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Effects of haze on net photosynthetic rate, stomatal conductance and yield of Malaysian rice (*Oryza sativa* L.) varieties

[Kesan jerebu kepada kadar fotosintesis bersih, konduktans stomata dan hasil varieti padi (*Oryza sativa* L.) Malaysia]

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Abstract

The potential direct effects of haze on net photosynthetic rate and stomatal conductance of several Malaysian rice varieties were investigated during the haze event in March 2014. The haze was at moderate level with Air Pollution Index (API) readings between 50 and 200 (moderate to unhealthy air pollution levels) but it worsened to very unhealthy and hazardous levels at certain areas. The gas exchange measurements were conducted on 60 and 78 days after transplanting on hazy and sunny clear days, respectively. The mean API readings on a hazy day and a clear day were 141 and 47 respectively. Solar radiation showed an average of 22% reduction on a hazy day from 0800 to 1700 h and a 45% reduction at 1430 h. Haze caused 12.9 – 53.2% and 26.1 – 73.8% reduction in net photosynthetic rate and stomatal conductance of rice throughout the day respectively. Net photosynthetic rate was highly correlated to Photosynthetically Active Radiation (PAR) with a regression coefficient (R^2) of 0.77 and 0.89 on clear and hazy days respectively. Haze significantly reduced net photosynthetic rate and stomatal conductance of all rice varieties largely through its effects on solar radiation/PAR reduction. Both net photosynthetic rate and stomatal conductance of all rice varieties generally showed similar responses to haze and there was no outstanding variety that can be considered resistant to the haze and solar radiation reduction. The yield of all rice varieties also showed 10 – 19% reduction as compared to the potential yield. Results indicated that 5 weeks of moderate haze that occurred during the late vegetative and early flowering stage had affected the physiological performance and yield of rice. A longer duration of severe level of haze (API 300 – 800) at flowering, grain filling and ripening stages will probably have greater effects on plant physiological performance and yield of rice.

Keywords: gas exchange measurements, air pollutant index, photosynthetically active radiation, solar radiation, rice yield

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Introduction

Uncontrolled forest fires and agricultural burning in Indonesia and Borneo which produces transboundary smoke haze is an annual phenomenon that causes deterioration in the local air quality in Malaysia (Mahmud 2013). Forest and peatland fires in Selangor, Perak, Pahang, Johor, Kedah, Kelantan and Terengganu also contributed to haze incidents (Department of Environment 2015). With increasing global warming, El Nino phenomenon and widespread incidents of drought, the occurrences of haze are expected to become more frequent as burning of the forest and peat fields turn out to be more rampant (Hawa 2008). Severe smoke haze episodes were recorded in April 1983, August 1990, June 1991, October 1991, August 1994 and March 1998. However, the worst episode occurred in 1997 when nearly the entire country was engulfed by thick haze for almost six months (Jamal et al. 2014). On 23rd September 1997, API reading at Kuching, Sarawak spiked to 839 and was the highest ever recorded in Malaysia (Ahmad et al. 2006). Severe smoke haze episodes also occurred in August 2005, August 2006 and June 2013. On 23 June 2013, the API in Muar, Johor, spiked to 746 which was almost 2.5 times above the minimum range of the hazardous level, thus resulting in the declaration of emergency state in Muar and Ledang of Johor.

Haze is defined as the presence of fine, solid or liquid particles (0.1 – 1.0 μm in diameter) in the air that are dispersed at high concentrations and barely visible to the naked eye (Soleiman et al. 2003). Five major pollutants in the haze are particulate matter, sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and ozone (O_3). Burned biomass contributes to increased aerosol loadings or smoke in the atmosphere (Reid et al. 2013). Atmospheric aerosols in haze directly influence the amount of solar radiation reaching the surface by scattering and absorbing light as it passes through the atmosphere (Greenwald et al. 2006). Field studies have shown that anthropogenic aerosols can reduce solar radiation by as much as 30% on clear days in the agriculturally important Yangtze delta region of China (Xu et al. 2003).

Haze greatly affects solar radiation, temperature and relative humidity resulting in reduced plant photosynthetic activity (Davies and Unam 1999). During the 1997 haze episode, atmospheric concentrations of particulate matter (SO_2, CO, CH_4 and CO_2) and relative humidity were elevated. Photosynthetically Active Radiation (PAR) which is solar radiation utilised by plants and ambient temperature were also reduced by the smoke haze. Despite elevated CO_2 levels, photosynthesis in three tree species (*Durio zibethinus, Dryobalanops rappa* and *Gonystylus bancanus*) were reduced by the smoke haze, both indirectly through reduced PAR levels, elevated aerosol and atmospheric pollutant levels. The level of PAR to which a plant is exposed is positively related to net photosynthetic rate and variation in PAR can therefore have a major effect on plant growth and development (McCree 1981). In the field, the intensity of solar radiation determines the level of PAR to which a crop is exposed, and variation in solar radiation can affect crop yield (Liu and Tollenaar 2009).

