducted at the Ehime University Senior High School Field (33°50'15.8" N, 132°47'35.0" E) in Matsuyama, Ehime, Japan, from May to October 2023. The Japonica rice cultivars, 'Himenorin' (HR) and 'Nikomaru' (NM) were sown on May 15 and transplanted on June 13. Each cultivar was transplanted into two 155 × 155 cm plots with a planting distance of 25 × 25 cm (Figure 1). Each plot contained 36 hills with three seedlings per hill. Each cultivar plot was divided into two subplots: a control plot and an irrigated plot, both of which were surrounded by a plastic barrier (*Nami-ita*). The control plots consisted of HR1 (Himenorin) and NM1 (Nikomaru), whereas the irrigated plots consisted of HR2 and NM2. The water level in all the plots was maintained at a depth of 2 cm every morning. Irrigating cooler water (ICWr) was conducted on August 28, September 2, and September 3, 2023, at approximately 14:00 JST. Cooler water (25.0–26.0 °C) was drawn from the tertiary canal near the rice plots and added to the irrigated plots to increase the water level to 10 cm on August 28 and September 2, 2023. On September 3, 2023, the treatment was reversed; the irrigated plots became control plots, and the control plots became irrigated plots.

The Tc was analyzed using thermal infrared (TIR) images captured by an unmanned aerial vehicle (UAV), the Parrot Anafi Thermal (ANAFI, PARROT, USA), equipped with a Microbolometer FLIR Lepton 3.5 (radiometric) thermal camera sensor. The UAV was flown at a height of 10 m above the plots, and Tc measurements were taken in the afternoon, from August 13 to September 13, 2023. During ICWr application, TIR images were captured periodically: before irrigation, immediately after irrigation, and at 15, 30, 60, and 120 min post-irrigation. The images were processed using FLIR tools for initial data analysis. Thermal data were averaged from three images covering 70% of the area in each plot, with three spot measurements placed in the middle of each plot. The CTD was calculated using Equation (1).

$$CTD = Tc - Ta \quad (1)$$

where Ta denotes the ambient air temperature. The CTd between the two cultivars was calculated as expressed in Equation (2).

$$CTd = Tc\_HR - Tc\_NM \quad (2)$$

where Tc_HR represents the canopy temperature of HR and Tc_NM represents the canopy temperature of NM, both expressed in degrees Celcius (°C).

Water temperature (Tw) was measured using a soil water content and temperature sensor (5TE, Meter, USA). Precipitation (P) and wind speed (u) were recorded at a weather station (Atmos 41, Meter, USA). Data from Atmos 41 and 5TE were automatically collected using a data logger (ZL6 and EM50, Meter, USA) and averaged every minute. Air temperature (Ta) and relative humidity (RH) were measured using a Vaisala ventilated system (HMP 155, Vaisala, Finland) mounted at a height of 2 m. Solar radiation (St) was measured using a net radiometer (CNR4, Kipp & Zonnen, Netherland) mounted at 1.2 m, then adjusted to 1.5 m after September 4, 2023, to account for increasing plant height. Data from the Vaisala system and CNR4 were automatically recorded every second, averaged, and logged every minute using a data logger (CR1000, Campbell, USA).


**Figure 1.** Aerial view of the rice research field at Ehime University Senior High School. The solid red lines indicate the Nami-ita barriers separating the control and ICWr plots. Water levels in all plots were maintained at 2 cm, except during the ICWr experiment when the water level in the ICWr plots was increased to 10 cm.

## Results

### Meteorological Data and Phenology Events

The meteorological data recorded during the experiment are presented in Table 1, while the phenology events of HR and NM are summarized in Table 2. Hourly meteorological data from the experiment were reported in a separate study [17]. The maximum solar radiation (St) recorded in June, July, August, and September was 1,218, 1,230, 1,259, and 1,274 W $m^{-2}$, respectively.

The maximum and minimum hourly Ta recorded were 34.50 °C and 23.35 °C in August and 34.41 °C and 21.70 °C in September, respectively. Additionally, Ta exceeded 35.0 °C on July 15, August 6, and September 4, reaching 35.64 °C, 35.03 °C, and 35.23 °C, respectively. Ta in August and September 2023 was slightly high for optimal rice growth, as the heading to milky stages typically occur during this period [18]. Exposure to elevated Ta during ripening can negatively affect rice production [17,19]. In Japan, Ta usually decreases gradually during the fall, beginning in September. However, in the summer of 2023, Ta remained high even in September, influenced by several factors, including a heatwave from the Pacific Ocean and a typhoon in August, which transported warm air masses northward at a slow pace. This phenomenon is classified as an extreme summer heat event in Japan [20]. As shown in Table 2, panicle emergence of HR and NM began in August, followed by the heading stage at the end of August. The rice was harvested on October 2, 2023 (111 DAT). The heading, flowering, and milky stages, which occurred in August and September, were likely influenced by high Ta.

**Table 1**. Monthly total precipitation (P) and monthly averages of solar radiation (St), air temperature (Ta), relative humidity (RH), and wind speed (u) in the rice fields. Data were collected from June 20 to September 30, 2023.

| No. | Meteorological parameters | 2023 | | | |
|---|---|---|---|---|---|
| | | Jun | Jul | Aug | Sep |
| 1 | P (mm) | 129.6 | 304.3 | 91.5 | 8.5 |
| 2 | St (W $m^{-2}$) | 173.80 | 213.29 | 209.36 | 184.87 |
| 3 | Ta (°C) | 26.40 | 27.37 | 28.31 | 26.76 |
| 4 | RH (%) | 76.10 | 75.89 | 76.36 | 74.26 |
| 5 | u (m $s^{-1}$) | 1.1 | 1.1 | 0.9 | 0.7 |

**Table 2**. Phenological events in rice during the cultivation period of 2023.

| No. | Events | NM | | HR | |
|---|---|---|---|---|---|
| | | Date | DAT* | Date | DAT* |
| 1 | Transplanting | 13-Jun | 0 | 13-Jun | 0 |
| 2 | Flag leaf initiation | 10-Aug | 58 | 16-Aug | 64 |
| 3 | Flag leaf fully extended | 16-Aug | 64 | 19-Aug | 67 |
| 4 | Panicle emergence | 22-Aug | 70 | 25-Aug | 73 |
| 5 | Heading | 26-Aug | 74 | 29-Aug | 77 |
| 6 | Flowering initiation | 27-Aug | 75 | 30-Aug | 78 |
| 7 | Full bloom 100% | 30-Aug | 78 | 2-Sep | 81 |
| 8 | Milky stage 100% | 2-Sep | 81 | 5-Sep | 84 |
| 9 | Harvest | 2-Oct | 111 | 2-Oct | 111 |

* DAT refers to days after transplantation.

