Australasian Plant Pathol. (2012) 41:541–549
DOI 10.1007/s13313-012-0145-3

Bio-efficacy of microbial-fortified rice straw compost on rice blast disease severity, growth and yield of aerobic rice

L. C. Ng · M. Sariah · O. Sariam · O. Radziah ·
M. A. Zainal Abidin

Received: 20 July 2011 / Accepted: 18 April 2012 / Published online: 12 May 2012

Abstract The bio-efficacy of microbial-fortified rice straw compost was evaluated for plant growth promotion, resistance induction and yield increment with *Pyricularia oryzae* challenged inoculation at 14, 56 and 80 days after sowing (DAS) on rice variety M4 under greenhouse conditions. Soil treatments included control (laterite soil alone), rice straw compost and rice straw compost fortified with four plant growth-promoting rhizobacteria: *Pseudomonas aeruginosa* (UPMP1), *Corynebacterium agropyri* (UPMP7), *Enterobacter gergoviae* (UPMP9), *Bacillus amyloliquefaciens* (UPMS3) and two plant growth-promoting fungi: *Trichoderma harzianum* (UPMT1) and *Trichoderma virens* (UPMT2). Soil amended with microbial-fortified rice straw compost significantly increased plant growth and productivity. Rice yield was highly correlated to productive tiller number (r=0.96), leaf area index (LAI) (r=0.96) and plant height (r=0.97) for *P. oryzae* inoculation at 14 DAS. However, 1000 grain weight (r=0.96), area under disease progress curve (AUDPC) (r=−0.62) and infected panicle (r=−0.59) were highly correlated to rice yield with *P. oryzae* inoculation at 80 DAS. Low productivity was expected with *P. oryzae* infection at the later growth stage. This was due to increase in panicle blast that caused deterioration of grain quality and resulting in severe yield loss (30.99 %) as compared to early infection at 14 DAS in soil amended with microbial-fortified rice straw compost. Disease development and yield loss data with different *P. oryzae* inoculation timings is important for disease management in rice under aerobic cultivation system.

Keywords Aerobic rice · *Pyricularia oryzae* · Microbial-fortified rice straw compost · Panicle blast

Introduction

Aerobic rice production system is a new concept in rice cultivation to increase water use efficiency (Bouman et al. 2002). However, under aerobic cultivation systems, drought-stressed rice plants were observed to be more susceptible to disease especially rice blast (Piotti et al. 2005). Rice blast caused by *Pyricularia oryzae*, (teleomorph: *Magnaporthe oryzae* B. Couch), is the most destructive and cosmopolitan disease of rice (*Oryza sativa* L.) (Ou 1985). Rice blast disease is a significant threat to food security worldwide. In Brazil, yield losses up to 100 % have been reported in a newly released upland cultivar (Prabhu et al. 2009). Chemical pesticides are reported to be highly effective in blast control (Yamaguchi 2004). However, chemicals with residual toxicity can result in environmental pollution, detrimental effects on non-target organisms and resistance development.

L. C. Ng · M. Sariah · O. Radziah
Laboratory of Food Crops, Institute of Tropical Agriculture,
Universiti Putra Malaysia,
43400 UPM Serdang, Selangor, Malaysia

O. Sariam
Malaysian Agriculture Research and Development Institute,
P.O. Box 12301, General Post Office,
50774 Kuala Lumpur, Malaysia

O. Radziah
Department of Land Management, Faculty of Agriculture,
Universiti Putra Malaysia,
43400 UPM Serdang, Selangor, Malaysia

M. Sariah (✉) · M. A. Zainal Abidin
Department of Plant Protection, Faculty of Agriculture,
Universiti Putra Malaysia,
43400 UPM Serdang, Selangor, Malaysia
e-mail: sariahm@putra.upm.edu.my

Plant growth-promoting microorganisms (PGPM) defined as rhizosphere bacteria (Kloepper et al. 1999) or fungi (Hyakumachi 1994) exert beneficial effects; on growth, yield and protection in a range of crops like cereals, pulses, ornamentals, vegetables and plantation crops. PGPM also served as determinants in triggering induced systemic resistance (ISR) in plant systems as well as eliminating deleterious rhizobacteria and fungi (Dilantha Fernando et al. 2005; Pandya and Saraf 2010).

On the other hand, compost in agriculture has long been implicated to benefit plant growth and health. Compost is a unique substrate that provides fundamental interactions between plant pathogens, biocontrol agents, soil organic matter and plant roots (Hoitink et al. 1997) that helps to improve soil physical, chemical and biological properties (Alfano et al. 2009; Bastida et al. 2010). For instance, the application of rice straw compost high in silicon and nutrients have been well documented in benefiting plant growth, soil health and disease control (Singh et al. 2007; Watanabe et al. 2009). Besides, the capability and potential of various types of composts in controlling soil-borne pathogens in various crops has been well documented (Erhart et al. 1999; Yogev et al. 2009).

However, most biocontrol agents are destroyed by heat during the composting process and recolonization of effective microorganisms during the curing process does not always occur especially in an enclosed composting system (De Ceuster and Hoitink 1999). Therefore, fortification of mature compost with biocontrol agents or PGPM was suggested to improve sustainability as well as performance in disease suppression (Hoitink et al. 2006).