Therefore, this study was carried out to determine the effects of haze on net photosynthetic rate, stomatal conductance and yield of several Malaysian rice (*Oryza sativa* L.) varieties during the haze event in March 2014. The effects of haze on Air Pollutant Index, relative humidity, temperature and solar radiation were also investigated.

Materials and methods

Plant preparation and experimental design

Seven Malaysian rice varieties, MR 269, MR 235, MR Q74, MR Q76, MR 219, MR 232 and MR 263 were chosen for this study as they are widely cultivated by paddy farmers in Malaysia. MR 219 and MR 263 were the two most popular varieties planted by farmers between 2011 and 2014 in Peninsular Malaysia (Jabatan Pertanian 2015). Seventeen days old rice seedlings were transplanted into 1 m x 3 m x 30 cm rectangular troughs containing soil from Tanjung Karang paddy field on 15 January 2014 and placed in an open field at MARDI Serdang, Selangor. The plants were fertilised with 120:70:80 $kgha^{-1}$ of N, P_2O_5 and K_2O and harvested for yield (tha^{-1}) at 105 days after transplanting (DAT).

Measurements of leaf gas exchange

All leaf gas exchange and PAR measurements were made with a portable steady-state photosynthesis system (LI-6400XT, LI-COR Biosciences, USA). The measurements were conducted during a hazy day (13 March 2014) and a sunny clear day (1 April 2014) on the same experimental plants. Plants were 60 days old after transplanting on a hazy day and 78 days old on a clear day and at booting and flowering stages depending on the varieties. Measurements were done using a clear leaf chamber, therefore sunlight was the light source for the photosynthesis. The leaf chamber temperature was maintained at 30 °C and the reference CO_2 concentration was 400 ppm ($\mu molmol^{-1}$). Photosynthetically active radiation measurements for photosynthetic rates and stomatal conductance were measured 4 times daily at 0930, 1130, 1430 and 1630 with three readings for each replication.

Air Pollutant Index (API) and weather data

The air quality in Malaysia is reported as the Air Pollutant Index (API). Air Pollutant Index is used by the Malaysian government for health classifications (*Table 1*). Four of the index's pollutant components (CO, O_3, NO_2 and SO_2) are reported in ppm but particulate matter (PM_{10}) is reported in μgm^{-3}. Dominant air pollutant with the highest concentration is normally the particulate matter which determines the API value. Following practice by the Malaysian government, air quality levels reaching the unhealthy category (API ≥101) is considered haze.

Table 1. Air Pollutant Index for health classifications used by the Malaysian government (Department of Environment 2014a)

API	Air pollution level
0 – 50	Good
51 – 100	Moderate
101 – 200	Unhealthy
201 – 300	Very unhealthy
>301	Hazardous

During the dry period between February and Mac 2014, Peninsular Malaysia had experienced moderate haze episodes where air quality deteriorated to unhealthy and hazardous levels (Department of Environment 2015). The affected areas and states were Klang Valley, Perak, Melaka, Negeri Sembilan and Johor. The haze worsened on 14 March 2014 as the API level rose to hazardous levels (API >300) in two areas namely Port Klang and Banting, Selangor.

Air Pollutant Index readings used in this study was referred to API Putrajaya (the closest API reading point) provided by Department of Environment, Ministry of Natural Resources and Environment, Malaysia (Department of Environment 2014b). Data on solar radiation, rainfall, temperature and relative humidity (RH) were obtained from a weather station located at MARDI Serdang, Selangor.

Statistical analysis

The experiments were laid out using Randomised Complete Block Design (RCBD) with three replications. Data obtained were subjected to statistical analysis, using a one-way Analysis of Variance (ANOVA) to test the significance effect of all variables investigated. Means separation was performed using the least significant difference (LSD) method at 5% (P = 0.05). Statistical analysis was done using the statistical package of SAS 9.3 Institute Inc. USA. Relationships between

PAR and net photosynthetic rate were determined using regression analysis with SAS version 9.3.