**Canopy Temperature (Tc), Canopy Temperature Depression (CTD), and Canopy Temperature Differences (CTd) of 'Himenorin' (HR) and 'Nikomaru' (NM)**

Canopy temperature (Tc) variations ranged from 30.20 to 34.40 °C in HR and 30.33 to 34.53 °C in NM on clear days, from the pre-heading to the post-milky stage. Variations in CTD for HR and NM and CTd between HR and NM are presented in Figure 2 and 3, respectively. Figure 2 shows that the CTD of HR was slightly lower than that of NM, with values ranging from –2.11 to 2.35 °C in both cultivars. Additionally, on clear days, the CTD ranged from 0.31 to 2.23 °C in HR and from 0.45 to 2.35 °C in NM during the measurement period. However, CTD decreased on cloudy days.

Figure 3 illustrates the CTd between HR and NM, calculated as CTd = Tc_HR – Tc_NM, where Tc_HR and Tc_NM represent the canopy temperatures of HR and NM, respectively. The Tc in HR was 0.07 °C lower than NM on September 2 and 0.32 °C lower on August 13. Despite phenological differences between genotypes (Table 2) under the same environmental conditions, Tc in HR remained slightly lower than in NM. The highest CTD of HR and NM was recorded on September 3, 2023, reaching 2.23 °C in HR and 2.35 °C in NM. Additionally, we observed that the CTD had positive values on clear days but negative values on cloudy days.

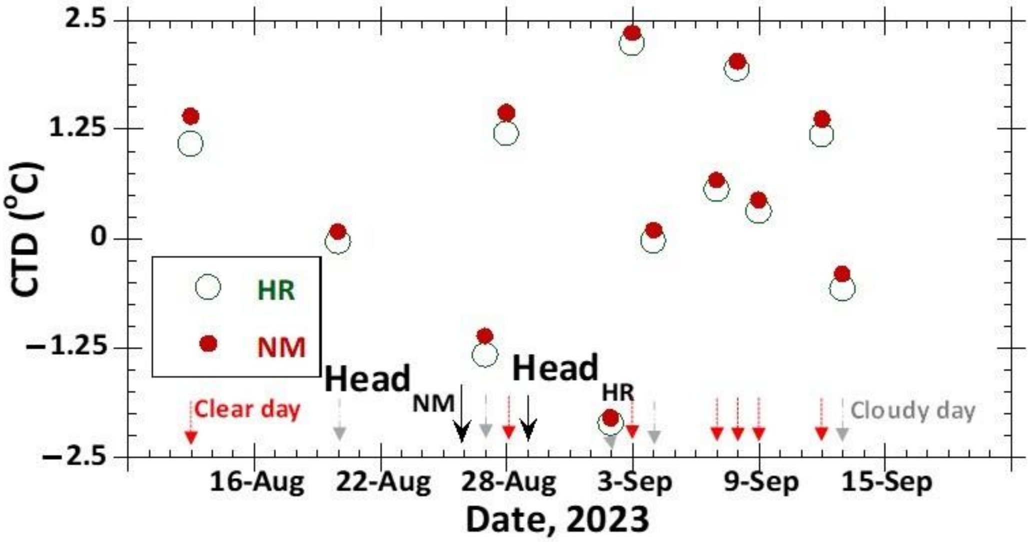


**Figure 2**. Canopy temperature depression (CTD), calculated as CTD = Tc − Ta, for 'Himenorin' (HR) and 'Nikomaru' (NM). The green circles represent the CTD of HR, whereas the red circles represent the CTD of NM.

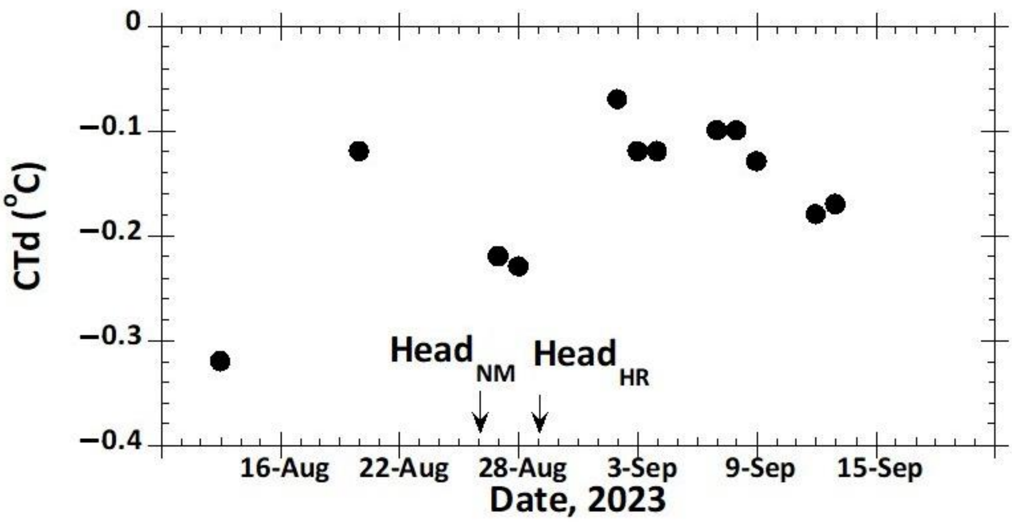


**Figure 3**. Canopy temperature difference (CTd), calculated as CTd = Tc_HR – Tc_NM, between HR and NM.

**Water Temperature in The Rice Field**

The ICWr was applied at approximately 14:00 JST on August 28, September 2, and September 3, 2023. Prior to the ICWr application, the water level in both plots was maintained at a depth of 2 cm in the morning. Following ICWr application, the Tw in the irrigated plot decreased rapidly after introduction of cooler water from the tertiary canal. Figure 4 illustrates the temporal variations in Tw in both the irrigated and control plots. ICWr was applied to HR2 and NM2 (Figure 1) on August 28 and September 2 and to HR1 and NM1 on September 3, 2023. Following ICWr application, the Tw in the irrigated plot decreased sharply and remained lower than that in the control plot for up to 210 min. However, after 270 min, the Tw in the irrigated plot exceeded that in the control plot. This increase in Tw may be attributed to the greater heat storage capacity of the deeper water in the irrigated plot compared with the shallower water in the control plot.