There is no information on the effect of microbial-fortified compost on blast disease severity and growth of aerobic rice in association with different *P. oryzae* inoculation timings. The aim of the current study was to evaluate the effect of rice straw compost fortified with a consortium of four plant growth-promoting rhizobacteria (PGPR) and two fungi (PGPF) in promoting growth, yield and suppressing rice blast severity at different *P. oryzae* inoculation timing.

Materials and methods

Isolates and microbial-fortified rice straw compost

The four PGPR: *Pseudomonas aeruginosa* (UPMP1), *Corynebacterium agropyri* (UPMP7), *Enterobacter gergoviae* (UPMP9) and *Bacillus amyloliquefaciens* (UPMS3), and two PGPF: *Trichoderma harzianum* (UPMT1) and *Trichoderma virens* (UPMT2) previously isolated from the rhizosphere soil of aerobic rice. All six isolates had the ability to produce indole-3-acetic acid (IAA), siderophore and chitinase, solubilize phosphate and were antagonistic against *P. oryzae* based on *in vitro* screenings conducted (our unpublished result). All PGPR were identified by BIOLOG system and the PGPF were identified based on morphological characteristics (Watanabe 2002) and sequence analysis of internal transcribed spacer (ITS) 1 and 2 (White et al. 1990).

Three month-old rice straw compost obtained from PPK (*Pertubuhan Peladang Kawasan*) B2, Kodiang, Perlis was used in the experiment. The physico-chemical and microbiological properties of the rice straw compost are presented in Table 1. Bacterial and fungal inoculums (10^8 cfu/ml) were aseptically inoculated into the rice straw compost at the ratio 1:20 (inoculum:rice straw compost v/w). The moisture content of the compost was adjusted to 50 % to maintain the biological activity of the microbes.

Plant materials and growing conditions

The greenhouse experiment was conducted at Agriculture Technology Unit of Universiti Putra Malaysia (UPM), Serdang, beginning end of December 2009 to March 2010. The daily temperature ranged from 25 to 36°C with 80 to 90 % RH. Rice variety M4 used in this study was obtained from Malaysian Agricultural Research and Development Institute (MARDI), which is suitable to grow under minimum water condition, high yielding but moderate resistance to rice blast. The growth duration of variety M4 was 110 days.

Rice straw compost or microbial-fortified rice straw compost was incorporated into the laterite soil with depth of 15 cm at a rate of 10 t/ha in pots (0.40 m diameter, 0.60 m height and with holes at the bottom to allow drainage). Rice

Table 1 Physico-chemical and microbiological properties of the raw rice straw compost (*Source*: PPK B2, Kodiang, Perlis)

Parameters	Value
Nitrogen (%)	2.09 (± 0.09)
Phosphorus (%)	0.93 (± 0.05)
Potassium (%)	0.21 (± 0)
Calcium (%)	4.36 (± 0.08)
Magnesium (%)	0.52 (± 0)
C:N ratio	12.80 (± 0.50)
pH	6.23 (± 0.04)
EC (mS/cm)	7.68 (± 0.06)
Bulk density (g/cm^3)	0.26 (± 0.01)
Moisture content (%)	47.00 (± 0.61)
Total bacteria (cfu/g)	2.70×10^6 (± 4.06×10^5)
Total fungi (cfu/g)	1.80×10^5 (± 2.24×10^4)
Total actinobacteria (cfu/g)	1.17×10^6 (± 4.38×10^5)

Values are means of five replicates with three determinations per replicate (Values in parenthesis indicate standard errors) seeds were sown and seedlings thinned at 7 days after sowing (DAS) to allow only 20 seedlings per pot. Fertiliser inputs consisted of N-P_2O_5-K_2O applied at 180-75-60 kg/ha as urea, Christmas Island Rock Phosphate (CIRP) and muriate of potash (MOP). Thirty percent of N was applied at 15, 35 and 55 DAS, respectively and the final 10 % was applied at 75 DAS. Full dose of P_2O_5 was applied at 15 DAS and K_2O was applied in two splits, 50 % each at 15 and 55 DAS. Each pot was watered twice daily (10 am and 6 pm) with an automatic intermittent 30 min of irrigation.

Inoculum preparation and disease assessment

The blast pathogen *(Pyricularia oryzae)* isolated from rice variety M4 was challenge inoculated to rice seedlings at three different growing stages: 14 (vegetative), 56 (panicle initiation) and 80 (heading) DAS. *Pyricularia oryzae* conidia were mass produced (Mackill and Bonman 1986) and conidia density was adjusted to 10^5 conidia per ml and sprayed until run-off using a hand sprayer with 100 ml per pot at 14 DAS and 300 ml per pot at 56 and 80 DAS. The *P. oryzae* conidia suspension was added with surfactant *Tween 20* (0.02 %v/v) to increase the adherence capacity of the conidia on plant surface. The *P. oryzae* challenged inoculation was conducted with single infection under specific greenhouse conditions where the inoculated rice seedlings were covered with plastic bag for 12 h to retain moisture and mist sprayer was continued to apply for the following 3 days to maintain RH of 95–98 % and temperature at 25–27°C.

Ten plants in each pot were randomly selected and tagged for disease severity assessment. Plant disease severity was assessed on the tagged plants at 7 days after inoculation. Rice blast rating was scored on individual plant basis using the standard evaluation system for rice (SESR) developed by IRRI (2002). Percentage of panicle blast was recorded at the harvesting stage by counting the number of blast infected panicles divided by the total number of panicles assessed. The disease severity was calculated using the following formula (Shrestha and Mishra 1994).

$$\text{Disease Severity}(\%) = \frac{\sum(\text{number of plants in the rating} \times \text{severity rating}) \times 100}{(\text{total number of plants observed} \times \text{maximum scale})}$$

Disease severity data recorded were used to calculate the disease progress curve [Area Under Disease Progress Curve (AUDPC)] (Shaner and Finney 1977).