Results and discussion

Air Pollutant Index and weather conditions

Air Pollutant Index readings on a hazy day were higher than on a clear day throughout the day (*Figure 1*). The API for a clear and a hazy day was between 102 and 182 (average 141) and 40 and 77 (average 47) respectively. Threefold increase of API readings was recorded on a hazy day compared to a clear day. Relative humidity on hazy day was significantly higher compared to clear day from 0700 until midnight (p ≤0.05) (*Figure 2*). Higher relative humidity during a hazy day compared to a clear day was also reported by Davies and Unam (1999) as

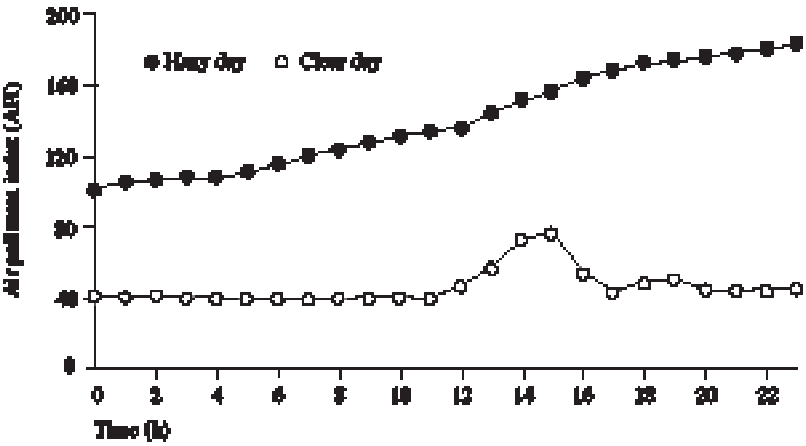

Figure 1. Air pollutant Index in 24 hours' time on hazy and clear days

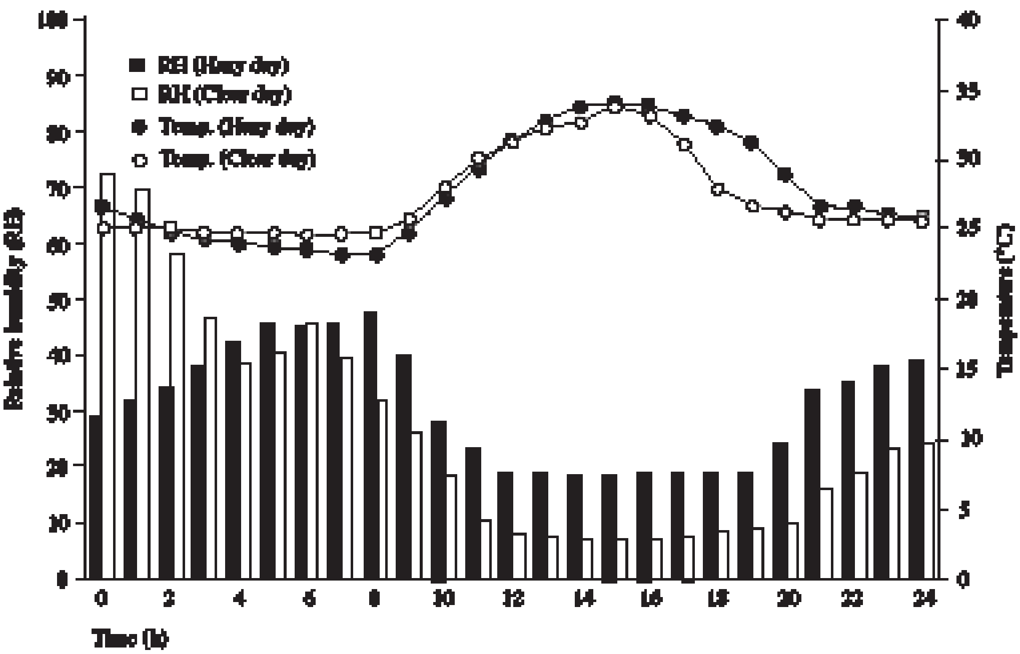

Figure 2. Relative humidity and temperature in 24 hours' time on hazy and clear days

well. However, between 0800 and 1900, the temperature on a hazy day and a clear day was not significantly different. Solar radiation during a clear day was higher than on a hazy day from 0800 to 1600 (*Figure 3*). The highest solar radiation was 1,050 and 812 wm^{-2} on a clear and a hazy day respectively. Haze caused 5 – 45% reduction in solar radiation from 0800 to 1700 h with an average of 22%. This indicated that haze reduced the solar radiation, as particles and pollutants in the air decrease the penetration of the sun light to the surface.

Photosynthesis and stomatal conductance

The study on photosynthesis (CO_2 gas exchange) and stomatal conductance are essential for a basic understanding of leaf physiology and plant productivity (Schaper and Chacko 1993). Leaf photosynthetic rate is important to determine the yield potential of rice because the photosynthetic rate of individual leaves affect dry matter production (Hirasawa et al. 2010). Clear differences of photosynthetic rate have been observed among varieties, species and progenies derived from crosses between species. Stomatal conductance has a significant effect on the photosynthetic rate. Significant differences among rice varieties in stomatal conductance have been reported by Ohsumi et al. (2008). Higher photosynthetic rate and stomatal conductance were recorded in high-yielding Japanese rice varieties during high irradiances (clear day) and low irradiances (cloudy day) compared to normal-yielding varieties (Takai et al. 2010).