Figure 5 presents the thermal images of the rice fields before and after irrigation. Prior to irrigation, Tc in HR was slightly lower than in NM for both plots. Immediately after ICWr application, Tc in the irrigated plots of HR and NM decreased compared to that in the control plots. Fifteen minutes post-irrigation, Tc in the irrigated plots dropped significantly lower than that in the control plots.

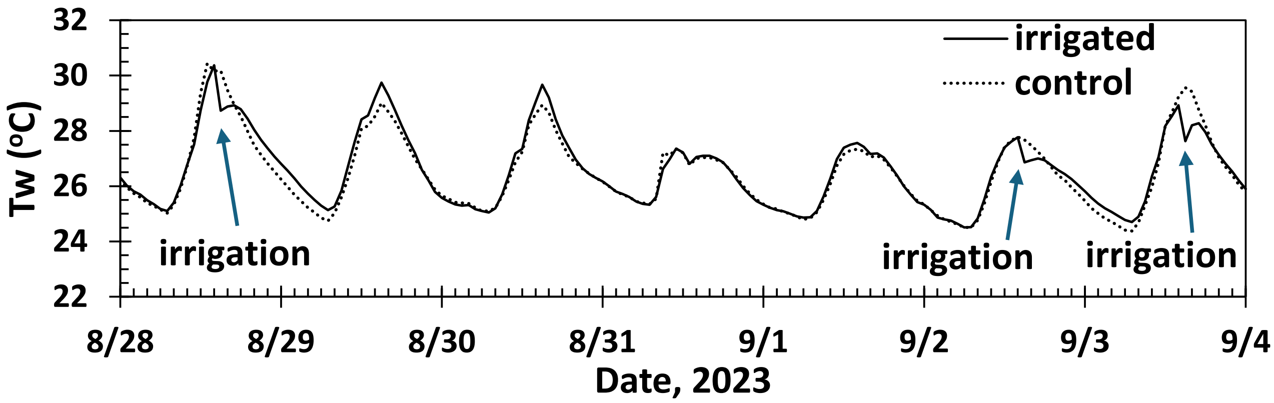


**Figure 4.** Temporal variations in water temperature (Tw) in the irrigated and control plots. The solid and dotted lines with round markers represent the irrigated and control plots, respectively.

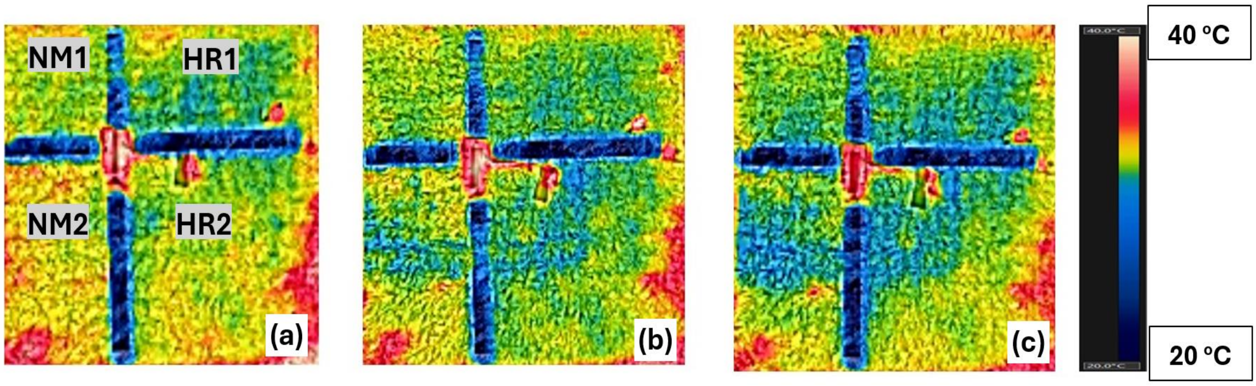


**Figure 5.** Thermal images of the rice field taken on August 28, 2023: (a) before irrigation (13:55 JST), (b) immediately after irrigation (14:22 JST), and (c) 15 min after (14:38) irrigation with cooler water (ICWr). HR1 and NM1 were control plots, whereas HR2 and NM2 were irrigated plots.

**Canopy Temperature (Tc) after ICWr**

Temporal variations in the Tc and CTD after ICWr are presented in Figures 6 and 7, respectively. On August 28, 2023 (a clear day), Figure 6a shows that prior to ICWr (13:55 JST), Tc reached 32.80 °C in HR and 33.03 °C in NM. After ICWr application, Tc in the irrigated plots of HR and NM was lower than that in the control plots, as calculated by Tccontrol – Tcirrigated. Under ambient air temperature (Ta) ranging from 31.37 °C (14:21 JST) to 32.08 °C (14:34 JST), the Tc reduction in the irrigated plots relative to the control plots was 0.53 °C in HR and 0.63 °C in NM immediately after ICWr. Fifteen minutes post-ICWr, Tc in the irrigated plots was lower than that in the control plots by 0.73 °C in HR and 0.67 °C in NM.

On September 2, 2023 (Figure 6b), under ambient air temperature (Ta) ranging from 28.92 °C (14:22 JST) to 29.47 °C (13:57 JST), Tc in the irrigated plot immediately after ICWr was 0.47 °C lower in HR and 0.50 °C lower in NM compared to the control plot. Fifteen minutes post-irrigation, Tc in the irrigated plot remained 0.40 °C lower in HR and 0.37 °C lower in NM. On September 3, 2023 (Figure 6c), under Ta ranging from 31.32 °C (13:55 JST) to 32.85 °C (14:39 JST), Tc in the irrigated plot was 0.87 °C lower in HR and 0.90 °C lower in NM than in the control plot. Fifteen minutes post-irrigation, Tc in the irrigated plot remained 0.80 °C lower in both HR and NM. Thirty minutes after ICWr, Tc was further reduced by 0.87 °C in HR and 0.93 °C in NM. Overall, ICWr reduced Tc by up to 1.83 °C, from 33.7 °C on September 3, 2023. These findings indicate that ICWr effectively reduces canopy temperatures under high air temperatures and strong solar radiation.