Evaluation of plant growth-promoting traits

At harvest, all 20 rice plants in each replicate were harvested and rice yields were expressed in tons per ha. Productive tillers (number of tillers with panicle) and 1000 grain weight (1000 fully filled grains) were also determined. Comparative or relative yield (%) in each treatment was calculated as follows (Shim et al. 2005).

$$\text{Comparative yield}(\%) = \frac{\text{yield in treatment} \times 100}{\text{yield in control}}$$

Percentage yield loss and AUDPC changes with *P. oryzae* inoculation between 14 and 80 DAS was calculated using the following formula.

$$\text{Loss }(\%) = \frac{\text{value in 14 DAS} - \text{value in 80 DAS} \times 100}{\text{value in 14 DAS}}$$

Growth performances of rice were determined based on plant height (cm) and leaf area index (LAI). Plant height was measured at harvest using a mechanical ruler, whereas leaf area was determined using a leaf area meter (Model LICOR-3100).

Experimental design and data analysis

The experiment was conducted in a randomized complete block design with five replications. Treatments were: soils amended with microbial-fortified rice straw compost (C), rice straw compost (N) and laterite soil alone (S). The treatments were arranged in a split-plot design where with or without *P. oryzae* inoculation treatments were assigned as main plot and inoculation time as subplot. All data collected were subjected to analysis of variance and tested for significance using Fisher's Protected Least Significant Difference Test with PC-SAS software (SAS Institute, Cary, NC, 2001). Correlation coefficients were analyzed for all parameters at the three different *P. oryzae* inoculation timing using *Statistix 8* software.

Results

Correlation of rice yield, plant growth and blast infection

It was observed that soil amended with microbial-fortified rice straw compost, significantly increased rice yield (ton/ha) at all *P. oryzae* inoculation timings, except at 56 DAS (Tables 2). With *P. oryzae* inoculation at 56 DAS, the rice yield obtained was not significantly different between the soil amended with microbial-fortified rice straw compost (5.76 t/ha) and rice straw compost alone (5.00 t/ha). *Pyricularia oryzae* inoculation at later stage (80 DAS) did not reduced significantly the percentage of infected panicle in soil amended with microbial-fortified rice straw compost (25.25 %) and soil amended with rice straw compost alone (27.75 %).

Table 2 Effect of *Pyricularia oryzae* inoculation at 14, 56 and 80 DAS on yield and disease parameters of rice cultivated at different soil treatments

Treatments	AUDPC	Infected panicle (%)	Productive tiller per pot	1000 grain weight (g)	LAI (cm^2)	Plant height (cm)	Yield (ton/ha)	Comparative yield (%)
P. oryzae inoculation at 14 DAS								
N without *P. oryzae*	0 d	0 b	54.00 b	28.38 b	309.95 b	109.90 b	9.07 b	100.00
C without *P. oryzae*	0 d	0 b	59.00 a	30.80 a	382.78 a	116.90 a	9.56 a	100.00
S without *P. oryzae*	0 d	0 b	24.00 e	23.90 c	59.70 e	48.50 d	1.02 e	100.00
N with *P. oryzae*	3062.89 b	0 b	39.80 d	28.98 b	205.87 d	97.10 c	6.56 d	72.30
C with *P.oryzae*	1381.30 c	0 b	47.80 c	30.35 a	250.24 c	110.70 ab	7.10 c	74.23
S with *P. oryzae*	5419.56 a	11.78 a	14.00 f	21.70 d	20.46 f	41.40 e	0.38 f	37.25
P. oryzae inoculation at 56 DAS								
N without *P. oryzae*	0 d	0 d	54.50 b	28.20 b	289.79 b	109.80 a	8.42 a	100.00
C without *P. oryzae*	0 d	0 d	60.00 a	29.50 a	410.15 a	112.10 a	8.89 a	100.00
S without *P. oryzae*	0 d	0 d	23.00 c	24.00 e	59.53 d	52.30 c	0.92 c	100.00
N with *P. oryzae*	736.55 b	16.15 b	53.80 b	25.29 d	252.51 c	104.50 b	5.00 b	59.40
C with *P. oryzae*	276.89 c	8.30 c	57.00 a	26.49 c	376.41 a	111.50 a	5.76 b	64.78
S with *P. oryzae*	2023.00 a	36.29 a	22.00 c	22.04 f	21.85 e	45.90 d	0.50 c	53.71
P. oryzae inoculation at 80 DAS								
N without *P. oryzae*	0 d	0 c	55.00 a	28.00 b	320.51 b	107.20 a	8.00 b	100.00
C without *P. oryzae*	0 d	0 c	59.00 a	30.13 a	450.10 a	111.60 a	9.10 a	100.00
S without *P. oryzae*	0 d	0 c	23.00 b	23.00 e	58.54 c	50.50 b	0.96 e	100.00
N with *P. oryzae*	535.89 b	27.75 b	54.00 a	24.96 d	291.82 b	106.90 a	4.18 d	52.27
C with *P. oryzae*	168.89 c	25.25 b	59.80 a	26.68 c	410.83 a	111.30 a	4.90 c	53.83
S with *P. oryzae*	1269.33 a	57.61 a	23.00 b	20.10 f	28.14 c	47.50 b	0.21 f	21.61