The effects of haze on net photosynthetic rate of rice varieties are shown in *Figure 4*. During a clear day, the highest rate of net photosynthetic rate recorded was 21.7 – 26.3 $\mu molm^{-2}s^{-1}$ at 1430 whilst for a hazy day the highest rate recorded was 18.0 – 22.1 $\mu molm^{-2}s^{-1}$ at 1130. Haze caused 53.2, 12.9, 47.3 and 17.7% reduction in net photosynthetic rate of rice at 0930, 1130, 1430 and 1630 respectively. Greater reduction of net photosynthetic rate was recorded at 0930 and 1430 as compared to 1130 and 1630. The reduction of net photosynthetic rate was in response to the reduction of solar radiation at an average of 22% throughout the day (*Figure 4*). The huge 47.3% decline of net photosynthetic rate during a hazy day at 1430 was due to 45% reduction in solar radiation. This showed that haze reduction in the net photosynthetic rates were largely through its effects in the reduction of solar radiation.

Reduction of PAR also caused

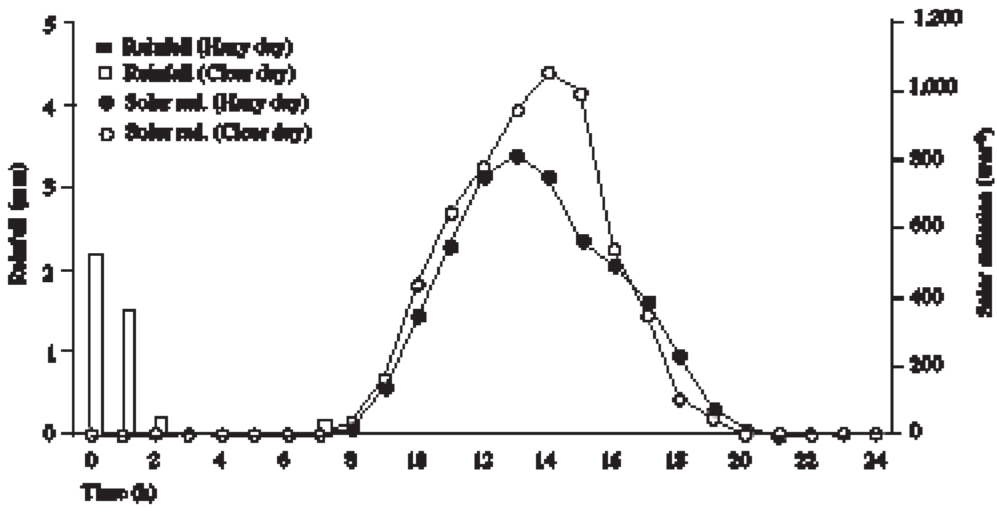

Figure 3. Solar radiation and rainfall in 24 hours' time on hazy and clear days

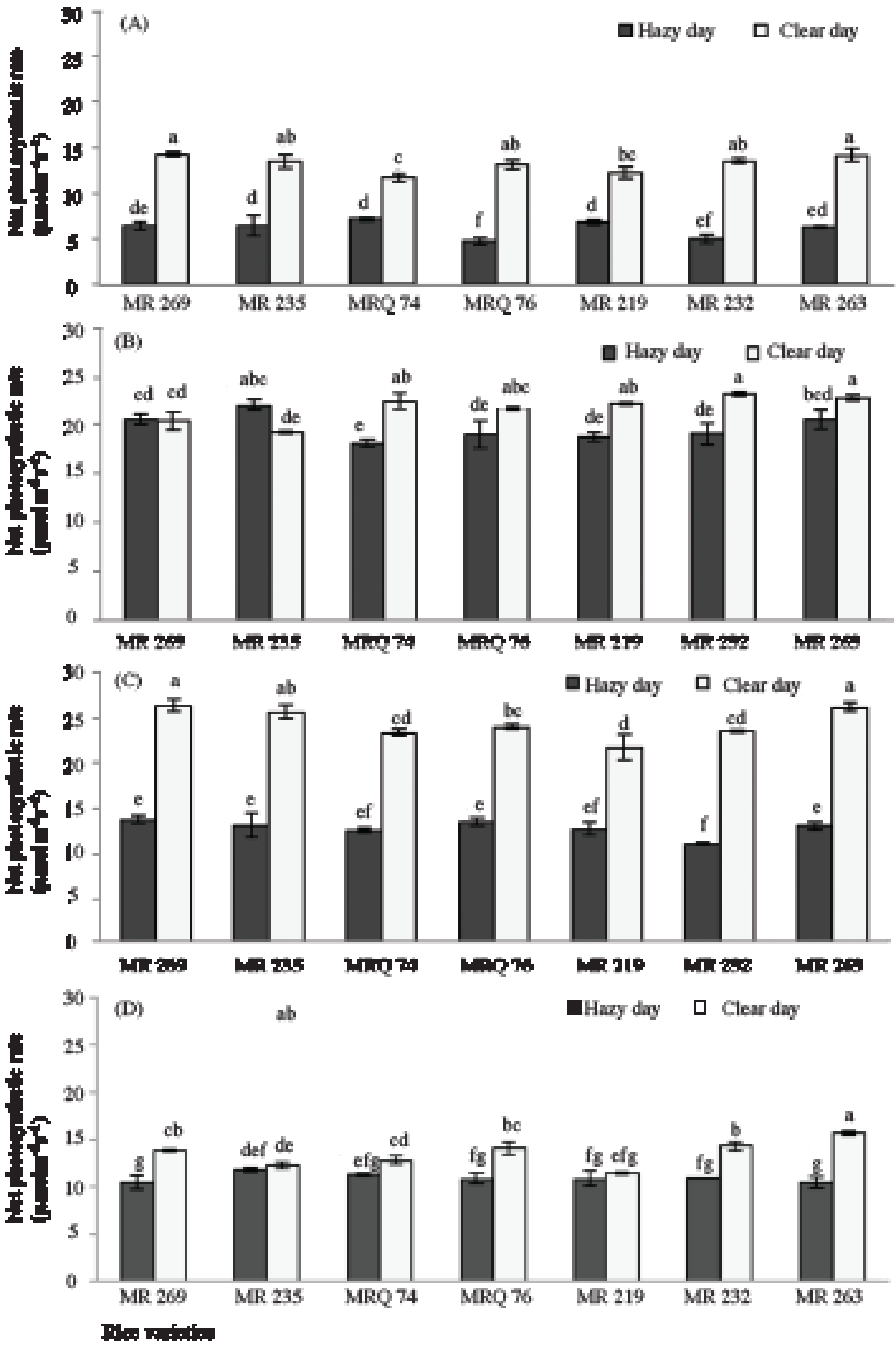

Figure 4. Net photosynthetic rate of several Malaysian rice varieties on a hazy day (60 DAT) and a clear day (78 DAT) measured at (A) 0930 (B) 1130 (C) 1430 and (D) 1630. Vertical bars represent standard error (n = 9). Identical letters indicate the absence of a significant difference at the 5% level Fisher's Least Significant Difference (LSD) test

significant reduction in the rate of stomatal conductance of all rice varieties (*Figure 5*). Haze caused 50.9, 26.1, 70.9 and 73.8% reduction in stomatal conductance at 0930, 1130, 1430 and 1630 respectively. Stomata tend to close not only in response to the low PAR, but