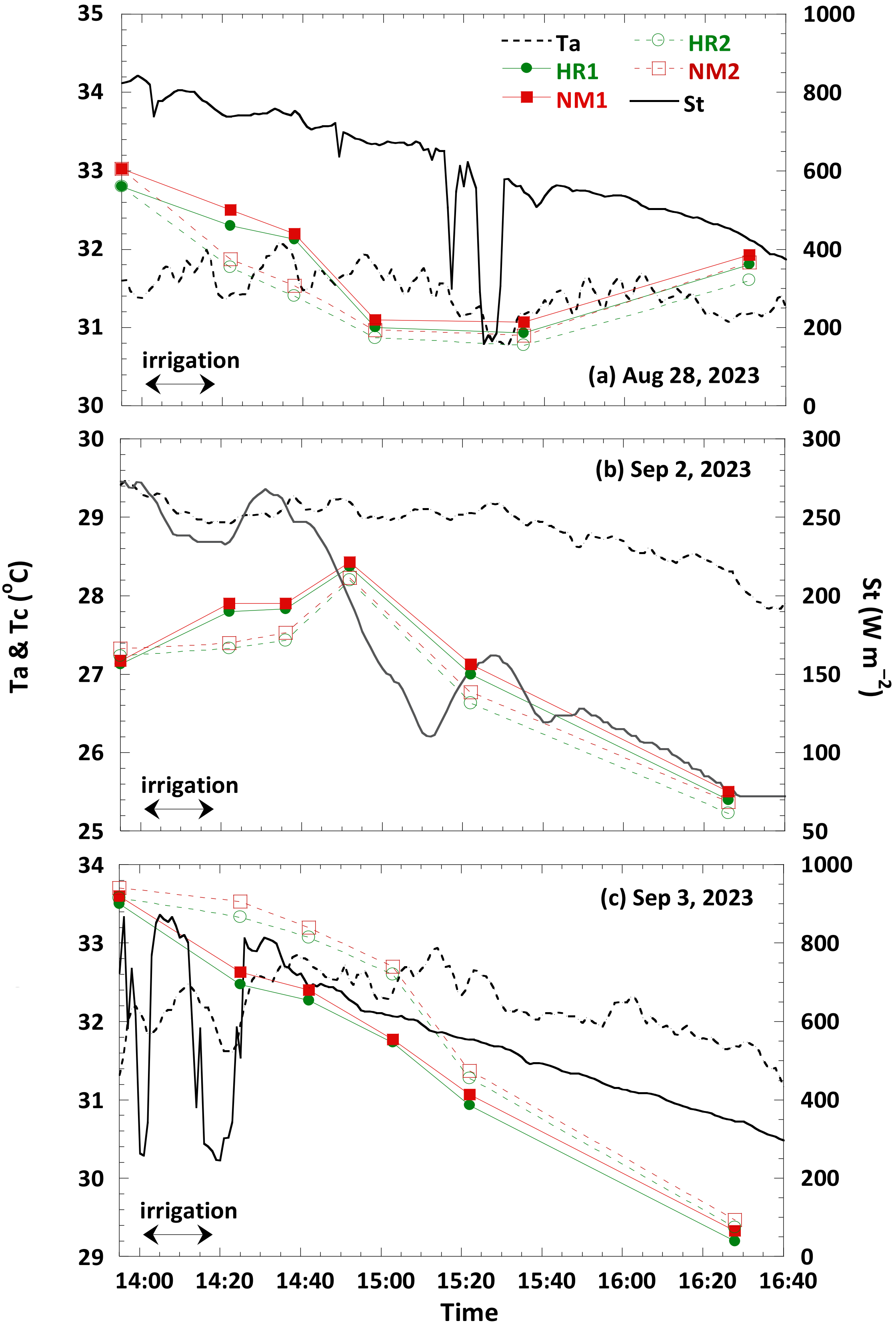


**Figure 6.** Variations in canopy temperature (Tc) of 'Himenorin' (HR) and 'Nikomaru' (NM) after ICWr, along with air temperature (Ta), and solar radiation (St) on (a) August 28, (b) September 2, and (c) September 3, 2023. The green-filled and unfilled circles represent HR1 and HR2, respectively, while the red-filled and unfilled squares denote NM1 and NM2, respectively. ICWr was applied to HR2 and NM2 on August 28 and September 2, while on September 3, 2023, ICWr was applied to HR1 and NM1.

### Canopy Temperature Depression (CTD) after ICWr

Figure 7 illustrates CTD after the ICWr. On August 28, 2023 (Figure 7a), CTD in the irrigated plot decreased to 0.34 °C in HR and 0.44 °C in NM, whereas in the control plot, CTD remained higher at 0.87 °C in HR and 1.07 °C in NM. Fifteen minutes after irrigation, the CTD in the irrigated plot became negative, whereas the control plot maintained a positive CTD. On September 2, 2023 (Figure 7b), the CTD in both plots was negative. The CTD on cloudy days also showed negative values, indicating no temperature depression at the rice canopy.