N = soil with rice straw compost, C = soil with microbial-fortified rice straw compost and S = laterite soil alone

Means within columns followed by the same letters at each of the *Pyricularia oryzae* inoculation stages are not significantly different by LSD test at $P \leq 0.05$. (Each value represents mean of five replicates)

The relationships between rice blast infection, yield and growth parameters at the three *P. oryzae* inoculation timings were presented in Table 3. Generally, rice yield at all three *P. oryzae* inoculation timings was positively and significantly correlated to productive tillers, 1000 grain weight, plant height and LAI. However, AUDPC and infected panicles were negatively and significantly associated with rice yield. Comparison between coefficients at the three *P. oryzae* inoculation timing showed that the correlation of rice yield was higher in productive tiller numbers per pot ($r=0.96$), LAI ($r=0.96$) and plant height ($r=0.97$) when inoculated at 14 DAS. Besides, AUDPC ($r=-0.62$), infected panicles ($r=-0.59$) and 1000 grain weight ($r=0.96$) showed greater correlation with rice yield for *P. oryzae* inoculated at 80 DAS as compared to inoculation at 14 and 56 DAS.

In terms of yield loss, *P. oryzae* infection at the later stage (80 DAS) caused more severe yield loss. Infection of *P. oryzae* at 80 DAS, resulted only 53.83 % of yield obtained for soil amended with microbial-fortified rice straw compost, 52.27 % for soil amended with rice straw compost and 21.61 % for laterite soil alone, as compared to the un-inoculated with *P. oryzae* treatment (100 %).

Estimation of growth performance, yield loss and blast development

The yield loss at different *P. oryzae* inoculation times were determined using the regression equations between rice yield and inoculation timing, where $y=-0.03x+7.58$ ($R^2=0.99$) for soil amended with microbial-fortified rice straw compost, $y=-0.04x+7.06$ ($R^2=0.99$) for soil amended with rice straw compost and $y=-0.002x+0.46$ ($R^2=0.20$) for laterite soil alone. In all the cases, there was a negative correlation between rice productivity and time of blast initiation. Yield obtained in soil amended with microbial-fortified rice straw compost was significantly higher as compared to soil amended with rice straw compost alone at all *P. oryzae* inoculation timings (Fig. 1a).

A negative correlation between 1000 grain weight and *P. oryzae* inoculation timings was observed (Fig. 1b). One thousand grain weight in all soil treatments decreased significantly when *P. oryzae* was inoculated at the later growth stages. The regression equations between 1000 grain weight loss and *P. oryzae* inoculation timings were $y=-0.06x+30.83$ ($R^2=0.84$) for soil amended with microbial-fortified rice straw compost, $y=-0.06x+29.61$ ($R^2=0.92$) for soil

Table 3 Correlation coefficients among disease, yield and growth traits with inoculation of *Pyricularia oryzae* at 14, 56 and 80 DAS

	AUDPC	Infected panicle (%)	Productive tiller per pot	1000 grain weight (g)	Yield (ton/ha)	LAI (cm^2)
P. oryzae inoculation at 14 DAS						
Infected panicle (%)	0.6272**					
Productive tiller per pot	−0.5619**	−0.5785**				
1000 grain weight (g)	−0.3782*	−0.6281**	0.9018**			
Yield (ton/ha)	−0.4589**	−0.5203**	0.9640**	0.9026**		
LAI (cm^2)	−0.5189**	−0.5003**	0.9518**	0.8749**	0.9582**	
Plant height (cm)	−0.3827*	−0.5414**	0.9555**	0.9423**	0.9686**	0.9337**
P. oryzae inoculation at 56 DAS						
Infected panicle (%)	0.9611**					
Productive tiller per pot	−0.5190**	−0.4462**				
1000 grain weight	−0.7187**	−0.6961**	0.8215**			
Yield (ton/ha)	−0.5965**	−0.5687**	0.8928**	0.9189**		
LAI (cm^2)	−0.5798**	−0.5604**	0.8312**	0.9010**	0.9207**	
Plant height (cm)	−0.5607**	−0.5007**	0.9673**	0.8166**	0.9165**	0.8304**
P. oryzae inoculation at 80 DAS						
Infected panicle (%)	0.9816**					
Productive tiller per pot	−0.4735**	−0.3282^{ns}				
1000 grain weight	−0.7551**	−0.6921**	0.8384**			
Yield (ton/ha)	−0.6168**	−0.5887**	0.8264**	0.9579**		
LAI (cm^2)	−0.5489**	−0.4086*	0.9280**	0.9088**	0.8754**	
Plant height (cm)	−0.4965**	−0.3543*	0.9534**	0.8524**	0.8403**	0.9267**

** = significant at 1 % level, * = significant at 5 % level, ns = not significant, - = negative correlation

Correlations were based on means of five replications in each treatment

amended with rice straw compost and y=−0.02x+22.31 (R^2=0.44) for laterite soil alone.