also due to the hazardous particulate that lingers in the air. Particulate matter and air pollutants can clog the stomata (Makmon et al. 2003), reducing the stomatal conductance and inducing it to close prematurely, thereby reducing CO_2 intake and hence decreasing growth and yield.

Both net photosynthetic rate and stomatal conductance of all rice varieties generally showed similar responses to haze. The haze significantly reduced net photosynthetic rate and stomatal conductance of all rice varieties. While most rice varieties showed similar response of net photosynthetic rate and stomatal conductance, MR 235 showed significantly higher net photosynthetic rate during hazy days at 1130 as compared to clear days. However, MR 235 showed significantly lower rate of net photosynthetic rate at 930, 1430 and 1630 as compared to a clear day. Nevertheless, it can be concluded that there was no outstanding variety that can be considered resistant to the haze and solar radiation reduction.

A regression analysis showed that the net photosynthetic rate and PAR on both clear and hazy days was found to be positively correlated and highly significant ($p \leq 0.05$) (*Figure 6*). The regression coefficient (R^2) was 0.77 and 0.89 on a clear and a hazy day respectively. The relationships between PAR and net photosynthetic rate were as follows:

Clear day: Net photosynthetic rate = 0.0150 PAR + 6.34
Hazy day: Net photosynthetic rate = 0.0198 PAR + 3.70

The above regression equation showed that the net photosynthetic rates were significantly increased by the increase in PAR. Thus this indicated that PAR plays a very important role in photosynthetic rates. Reduction of PAR by haze will significantly cause reduction in net photosynthetic rate.