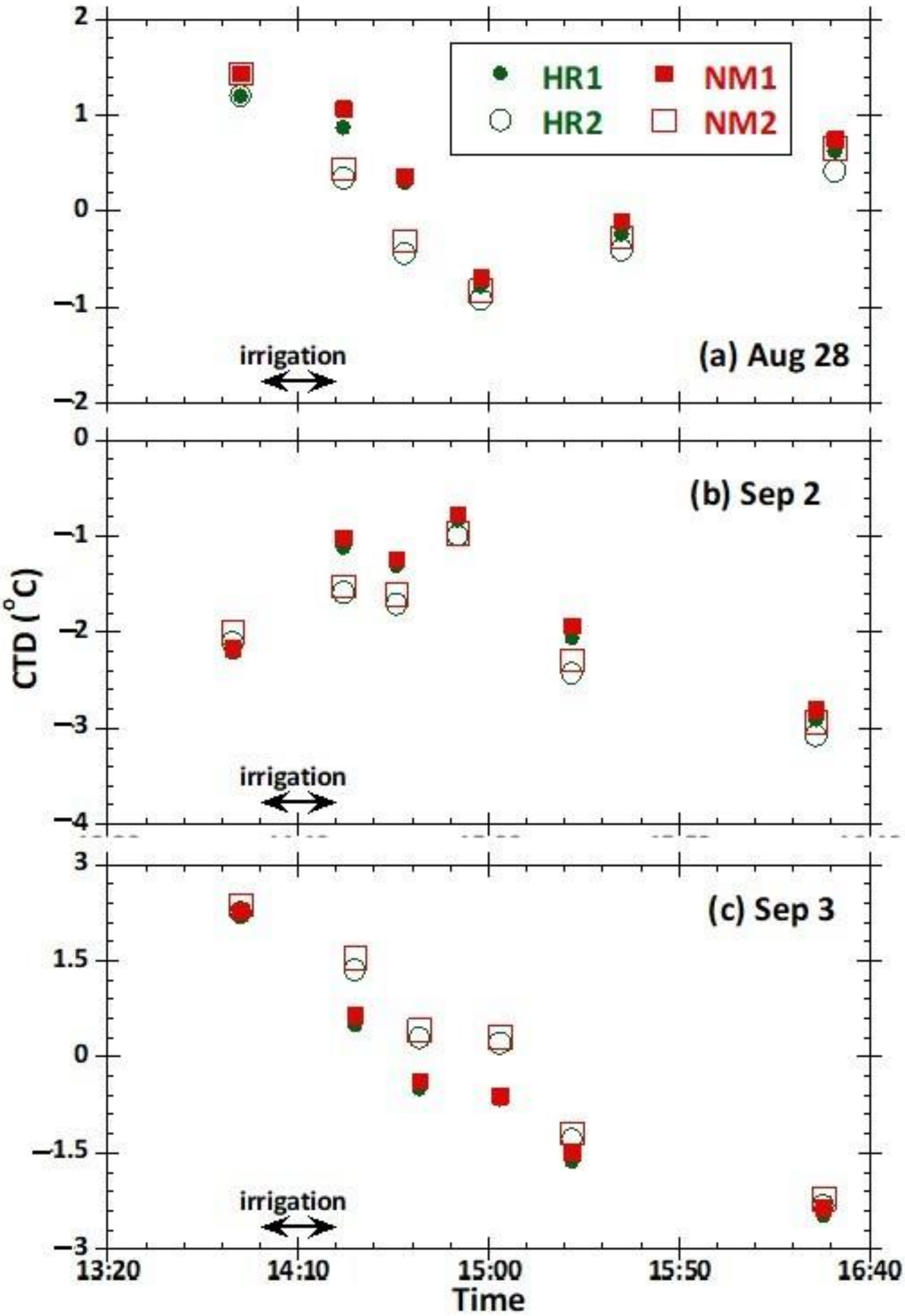


**Figure 7.** Canopy temperature depression (CTD) of 'Himenorin' (HR) and 'Nikomaru' (NM) in the control and irrigated plots on (a) August 28, (b) September 2, and (c) September 3, 2023. The green-filled and unfilled circles represent HR1 and HR2, respectively, while the red-filled and unfilled squares represent NM1 and NM2, respectively. ICWr was applied to HR2 and NM2 on August 28 and September 2, while on September 3, 2023, ICWr was applied to HR1 and NM1.

On September 3, 2023 (Figure 7c), CTD in the irrigated plot decreased to 0.49 °C in HR and 0.65 °C in NM, whereas CTD in the control plot remained higher at 1.35 °C in HR and 1.55 °C in NM. Furthermore, the CTD in the irrigated plot was negative, whereas the CTD in the control plot remained positive. Considering Tc before and after ICWr, the application of ICWr reduced CTD by up to 2.69 °C in HR and up to 2.66 °C in NM, fifteen minutes post-irrigation (Figure 7c) under ambient temperatures ranging from 31.32 to 32.85 °C. These findings indicate that ICWr can reduce the CTD to a negative value within at least 15 minutes after application.

## Discussion

### Effect of Shallower Ponding on Canopy Depression in HR and NM

In our study, CTD in HR and NM rice cultivars under shallower ponding (2 cm depth) was positive on clear days but negative on cloudy days (Figure 2). Under high solar radiation and elevated temperatures [17], the CTD reached 2.23 °C in HR and 2.35 °C in NM on September 3, 2023 (Figure 2). A positive CTD indicates that the Tc is higher than the ambient Ta. However, during the hottest weather of 2023, the CTD in HR and NM was relatively low compared with previous studies [21]. Irsyad et al. [21] reported that CTD in the 'Kosihikari' cultivar reached approximately 2.50 °C under high solar radiation.

In Ghana, CTD can reach up to 5.9 °C during the dry season with flooded irrigation, accompanied by air temperatures of up to 35.0 °C [22]. The relatively low CTD observed in HR and NM in this study is likely attributable to the high stomatal conductance (gs) in these genotypes. Because Tc is fundamentally linked to gs, it is important to recognize that environmental conditions significantly influence both Tc and gs [23]. Oue [16] reported that gs in HR was higher than in NM from pre-flag leaf extension to the maturity stage. This high gs serves as an adaptive mechanism, helping moderate the canopy thermal conditions [23]. Additionally, when comparing high-water ponding to shallower ponding, both HR and NM demonstrated higher yield potentials under deeper water conditions [17,24]. Notably, NM is a Japanese cultivar that is unaffected by elevated ozone and temperature in terms of amylose content [25]. However, lower amylose content is associated with an increased proportion of chalky grains.

Karwa et al. [26] highlighted the relationship between induced polyamines and antioxidant enzyme activity in rice under heat stress, demonstrating that these factors contribute to reduced oxidative stress, improved pollen viability, and enhanced spikelet fertility under challenging conditions. Additionally, high daytime temperatures during the early growth period can disrupt tillering formation, ultimately leading to lower yields [27]. Heat-tolerant genotypes exhibit different mechanisms in response to high day and night temperatures. Notably, changes in enzymatic activity do not hinder starch accumulation at high nighttime temperatures, provided sufficient assimilates are available. In contrast, high daytime temperatures negatively impact both sucrose supply and its conversion to starch, and the combined effects of high daytime and nighttime temperatures exacerbate these challenges [13].

### Effect of ICWr on Tw, Tc, and CTD

Tc decreased sharply when cooler water was applied to the irrigated plot (Figure 4). Our findings indicate that ICWr in the afternoon effectively reduced Tw in the irrigated plot compared to the control plot. Figure 5 illustrates how Tw influences Tc over time following the application of ICWr. Tsujimoto et al. [22] reported that the gap between Tc and Ta was smaller in the morning, gradually increased in the afternoon, and peaked at sunset. In our study, ICWr in the afternoon reduced Tc in HR from 33.50 to 32.47 °C immediately after ICWr application (Figure 6c). Additionally, applying ICWr in the afternoon extended the cooling effect on Tc in the irrigated plot by up to three hours, compared to the control plot. Typically, Tc is influenced by heat exchange with the atmosphere and water surface, particularly through the long-wave radiation flux from paddy water, which is affected by cooler water [11]. When cooler water was added to the rice field, Tc was immediately influenced by Tw, leading to a decrease in Tc in the irrigated plot, which in turn reduced the CTD.