To estimate rice blast severity at different growth stages with the different soil treatments, the regression between AUDPC and *P. oryzae* inoculation timings was developed. The AUDPC derived from leaf blast disease severity data showed negative correlation with time of blast initiation. Rice blast occurrence at early growth stages gave higher AUDPC values compared to later growth stages. The regression equations for soil amended with microbial-fortified rice straw compost, rice straw compost and laterite soil alone were y=−19.27x+1572.30 (R^2=0.92), y=−40.22x+3456 (R^2=0.92) and y=−64.91x+6149.6 (R^2=0.96), respectively (Fig. 1c). However, blast infected panicle (%) was found to be positively correlated with *P. oryzae* inoculation timing (Fig. 1d). In the treatment with laterite soil alone, when *P. oryzae* was inoculated at 14 DAS, incidence of panicle blast was observed at harvesting stage. However, no panicle blast was detected in soils amended with microbial-fortified or rice straw compost. Panicle blast was very severe in non-amended soil (laterite soil alone) (y=0.68x+1.13, R^2=0.99), followed by soil amended with rice straw compost (y=0.42x – 6.19, R^2=0.99) and soil amended with microbial-fortified rice straw compost (y=0.36x – 6.90, R^2=0.88).

Pyricularia oryzae inoculation at the later stages increased the number of productive tillers in all treatments (Fig. 1e). Plants in soil treated with microbial-fortified rice straw compost had significantly higher number of productive tillers than in soil amended with only rice straw compost. The regression equations for productive tiller numbers in relation to *P. oryzae* inoculation timings were y=0.19x+45.57 (R^2=0.98), in soil amended with microbial-fortified rice straw compost, y=0.23x+37.76 (R^2=0.88) in soil amended with rice straw compost and y=0.14x+12.54 (R^2=0.93) in laterite soil alone.

Leaf area index of rice grown in soil treated with microbial-fortified rice straw compost was significantly and positively correlated to *P. oryzae* inoculation timing (Fig. 1f). However, there was no significant correlation between LAI and *P. oryzae* inoculation timing in laterite soil alone, where the correlation equation was y=0.11x+18.14 (R^2=0.76). The linear regression equations for LAI and the *P. oryzae* occurrence timing were y=2.50x+220.94 (R^2=0.97) in soil amended with microbial-fortified rice straw compost and y=1.28x+186.04 (R^2=0.99) in soil amended with rice straw compost.

Plant height in soil amended with microbial-fortified rice straw compost ranged from 110.70 to 111.50 cm, but was