Yield performance

Yield performance of Malaysian rice varieties as affected by haze incident is presented in *Figure 7*. Yield of MR 269 was significantly higher than MRQ 76, MRQ 74 and MR 235, however, was not significantly different as compared to MR 219, MR 232 and MR 263. The yield of all rice varieties in this study was between 6.57 – 8.41 tha^{-1} and higher than the average yield (5.17 tha^{-1}) of field rice production grown in main granary areas in Peninsular Malaysia in 2014 (Jabatan Pertanian 2015). Higher yield was obtained in this study by growing the plants in troughs, thus the loss of fertilizers was greatly reduced. This study was conducted in a smaller area compared to a field study, therefore better control of pests and diseases incidents as well as post-harvest loss contributed to higher yield recorded. Therefore, the yield in this study was compared to its potential yield. The yield of MR 269 in this study (8.41 tha^{-1}) was 15.1% lower than the highest potential yield at 9.9 tha^{-1} (Zainal 2015). The yield of MR 219, MR 232 and MR 263 showed 19.0, 14.8 and 14.5% reduction respectively with the highest potential yield at 9.54, 8.7 and 9.12 tha^{-1} (Zainudin et al. 2012). Specialty rice varieties MRQ 76 and MRQ 74 (fragrant rice) showed lower yield, however, these varieties were reported to produce 15 – 20% lower yield compared to other varieties such as MR 219 under normal conditions (Zainal 2015). The decrease in yield of MRQ 76, MRQ 74 and MR 235 was 10.1, 13.6 and 19.1% respectively.

The yield of rice varieties as affected by moderate haze showed a reduction of 10 – 19% compared to their potential yield. In this study, the haze occurred for 5 weeks from middle of February to end of March 2014 during the final stage of tillering

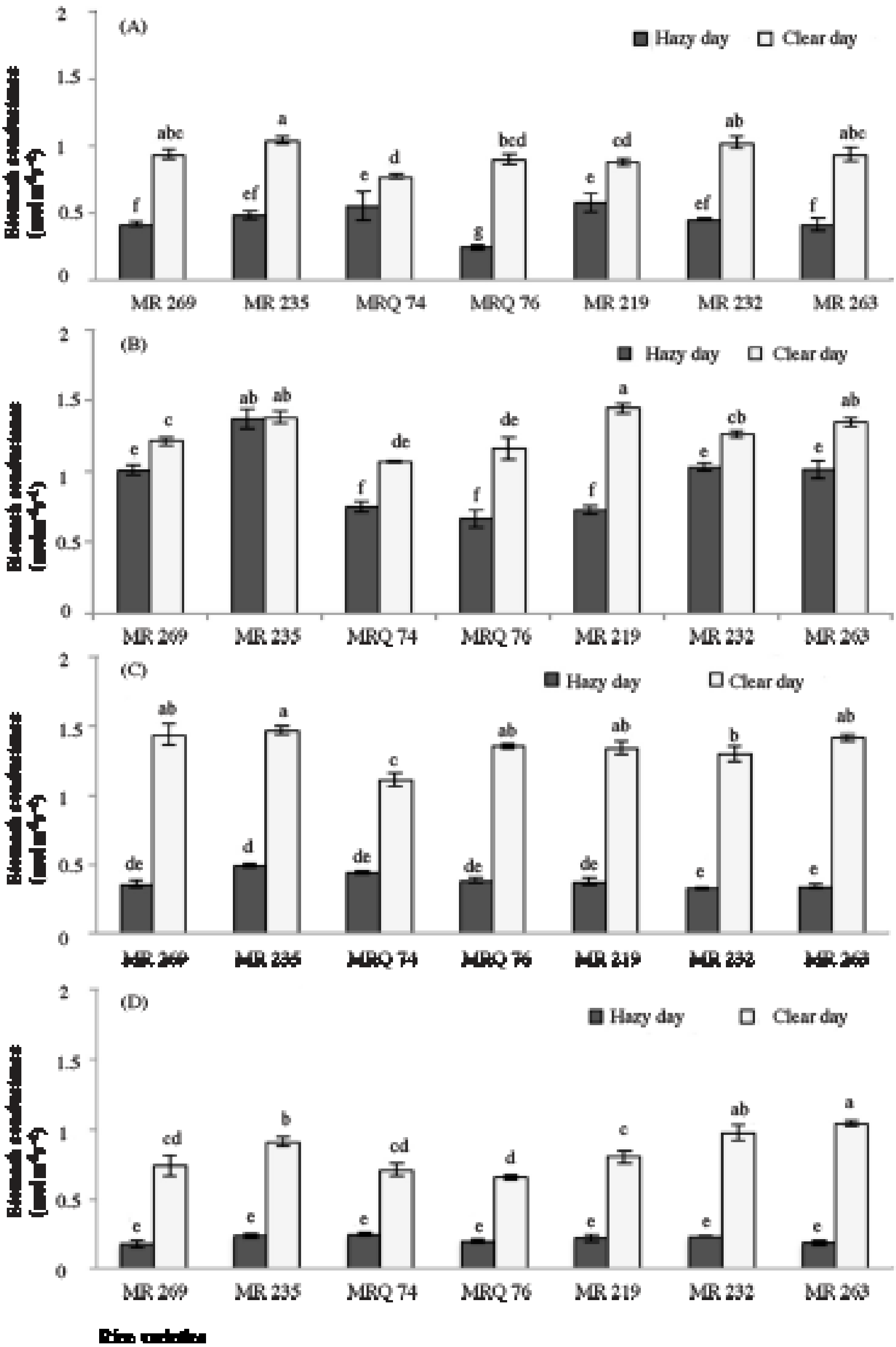

Figure 5. Stomatal conductance of several Malaysian rice varieties on a hazy day (60 DAT) and a clear day (78 DAT) measured at (A) 0930 (B) 1130 (C) 1430 and (D) 1630. Vertical bars represent standard error (n = 9). Identical letters indicate the absence of a significant difference at the 5% level Fisher's LSD test