Our findings indicate that ICWr in the afternoon eliminated CTD for at least 30 min after ICWr application. Furthermore, increased temperature combined with decreased humidity leads to significant canopy temperature depression in rice and vice versa [28]. In addition, high canopy humidity can negatively affect rice quality [29]. Although ICWr effectively reduces rice canopy temperature, it is important to acknowledge its potential limitations. Although ICWr has shown effectiveness in HR and NM, further research is needed to assess its impact on other rice cultivars. Additionally, the applicability of ICWr in water-scarce regions should be considered because water availability may limit its feasibility. Integrating ICWr with other crop management strategies, such as nitrogen fertilizer application, may further enhance its effectiveness [30].

Further investigation is essential to unravel the underlying mechanisms and develop strategies to mitigate heat exposure in rice, thereby ensuring its resilience and sustainability in a changing climate.

A decrease in Tc is particularly crucial, as rice cultivars exposed to temperatures exceeding the spikelet threshold of 33.7 °C experience reduced spikelet fertility, grain number, and overall yield under elevated daytime temperatures [19]. Wang et al. [31] reported that elevated temperatures reduced yield due to a decline in the percentage of filled grains and 1000-grain weight. Similarly, Shi et al. [32] found that heat stress significantly reduced grain yield by 33 to 43%, with additional reductions in panicles per square meter (9 to 10%), spikelets per square meter (15 to 22%), grain filling percentage (13 to 26%), and 1000-grain weight (3 to 5%). Furthermore, heat stress increases chalkiness and protein content, further affecting the grain quality [32]. Sawada et al. [25] demonstrated the impact of elevated ozone and air temperature on grain quality. Their findings revealed that rice cultivars with lower amylose contents exhibited a decline in grain appearance quality, which was further exacerbated by higher temperatures. Beyond reducing yields, high temperatures also pose a risk to human consumption by increasing inorganic arsenic concentrations. The arsenic levels reached 55.3 mg/L, which was significantly higher ($P < 0.05$) than that in the control plot (48.1 mg/L) [33].

In addition to water management, agronomic practices that enhance nitrogen levels have been shown to mitigate the impact of elevated temperatures on rice fields [30,34]. Shen et al. [30] reported that nitrogen application improved rice production under warming conditions by increasing plant nitrogen content, biomass, harvest index, and soil fertility. Furthermore, Tang et al. [34] found that applying nitrogen fertilizer during the heading stage effectively delayed the increase in total starch, amylose, and amylopectin accumulation induced by high temperatures. This application also reduced the starch particle size, chain length distribution, and crystal structure alterations, thereby compensating for the decline in rice quality caused by elevated temperatures. Jiang et al. [9] compared Tc under different nitrogen fertilizer doses in rice fields. Their findings indicated that rice plants with high nitrogen levels exhibited significantly lower Tc during the tillering, jointing, booting, and heading stages than those receiving lower nitrogen treatments. However, no significant differences in Tc were observed between nitrogen treatments during the milky and waxy stages [9]. Additionally, Namikawa et al. [35] emphasized that crop nitrogen content at the heading stage strongly influences grain yield, with its effect being more pronounced in canopy cover than in spikelet density.

Recent studies have modeled the effects of elevated temperatures and increased $CO_2$ concentrations on rice production. In Japan, nationwide rice production is projected to decline by up to 28%, while the percentage of white chalky grains could increase by as much as 16%, particularly under the RCP8.5 [36]. In Southeastern China [4], changes in $CO_2$ levels and temperature could lead to a mean rice yield reduction of 3.5% and 9.4% under RCP4.5, and 10.5% and 47.9% under RCP8.5, respectively. The primary factor contributing to yield reduction in this region is warmer temperatures, which negatively affect spikelet fertility and spikelet number [4]. In Vietnam, rice yield is projected to decline by 5.5 to 8.5% if $CO_2$ fertilization is not considered. However, under RCP4.5 and RCP8.5, the yield could increase by up to 23% when $CO_2$ fertilization effects were accounted for [37]. Additionally, Jing et al. [8] reported that elevated temperatures and $CO_2$ concentrations increased the surface area of starch granules and the proportion of large starch granules, which may affect the texture and taste of cooked rice.

## Conclusions

This study analyzed Tc, CTD, and CTd in HR and NM under extremely hot conditions in Japan. On clear days, Tc ranged from 30.20 to 34.40 °C in HR and from 30.33 to 34.53 °C in NM. We found that the CTD in HR and NM was positive on clear days and negative on cloudy days. Specifically, the CTD ranged from 0.31 to 2.23 °C in HR and from 0.45 to 2.35 °C in NM. Additionally, the CTd in HR was consistently 0.07 to 0.32 °C lower than in NM. To mitigate elevated Tc in rice, ICWr in the afternoon was successfully implemented. Our findings demonstrate that ICWr effectively reduces Tc at high air temperatures and strong solar radiation. This method lowered Tc in HR by 0.53 to 0.87 °C and in NM by 0.63 to 0.90 °C compared to the control plot immediately after irrigation. Furthermore, under ambient temperatures ranging from 31.32 to 32.85 °C, ICWr reduced CTD by up to 2.69 °C in HR and up to 2.66 °C in NM 15 min post-irrigation, resulting in a negative CTD in the irrigated plot. At the same time, CTD remained positive in the control plot. Applying ICWr in the afternoon extended the reduction in Tc for up to three hours compared with the control plot, making it a promising countermeasure to mitigate heat stress in rice. Also, cultivar selection is crucial in heat stress management, as HR consistently exhibited a lower Tc than NM did. However, further investigation is essential to unravel the underlying mechanisms and enhance strategies for mitigating heat exposure, ensuring rice resilience, and sustainability in a changing climate.

## Author Contributions

**NI:** Conceptualization, Methodology, Investigation, Forma Analysis, Visualization, Writing – original draft; **TY:** Conceptualization, Methodology, investigation; **AU:** Methodology, Investigation; **HO:** Conceptualization, Resources, Supervision, Validation, Writing - Review & Editing.

## Conflicts of interest

There are no conflicts to declare.