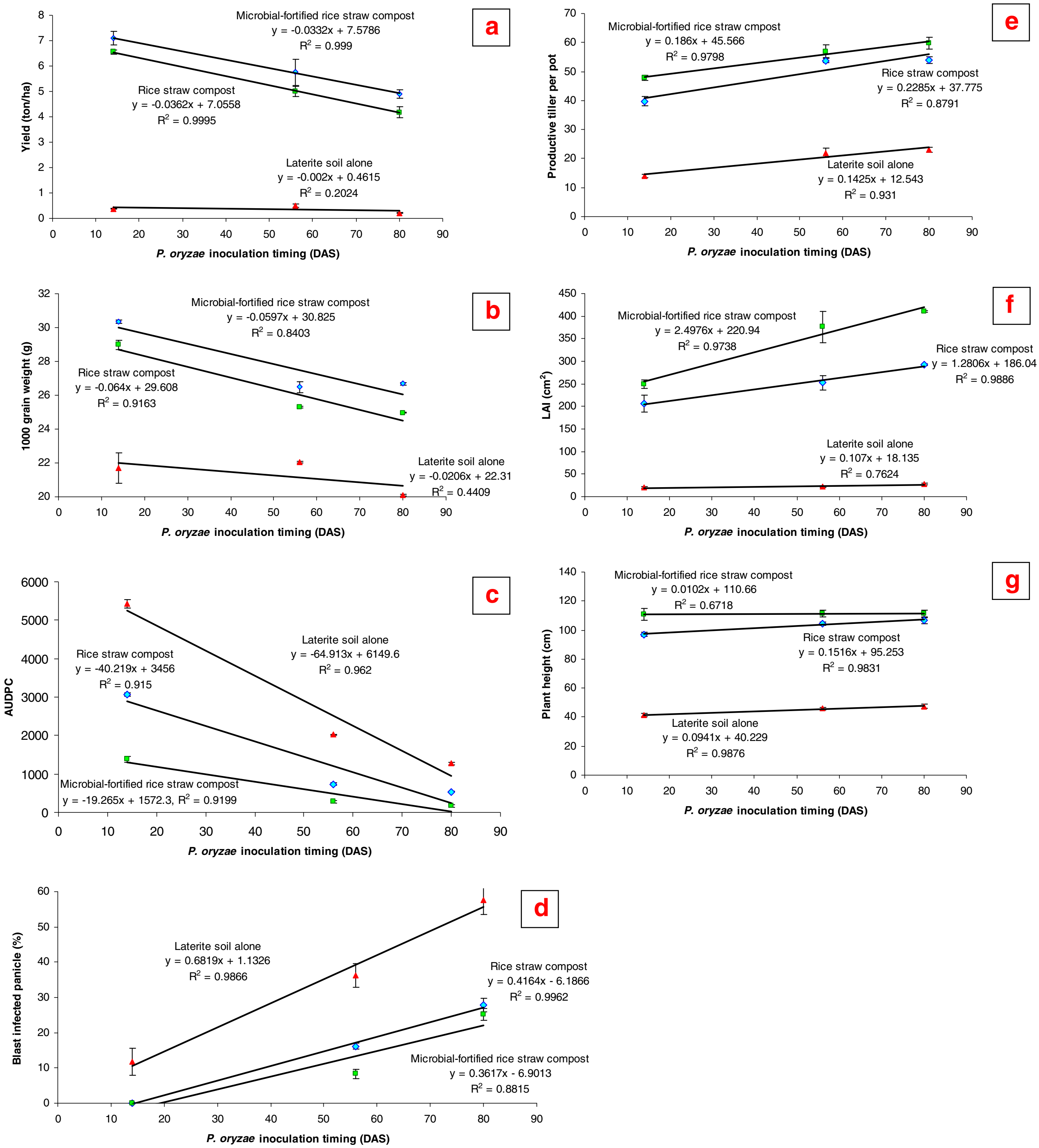

Fig. 1 Linear correlation between rice yield (**a**), 1000 grain weight (**b**), AUDPC (**c**), blast infected panicle incident (**d**), productive tiller per pot (**e**), leaf area index (**f**), plant height (**g**) and *P. oryzae* inoculation timings in different soil treatments (Each value represents the mean of five replicates; vertical bars represent standard errors)

weakly correlated with *P. oryzae* inoculation timing, where the regression equation was y=0.01x+110.66 (R^2=0.67) (Fig. 1g). However, in soil amended with rice straw compost, delaying *P. oryzae* inoculation increased plant height (y=0.15x+95.25; R^2=0.98). In the laterite soil alone, plant height was not significantly correlated to *P. oryzae* inoculation timing, where plant height recorded was consistent and ranged between 41.40 and 47.50 cm (y=0.09x+40.23; R^2=0.99).

Discussion

Rice blast disease is a major constraint in rice production world wide and panicle infection is capable of causing complete yield loss (Shim et al. 2005). In the current study, rice straw compost fortified with *P. aeruginosa, B. amyloliquefaciens, C. agropyri, E. gergoviae, T. harzianum* and *T. virens* demonstrated significant effects in promoting plant growth, controlling rice blast and resulting in yield increments especially at early *P. oryzae* inoculation. However, blast disease inoculation at the mature plant stage (56 DAS) did not cause significant yield loss between soil amended with microbial-fortified rice straw compost (5.76 t/ha) or rice straw compost (5 t/ha). This observation reflects the high resistance of mature plants against *P. oryzae* infection as compared to the seedling stage with higher leaf blast severity (14 DAS). Consequently, the low leaf blast severity with infection of mature plants (56 DAS) did not significantly disturb the carbohydrate supply of the canopy during the specific panicle initiation period and hence did not affect floret number and spikelet number which were determined before heading (Penning de Vries et al. 1990).

The potential of *Pseudomonas* sp. (Ryu et al. 2004), *Bacillus* sp. (Idriss et al. 2002), *Enterobacter* (Gupta et al. 1998), *Corynebacterium* (El-Banna and Winkelmann 1998) and *Trichoderma* (Pandya and Saraf 2010) in enhancing plant growth and improving plant health through various direct and indirect mechanisms have been reported. The positive results of PGPM in controlling leaf blast were also reported in irrigated rice (Lucas et al. 2009) and aerobic rice (Filippi et al. 2011). In our study, the capability of PGPM to enhance productivity was explained by the production of peroxidase, polyphenol oxidase and phenylalanine ammonia-lyase as inducers of systemic resistance in the rice plant (Filippi et al. 2011) and also the plant growth promoting effects of the fortified microbial which related to the production of IAA (Khalid et al. 2004) and solubilizing of phosphate (Vyas and Gulati 2009).

Efficiency in blast management is dependent on accurate and precise knowledge of disease incidence and relationship between disease severity and yield loss (Tsai 1988). In our current study, correlation and estimation of various plant growth and blast disease parameters in different soil treatments at different *P. oryzae* inoculation timings were stressed. *Pyricularia oryzae* inoculation at 14 DAS demonstrated highest positive correlation in rice yield (ton/ha) to LAI, plant height and productive tiller number. Early *P. oryzae* inoculation led to decline in leaf area formation, plant height and productive tillers. These results are in agreement with Crill et al. (1982); Yeh and Bonman (1986), where rice plants at seedling and early tillering stages were more susceptible to leaf blast infection. Leaf blast was reported to reduce yield by causing lesion coverage, premature leaf senescence, reducing leaf area formation and phothosynthetic efficiency (Bastiaans et al. 1994). From our observation, heavily blast infected leaf tissues were found dying, but with the formation of new green leaves there was a gradual decline in leaf blast infection attributed to increased resistance in mature plants. Blast infected panicles were not observed at harvest except in treatments with laterite soil alone. Despite the high correlation of rice productivity to LAI, plant height and productive tillers at early *P. oryzae* inoculation, the comparative yield scored was still the highest compared to late inoculation of *P. oryzae*. This was in agreement with Crill et al. (1982), where leaf blast was the most commonly found in seedling but least destructive as compared to panicle blast.

The low rice yield with late inoculation of *P. oryzae* was correlated with high AUDPC, blast infected panicles and low 1000 grain weight. Similar observations by Bastiaans (1993) led to the suggestion that leaf blast mainly affected grain yield indirectly. Despite the low AUDPC value in mature plants, yield reduction might also be affected by low efficiency of blast lesions on leaf photosynthesis and respiration causing reduced carbohydrate production (Bastiaans 1991). These observations are in line with those reported by Goto (1965), who also observed reduced spikelet number, 1000 grain weight and fraction of filled grains due to leaf blast in mature plants. In addition, AUDPC value at late *P. oryzae* inoculation (80 DAS) was highly correlated to panicle blast infection. This resulting percentage of panicle blast was not significantly different in soil amended with microbial-fortified rice straw compost or with rice straw compost alone. Panicle blast at late *P. oryzae* infection had also directly affects on yield loss (Shim et al. 2005) by causing sterile or poorly filled grain and resulting in light weight kernels (Crill et al. 1982).