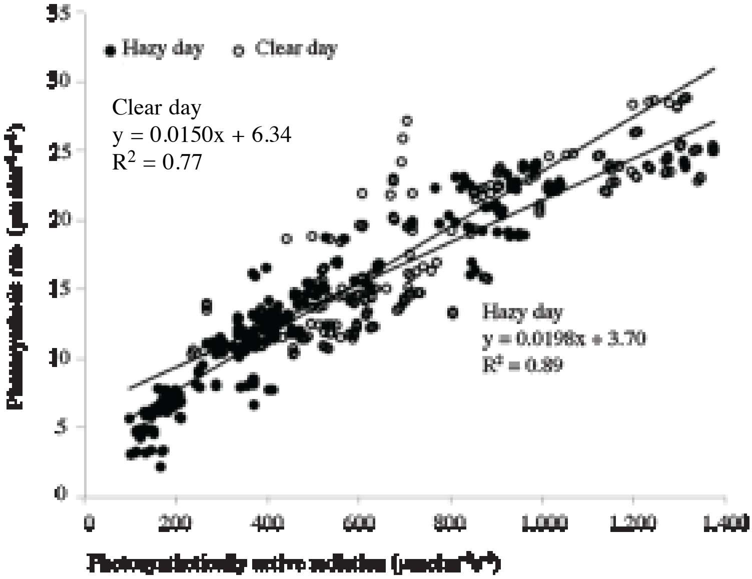

Figure 6. Regression analysis of relationship between photosynthetic rates and PAR of Malaysian rice varieties on hazy and clear days

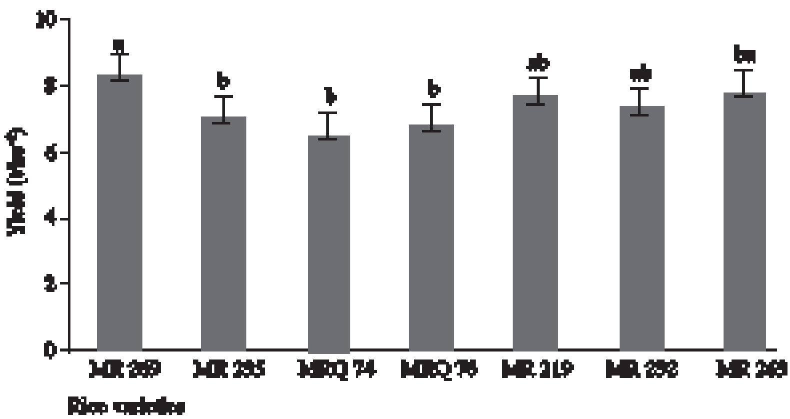

Figure 7. Yield of Malaysian rice (Oryza sativa L.) varieties as affected by moderate haze incident

and ended at early flowering stages. The reduction in yield was mainly due to the lower solar radiation/PAR that resulted in the reduction of net photosynthetic rate throughout the haze incident. Cumulative total solar radiation received per day eventually determines the total biomass production and yield, which depends on the severity and duration under haze condition (Hawa 2008). During the most severe haze incident in September 1997, PAR registered a tremendous reduction between 44 and 83% for two consecutive weeks with reducing sunshine hours which proved fatal to the process of photosynthesis. Paddy plants require higher saturation point of at least 70% solar radiation for maximum photosynthesis. Any reduction for 2 consecutive months will result in lower biomass accumulation and significant reduction of grain yields. Therefore, longer period and severe haze incidents with API at 300 – 800 may cause greater effect on plant physiological performance and yield of rice.

The plant stages of rice during haze incident also play a significant factor in affecting the growth and yield of rice. It has been observed in many crops that haze incidents occurring during flower initiation or flower blooming stages caused flower drop, resulting in lower yield (Hawa 2008). Besides direct effect of haze on photosynthate accumulation, some hormonal changes may also occur to hasten the process of flower and leaf drop, senescing of immature leaves and fading of young flowers (Jaafar et al. 1998). For rice, tillering period or grain filling is the most sensitive period to haze or any other stress. Severe decline in PAR during this period may cause reduction in yield. Yoshida (1981) reported that the effects of shading (reduction in solar radiation) on the yield of rice were dependent on the rice growth stage. Shading during the vegetative stage showed slight effect with 10.9% reduction in yield. Shading during the reproductive stage, however, has a pronounced effect on spikelet number. At this stage, 25% reduction of solar radiation will reduce grain yield by 19.7% while 50% reduction of solar radiation will reduce grain yield by 37.4%. During ripening it reduces grain yield considerably because of a decrease in the percentage of filled spikelets. At this stage, 25% and 50% reduction of solar radiation will reduce grain yield by 8.2% and 27.4% respectively.