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## References

1. IPCC (Intergovernmental Panel on Climate Change). *Climate Change 2022: Impacts, Adaptaion and Vulnerability*, Portner, H.O., Roberts, D., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegria, A., Craig, M., Langsdorf, S., Lozchke, S., Moller, V., et al.; Cambridge University Press: Cambridge, UK and New York, USA, 2022;
2. Ahmed, S.; Ahmed, S.F.; Biswas, A.; Sultana, A.; Issak, M. Salicylic acid and chitosan mitigate high temperature stress of rice via growth improvement, physio-biochemical adjustments and enhanced antioxidant activity. *Plant Stress* **2024**, *11*, 100343, doi:doi.org/10.1016/j.stress.2023.100343.
3. Wang, B.; Caib, W.; Lia, J.; Wana, Y.; Lia, Y.; Guod, C.; Wilkesa, A.; Youa, S.; Qina, X.; Gaoa, Q.; et al. Leaf photosynthesis and stomatal conductance acclimate to elevated [$CO_2$] and temperature thus increasing dry matter productivity in a double rice cropping system. *Field Crop Research* **2020**, *248*, 107735.
4. Wang, W.; Yuan, S.; Wu, C.; Yang, S.; Zhang, W.; Xu, Y.; Gu, J.; Zhang, H.; Wang, Z.; Yang, J.; et al. Field experiments and model simulation based evaluation of rice yield response to projected climate change in Southeastern China. *Science of the Total Environment* **2021**, *761*, 143206, doi:doi.org/10.1016/j.scitotenv.2020.143206.
5. Yoshimoto, M.; Fukuoka, M.; Tsujimoto, Y.; Matsui, T.; Kobayasi, K.; Saito, K.; van Oort, P.A.J.; Inusah, B.I.Y.; Vijayalakshmi, C.; Vijayalakshmi, D.; et al. Monitoring canopy micrometeorology in diverse climates to improve the prediction of heat-induced spikelet sterility in rice under climate change. *Agricultural and Forest Meteorology* **2022**, *316*, 108860, doi:doi.org/10.1016/j.agrformet.2022.108860.
6. Korres, N.E.; Norsworthy, J.K.; Burgos, N.R.; Oosterhuis, D.M. Temperature and drought impacts on rice production: An agronomic perspective regarding short- and long-term adaptation measures. *Water Resources and Rural Development* **2017**, *9*, 12–27.
7. Kang, M.; Wang, S.; Xu, Z.; Xu, C.; An, J.; Zhang, Y.; Zeng, Y.; Ali, I.; Tang, L.; Xiao, L.; et al. Simulating the effects of low-temperature stress during flowering stage on leaf-level photosynthesis with current rice models. *Agricultural and Forest Meteorology* **2024**, *354*, 110087.
8. Jing, L.; Chen, C.; Hu, S.; Dong, S.; Pan, Y.; Wang, Y.; Lai, S.; Wang, Y.; Yang, L. Effects of elevated atmosphere $CO_2$ and temperature on the morphology, structure and thermal properties of starch granules and their relationship to cooked rice quality. *Food Hydrocolloids* **2021**, *112*, 106360.
9. Jiang, M.; Chen, Z.; Li, Y.; Huang, X.; Huang, L.; Huo, Z. Rice canopy temperature is affected by nitrogen fertilizer. *Journal of Integrative Agriculture* **2024**, *23*, 824–835, doi:10.1016/j.jia.2023.05.005.
10. Wang, Y.; Oue, H.; Limin, S.G.; Laban, S. Effects of water ponding on decreasing leaf and panicle temperature in rice paddy fields. *Jurnal Teknologi* **2015**, *76*, 131–137, doi:10.11113/jt.v76.5965.
11. Nishida, K.; Yoshida, S.; Shiozawa, S. Theoretical analysis of the effects of irrigation rate and paddy water depth on water and leaf temperatures in a paddy field continuously irrigated with running water. *Agricultural Water Management* **2018**, *198*, 10–18, doi:doi.org/10.1016/j.agwat.2017.11.021.

12. Zang, Y.; Wu, G.; Li, Q.; Xu, Y.; Xue, M.; Chen, X.; Wei, H.; Zhang, W.; Zhang, H.; Liu, L.; et al. Irrigation regimes modulate non-structural carbohydrate remobilization and improve grain filling in rice (*Oryza sativa* L.) by regulating starch metabolism. *Journal of Integrative Agriculture* **2024**, *23*, 1507–1522, doi:10.1016/j.jia.2023.05.012.
13. Shi, W.; Yin, X.; Struik, P.C.; Solis, C.; Xie, F.; Schmidt, R.C.; Huang, M.; Zou, Y.; Ye, C.; Jagadish, S.V.K. High day- and night-time temperatures affect grain growth dynamics in contrasting rice genotypes. *Journal of Experimental Botany* **2017**, *68*, 5233–5245, doi:10.1093/jxb/erx344.
14. Vinarao, R.; Proud, C.; Snell, P.; Fukai, S.; Mitchell, J. Narrow root cone angle promotes deeper rooting, cooler canopy temperatures and higher grain yield in a rice (*Oryza sativa* L.) recombinant inbred line population grown under different water availabilities in aerobic production systems. *Field Crops Research* **2023**, *299*, 108989, doi:doi.org/10.1016/j.fcr.2023.108989.
15. Liu, M.; Zhou, Y.; Sun, J.; Mao, F.; Yao, Q.; Li, B.; Wang, Y.; Gao, Y.; Dong, X.; Liao, S.; et al. From the floret to the canopy: High temperature tolerance during flowering. *Plant Communications* **2023**, *4*, 100629, doi:doi.org/10.1016/j.xplc.2023.100629.
16. Oue, H. Comparisons of the stomatal conductance and electron transport rate of three Japanese rice cultivars including Himenorin in Ehime Prefecture. *Journal of Agricultural Meteorology* **2023**, *79*, 77–84, doi:10.2480/agrmet.D-22-00025.
17. Yuliawan, T.; Ichwan N.; Ukpoju, A.; Irsyad, F.; Oue, H. Comparisons of growth, yield, and meteorological properties of rice canopy under double-row (*jajar legowo* and *jejer manten*) and tile transplanting systems. *Journal of Natural Resources and Environmental Management* **2024**, *14*, 325–340, doi:10.29244/jpsl.14.2.325.
18. Yoshida, S. *Fundamentals of Rice Crop Science*; International Research Institute: Los Banos, Philippines, 1981;
19. Pasuquin, E.M.; Eberbach, P.L.; Hasegawa, T.; Lafarge, T.; Harnpichitvitaya, D.; Wade, L.J. Response to elevated daytime air and canopy temperature during panicle development in four rice genotypes under paddy conditions in large field chambers. *Crop and Environment* **2023**, *2*, 147–156, doi:10.1016/j.crope.2023.04.004.
20. TCC (Tokyo Climate Center). Climate characteristics and factors behind heavy rainfall during the Baiu season in 2023 and extremely high temperatures from mid-July onward. 2023. https://www.data.jma.go.jp/tcc/data/news/press_20230928.pdf (accessed on 16 May 2024).
21. Irsyad, F.; Oue,H.; Mon, M.M. Monitoring responses of NDVI and canopy temperature in a rice field to soil water and meteorological conditions. *IOP Conf. Series: Earth and Environmental Science* **2022**, *1059*, 012037, doi:10.1088/1755-1315/1059/1/012037.
22. Tsujimoto, Y.; Fuseini, A.; Inusah, B.I.Y.; Dogbe, W.; Yoshimoto, M.; Fukuoka, M. Different effects of water-saving management on canopy microclimate, spikelet sterility, and rice yield in the dry and wet seasons of the sub-humid tropics in northern Ghana. *Field Crops Research* **2021**, *260*, 107978, doi:doi.org/10.1016/j.fcr.2020.107978.
23. Fukai, S.; Mitchell, J. Role of canopy temperature depression in rice. *Crop and Environment* **2022**, *1*, 198–213, doi:10.1016/j.crope.2022.09.001.
24. Ichwan, N.; Oue, H.; Yuliawan, T.; Augustine, U. Yield and biomass under the different water levels on three Japonica rice cultivars. *IOP Conf. Series: Earth and Environmental Science* **2023**, *1182*, 012038, doi:10.1088/1735-1315/1182/1/012038.
25. Sawada, H.; Kohno, Y.; Tamaoki, M. Combined Effects of Elevated Ozone and Air Temperature on Grain Quality in 17 Cultivars of Rice. *Journal of Japan Society for Atmospheric Environment* **2017,** *52*, 59–67, doi:doi.org/10.11298/taiki.52.59.
26. Karwa, S.; Bahuguna, R.N.; Chaturvedi, A.K.; Maurya, S.; Arya, S.S.; Chinnusamy, V.; Pal, M. Phenotyping and characterization of heat stress tolerance at reproductive stage in rice (*Oryza sativa* L.). *Acta Physiologiae Plantarum* **2020**, *42*, 29, doi:10.1007/s11738-0020-3016-5.
27. Jing, L.; Zhou, N.; Lai, S.; Wang, Y.; Zhu, J.; Wang, Y.; Yang, L. Interactions between elevated atmospheric $CO_2$ and temperature on rice yield are highly dependent on growth season temperature. *Field Crops Research* **2024**, *307*, 109270, doi:doi.org/10.1016/j.fcr.2024.109270.