The low comparative yield with late *P. oryzae* inoculation may be explained by the fact that *P. oryzae* infection at late growing stages increased blast panicle incidence and affected the 1000 grain weight. The later inoculation of *P. oryzae* at 80 DAS caused yield losses of 30.99 % and 36.28 % in soil amended with microbial-fortified rice straw compost and with rice straw compost alone as compared to early infection at 14 DAS. Yield reductions were caused by panicle blast which reduced 1000 grain weight, percentage of ripe spikelets and percentage of fully mature grains (Teng et al. 1990). This indicates that panicle infection was critical for significant economic losses.

The application of microbial-fortified rice straw compost was beneficial in the control of rice blast development, promotion of crop growth and improving productivity. However, reduced grain filling in blast infected panicles was the most critical factor contributing to yield loss in aerobic rice (variety M4) production. The ability of prediction equations to accurately estimate yield loss and various plant growth parameters due to blast disease development at different *P. oryzae* inoculation timings can be useful for blast management in aerobic rice cultivation systems.

Acknowledgements The authors wish to express their sincere thanks and appreciations to the Ministry of Science, Technology and Innovation (MOSTI) for the research grant administered through the Science Fund of MOA (05-01-24-SF 1034), the Universiti Malaysia Terengganu and the Ministry of Higher Education Malaysia through a doctorial fellowship and the Institute of Tropical Agriculture and the Faculty of Agriculture, Universiti Putra Malaysia for providing the research facilities.

References

Alfano G, Lustrato G, Lima G, Vitullo D, Delfine S, Tognetti R, Ranalli G (2009) Physico-chemical, microbiological, agronomical and phytopathological aspects in the recycling of olive waste composted residues. Dyn Soil Dyn Plant 3(1):64–72

Bastiaans L (1991) Ratio between virtual and visual lesion size as a measure to describe reduction in leaf photosynthesis due to leaf blast. Phytopathology 81:611–615

Bastiaans L (1993) Effects of leaf blast on growth and production of a rice crop. Determining the mechanism of yield reduction. Neth J Plant Pathol 99:323–334

Bastiaans L, Rabbinge R, Zadoks JC (1994) Understanding and modeling leaf blast effects on crop physiology and yield. In: Zeigler RS, Leong SA, Teng PS (eds) Rice blast disease. CAB International, Wallingford, pp 357–380

Bastida F, Hernandez T, Garcia C (2010) Soil degradation and rehabilitation: microorganisms and functionality. In: Insam H, Franke-Whittle IH, Goberna M (eds) Microbes at work: from wastes to resources. Springer, Heidelberg, pp 253–270

Bouman BAM, Yang XG, Wang HQ, Wang ZM, Zhao JF, Wang CG, Cheng B (2002) Aerobic rice (Han Dao): a new way of growing-rice in water-shortareas. Proceedings of the 12th international soil conservationorganization conference. Tsinghua University Press, Beijing, China, pp 175–181

Crill P, Ikehashi H, Beachell HM (1982) Rice blast control strategies. In: Rice research strategies for the future. International Rice Research Institute, Manila, Philippines, pp 129–146

De Ceuster TJJ, Hoitink HAJ (1999) Using compost to control plant diseases.
Ohio State University. http://www.jgpress.com/BCArticles/1999/0699Art5.htm. Accessed 20 Dec 2010

Dilantha Fernando WG, Nakkeeran S, Zhang YL (2005) Biosynthesis of antibiotics by PGPR and its relation in biocontrol of plant disease. In: Siddiqui ZA (ed) PGPR: biocontrol and biofertiliser. Springer, Netherlands, pp 67–109

El-Banna N, Winkelmann G (1998) Pyrrolnitrin from Burkholderia cepacia: antibiotic activity against fungi and novel activities against streptomycetes. J Appl Microbiol 85:69–78

Erhart E, Burian K, Hartle W, Stich K (1999) Suppression of Pythium ultimum by bio-waste composts in relation to compost microbial biomass, activity and content of phenolic compounds. Phytopathology 147:299–305

Filippi MCC, Silva GB, Silva-Lobo VL, Cortes MVCB, Moraes AJG, Prabhu AS (2011) Leaf blast (Magnaporthe oryzae) suppression and growth promotion by Rhizobacteria on aerobic rice in Brazil. Biol Control 58:160–166

Goto K (1965) Estimating losses from rice blast in Japan, In: The rice blast disease. The Jones Hopkins Press, Baltimore, Maryland, pp 195–202

Gupta A, Saxena AK, Gopal M, Tilak KVBR (1998) Effect of plant growth promoting rhizobacteria on competitive ability of introduced Bradyrhizobium sp. (Vigna) for nodulation. Microbiol Res 153:113–117

Hoitink HAJ, Stone AG, Han DY (1997) Suppression of plant diseases by composts. J Hortic Sci 32:184–187