Low light radiation due to haze from pollution were found to decrease the net photosynthetic rate and saturation irradiance of several rice varieties in Sichuan, China, which resulted in a sharply fall in grain yield mainly due to reduced spikelet filling and grain weight (Wang et al. 2015). Shading stress also delayed flowering, decreased biomass and grain yield and altered rice quality (Wang et al. 2013). Deng et al. (2009) found that shading obviously affected the filled grain percentage and yield. Liu et al. (2008) also found that lower light during grain filling affected rice yield, physiological characteristics and quality, particularly the rate of chalky grains. Ren et al. (2003) reported that the distribution and transformation of plant dry matter is affected by shading, and some shading levels decreased rice yield. Shading after heading reduced the photosynthesis of the flag leaf and the degree of the grain-filling was lower than that of under higher light intensity (Ding et al. 2004).

A prolonged haze may also cause a decline of 10 – 20% palm oil production in Malaysia (Ganling 2015). Heavy haze will limit the amount of sunlight reaching trees and hinders photosynthesis, and longer periods of haze between 4 and 8 weeks resulted in lower yields of palm oil for six months. Others reported that current flower drop due to haze will be translated in the next two years of palm oil production (Hawa 2008).

Conclusion

The haze significantly reduced the net photosynthetic rate and stomatal conductance largely through its reduction on solar radiation and PAR. All rice varieties generally showed similar responses to haze and it can be concluded that there was no outstanding variety that can be considered resistant to the haze. In this study, lower net photosynthetic rate resulted from the reduction of PAR during 5 weeks duration of haze which caused lower yield of all rice varieties compared to their potential yield. It is expected that a severe and long duration of haze may have greater effects on rice cultivation thus affecting sustainable food production and security. However, further study is required to determine the effects of haze on Malaysian rice varieties especially at different plant growth stages. The study on the effects of haze on rice grown in the paddy field is also important as it will demonstrate the actual effects of haze on plant physiological performances, growth and yield. While most current rice varieties can only be cultivated under moderate conditions, determining and developing rice varieties that are tolerant to extreme weather condition such as haze or other stress factors is crucial.

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Abstrak

Kesan jerebu ke atas kadar fotosintesis dan konduksi stomata beberapa varieti padi Malaysia telah dikaji semasa kejadian jerebu pada Mac 2014. Jerebu tersebut adalah pada tahap sederhana dengan bacaan Indeks Pencemaran Udara (API) antara 50 – 200 (tahap pencemaran udara sederhana kepada tidak sihat) tetapi berubah kepada sangat tidak sihat dan amat berbahaya di kawasan tertentu. Pengukuran pertukaran gas telah dijalankan pada hari ke 60 dan 78 iaitu semasa hari jerebu dan hari cerah. Purata bacaan API pada hari jerebu adalah sebanyak 141 manakala pada hari cerah adalah sebanyak 47. Radiasi solar menunjukkan purata pengurangan sebanyak 22% pada hari jerebu dari jam 0800 hingga 1700, manakala penurunan sebanyak 45% dicatatkan pada jam 1430. Jerebu menyebabkan penurunan kadar fotosintesis bersih sebanyak 12.9 – 53.2% manakala penurunan kadar konduksi stomata adalah sebanyak 26.1 – 73.8%. Kadar fotosintesis menunjukkan korelasi yang tinggi kepada Radiasi Aktif Fotosintesis (PAR) dengan koefisien regrasi (R^2) pada hari cerah adalah 0.77 manakala pada hari jerebu adalah 0.89. Jerebu secara signifikan merendahkan kadar fotosintesis dan konduksi stomata semua varieti padi melalui kesan penurunan radiasi solar/PAR. Kadar fotosintesis dan konduksi stomata untuk semua varieti padi menunjukkan tindakbalas yang sama kepada jerebu dan didapati tiada varieti yang rintang kepada kesan jerebu dan penurunan radiasi solar. Hasil bagi semua varieti padi menunjukkan penurunan sebanyak 10 – 19% jika dibandingkan dengan potensi hasil. Ini menunjukkan jerebu pada tahap sederhana yang berlaku selama 5 minggu di peringkat akhir tampang sehingga awal pembungaan telah menjejaskan fungsi fisiologi dan hasil tanaman padi. Tempoh jerebu lebih panjang pada tahap yang lebih teruk (API 300 – 800) pada peringkat pembungaan, pengisian bijian dan pemasakan berkemungkinan akan menyebabkan kesan yang lebih besar kepada fungsi fisiologi dan hasil tanaman padi.