28. Horie, T. Global warming and rice production in Asia: Modeling, impact prediction and adaptation. *Proceedings of the Japan Academy, Series B* **2019,** *95*, 211–245, doi:doi.org/10.2183/pjab.95.016.
29. Chen, L.; Deng, X.; Duan, H.; Tan, X.; Xie, X.; Pan, X.; Guo, L.; Gao, H.; Wei, H.; Zhang, H.; et al. Water management can alleviate the deterioration of rice quality caused by high canopy humidity. *Agricultural Water Management* **2023**, *289*, 108567, doi:10.1016/j.agwat.2023.108567.
30. Shen, Y.; Xu, L.; Guo, H.; Ismail, H.; Ran, X.; Zhang, C.; Peng, Y.; Zhao, Y.; Liu, W.; Ding, Y.; et al. Mitigating the adverse effect of warming on rice canopy and rhizosphere microbial community by nitrogen application: An approach to counteract future climate change for rice. *Science of the Total Environment* **2023**, *905*, 167151, doi:doi.org/10.1016/j.scitotenv.2023.167151.
31. Wang, B.; Lia, J.; Wana, Y.; Caic, W.; Guod, C.; Youa, S.; Lia, R.; Qina, X.; Gaoa, Q.; Zhoue, S.; et al. Variable effects of 2°C air warming on yield formation under elevated [$CO_2$] in a Chinese double rice cropping system. *Agricultural and Forest Meteorology* **2019**, *278*, 107662, doi:doi.org/10.1016/j.agrformet.2019.107662.
32. Shi, W.; Zhang, X.; Yang, J.; Impa, S.M.; Wang, D.; Lai, Y.; Yang, Z.; Xu, H.; Wu, J.; Zhang, J.; et al. Irrigating cooler water does not reverse high temperature impact on grain yield and quality in hybrid rice. *The Crop Journal* **2023**, *11*, 904–913, doi:10.1016/j.cj.2022.09.006.
33. Dhar, P.; Kobayasi, K.; Ujiie, K.; Adachi, F.; Kasuga, J.; Akahane, I.; Arao, T.; Matsumoto, S. Effect of High Temperature during the Ripening Period on the Arsenic Accumulation in Rice Grain Grown on Uncontaminated Soil with Relatively Low Level of Arsenic. *Journal of the Japanese Society of Agricultural Technology Management* **2022**, *27*, 133–145, doi:doi.org/10.20809/seisan.27.3_133.
34. Tang, S.; Zhanga, H.; Liua, W.; Doua, Z.; Zhoua, Q.; Chena, W.; Wanga, S.; Ding, Y. Nitrogen fertilizer at heading stage effectively compensates for the deterioration of rice quality by affecting the starch-related properties under elevated temperatures. *Food Chemistry* **2019**, *277*, 455–462, doi:doi.org/10.1016/j.foodchem.2018.10.137.
35. Namikawa, M.; Matsunami, T.; Yabiku, T.; Takahashi, T.; Matsunami, M.; Hasegawa, T. Analysis of yield constraints and seasonal solar radiation and temperature limits for stable cultivation of dry direct-seeded rice in northeastern Japan. *Field Crops Research* **2023**, *295*, 108896, doi:doi.org/10.1016/j.fcr.2023.108896.
36. Ishigooka, Y.; Hasegawa, T.; Kuwagata, T.; Nishimori, M.; Wakatsuki, H. Revision of estimates of climate change impacts on rice yield and quality in Japan by considering the combined effects of temperature and $CO_2$ concentration. *Journal of Agricultural Meteorology* **2021**, *77*, 139–149, doi:doi.org/10.2480/agrmet.D-20-00038.
37. Kontgis, C.; Schneidera, A.; Ozdogana, M.; Kucharika, C.; Trie, V.P.D.; Duce, N.H.; Schatz, J. Climate change impacts on rice productivity in the Mekong River Delta. *Applied Geography* **2019**, *102*, 71–83, doi:doi.org/10.1016/j.apgeog.2018.12.004.