Hoitink HAJ, Madden LV, Dorrance AE (2006) Systemic resistance induced by Trichoderma: interactions between the host, the pathogen, the biocontrol agent and soil organic matter quality. Phytopathology 96:186–189

Hyakumachi M (1994) Plant growth-promoting fungi from turf grass rhizosphere with potential for disease suppression. Soil Microorganisms 44:53–68

Idriss EE, Makarewicz O, Farouk A, Rosner K, Greiner R, Bochow H, Richter T, Borriss R (2002) Extracellular phytase activity of Bacillus amyloliquefaciens FZB45 contributes to its plant-growth-promoting effect. Microbiol 148:2097–2109

IRRI (2002) Standard evaluation system for rice. International Rice Research Institute, Los Banos, Manila, Philippines

Khalid A, Arshad M, Zahir ZA (2004) Screening plant growth promoting rhizobacteria for improving growth and yield of wheat. Appl Microbiol 46:473–480

Kloepper JW, Rodriguez-Ubana R, Zehnder GW, Murphy JF, Sikora E, Fernandez C (1999) Plant root-bacterial interactions in biological control of soilborne diseases and potential extension to systemic and foliar diseases. Australas Plant Pathol 28:21–26

Lucas JA, Ramos Solano B, Montes F, Ojeda J, Megias M, Gutierrez Manero FJ (2009) Use of two PGPR strains in the integrated management of blast disease in rice (Oryzae sativa) in Southern Spain. Field Crops Res 14:404–410

Mackill AO, Bonman JM (1986) New hosts of *Pyricularia oryzae*. Plant Dis 70:125–127

Ou SH (1985) Rice diseases, 2nd edn. Commonwealth Mycological Institute, Kew, England

Pandya U, Saraf M (2010) Application of fungi as a biocontrol agent and their biofertilizer potential in agriculture. J Adv Dev Res 1 (1):90–99

Penning de Vries FWT, Van Keulen H, Alogos JC (1990) Nitrogen redistributionandpotential production in rice. Proceedings of the internationalcongress of plantphysiology, New Delhi, India. Society for PlantPhysiology and Biochemistry, New Delhi, pp 513–520

Piotti E, Rigano MM, Rodino D, Rodolfi M, Castiglione S, Picco AM, Sala F (2005) Genetic structure of Pyricularia grisea (Cooke) Sacc. isolates from Italian paddy fields. Phytopathology 153:80–86

Prabhu AS, Filippi MC, Silva GB, Lobo VLS, Moraes OP (2009) An unprecedented outbreak of rice blast on a newly released cultivar BRS Colosso in Brazil. In: Wang GL, Valente B (eds) Advances in genetics, genomics and control of rice blast disease. Springer, New York, pp 257–266

Ryu CM, Farag MA, Hu CH, Reddy MS, Kloepper JW, Pare PW (2004) Bacterial volatiles induce systemic resistance in Arabidopsis. Plant Physiol 134:1017–1026

Shaner G, Finney RE (1977) The effect of nitrogen fertilization on the expression of slow-mildewing resistance in Knox wheat. Phytopathology 67:1051–1056

Shim HK, Hong SJ, Yeh WH, Ha SS, Sung JM (2005) Damage analysis of rice panicle blast on disease occurrence time and severity. Plant Pathol 21:87–92

Shrestha SM, Mishra NK (1994) Evaluation of common cultivars of rice against leaf and neck blast in Nepal. Nepal J Inst Agric Anim Sci 15:101–103

Singh K, Singh R, Singh KK, Singh Y (2007) Effect of silicon carriers and time ofapplication on rice productivity in a rice-wheat cropping sequence. Soil,nutrient, & water management. International Rice Research Notes (IRRN) 32:30–31

Teng PS, Torres CQ, Nuque FL, Calvero SB (1990) Current knowledge on crop losses in tropical rice. In: Crop loss assessment in rice. International Rice Research Institute, Los Banos, Phillipines, pp 39–54

Tsai WH (1988) Estimation of rice yield losses caused by panicle blast disease. J Agric Res China 37:86–90

Vyas P, Gulati A (2009) Organic acid production in vitro and plant growth promotion in maize under controlled environment by phosphate-solubilizing fluorescent Pseudomonas. BMC Microbiol 9:1–15

Watanabe T (2002) *Trichoderma harzianum* Rifai. In: Pictorial atlas of soil and seed fungi morphologies of cultured fungi and key to species, 2nd edn. CRC Press, pp 43–283

Watanabe T, Man LH, Vien DM, Khang VT, Ha NN, Linh TB, Ito O (2009) Effects of continuous rice straw compost application on rice yield and soil properties in the Mekong Delta. Soil Sci Plant Nutr 55:754–763

White TJ, Bruns T, Lee S, Taylor J (1990) Amplification and direct sequencing offungal ribosomal RNA genes for phylogenetics. In: Innis MA (ed) PCRprotocols, a guide to methods and applications. Academic, NewYork, pp 315–322

Yamaguchi I (2004) Overview on the chemical control of rice blast disease. In: Kawasaki S (ed) Rice blast: interaction with rice and control. Kluwer Academic Publishers, The Netherlands, pp 1–13

Yeh WH, Bonman JM (1986) Assessment of partial resistance to Pyricularia oryzae in six rice cultivars. Plant Pathol 35:319–323

Yogev A, Raviv M, Kritzman G, Hadar Y, Cohen R, Kirshner B, Katan J (2009) Suppression of bacteria canker of tomato by compost. Crop Prot 28:97–103