RICE-BASED BIOSYSTEMS JOURNAL

2015

Volume 8 • February 2021

DEPARTMENT OF AGRICULTURE
1898

Philippine Rice Research Institute
Central Experiment Station
Maligaya, Science City of Muñoz, 3119 Nueva Ecija

ABOUT THE COVER

New rice technologies are results of continuous research that bring new ideas to improve living conditions of humankind. These technologies have evolved through time in establishing state of the art products, designs, methods, and transferring them to the users. In this issue, research innovations have focused on herbicide utilization, biochar production, improved sprinkler irrigation system, hybrid rice development, genetic diversity, green manuring, and soil-related technologies that are important in understanding applications in rice production. These innovations create an important niche in bringing opportunities for farmers and entrepreneurs in advancing economic growth and in improving living conditions.

Instructions on manuscript submission are found on pages 106-108.
For more information, please visit www.philrice.gov.ph/grants/call-publication/.

RICE-BASED BIOSYSTEMS JOURNAL

VOLUME 8 ▪ FEBRUARY 2021

Published by:

Philippine Rice Research Institute
Central Experiment Station
Maligaya, Science City of Muñoz, 3119 Nueva Ecija

RBBJ

VOLUME 8, FEBRUARY 2021

CONTENTS

FULL PAPER

RESEARCH NOTE

FULL PAPER

EFFECTS OF DIFFERENT WEED MANAGEMENT STRATEGIES IN WET DIRECT-SEEDED RICE UNDER RAINFED CONDITIONS

Dindo King M. Donayre[1], Cherry E. Tayson[2], and Ian Mark G. Ciocon[2]

[1]Philippine Rice Research Institute, Science City of Muñoz, Nueva Ecija, Philippines, [2]Regional Crop Protection Center Department of Agriculture-Regional Field Office VI, WESVIARC Compound, Hamungaya, Buntatala, Jaro, Iloilo, Philippines

*Corresponding Author: dkmdonayre@philrice.gov.ph

Abstract

Herbicide application and hand weeding, two of the most commonly practiced weed control techniques by Filipino farmers, showed effects in wet direct-seeded rice (DWSR) under irrigated-lowland conditions. However, effects under rainfed conditions in the Philippines are still unreported. Two experimental field trials determined the effects of applying herbicide and hand weeding in terms of diversity, abundance, and dominance in DWSR under rainfed conditions. Four experimental treatments [unweeded (T1), hand weeding alone (T2), pre-emergence herbicide + hand weeding (T3), and post-emergence herbicide + hand weeding (T4)] were tested and arranged in Randomized Complete Block Design (RCBD) with four replications. T1 and T2 favored weed diversity at 15, 30, and 45 days after seeding (DAS). Low diversity of weeds was observed in T4. Cluster analysis showed that annual sedges (*C. difformis* and *C. iria*) were the most abundant weeds in T1 and T2 while perennial grasses (*P. distichum* and *L. chinensis*) in T3 and T4. The analysis of summed-dominance ratio showed that T1 was mainly dominated by *Cyperus* spp.; T2 by *Cyperus* spp., *L. chinensis*, *Fimbristylis* spp., and *Ludwigia* spp.; T3 by *P. distichum*; and T4 by *L. chinensis*. In both trials, DWSR yielded 1311.8 and 651.1 kg ha^{-1} in T1; 2886.9 and 1939.2 kg ha^{-1} in T2; 3288 and 1289 kg ha^{-1} in T3; and 3874.9 and 1448.2 kg ha^{-1} in T4. Highest weed control cost was recorded in T2 (PhP 2,384.50) and least expenses in T4 (PhP 970.40).

Keywords: *Direct-Seeding, Bispyribac-Sodium, Pretilachlor, Rainfed Lowland, Weed Abundance.*

Introduction

Rainfed lowland is a type of ecosystem where rice plants are grown leveled, bunded, and supplied with water from the rain (Mackill et al., 1996). It is also a type of rice culture where the soil surface is flooded to a maximum depth of less than 50 cm during a portion of the crop's cycle (Ampong-Nyarko and De Datta, 1991). In the Philippines, rainfed rice farming is one of the contributors in the total rice production. Data from the Philippine Statistics Authority (2014, 2017, 2019) showed that areas devoted to rainfed rice farming from 2009 to 2013 ranged from 1.48 to 1.51 M ha with volume of palay production of 4.18 - 4.62 M mt and average yield of 2.83 - 3.06 t ha^{-1}. Records also show a production area of 4.66 - 4.8 M ha with palay production of 4.21 to 4.7 M mt and average yield of 1.42 to 3.12 t ha^{-1} in 2015 - 2018.

Direct wet-seeding is a method of rice establishment, in which pre-germinated seeds are sown directly onto the puddled soil. Once seedling is established, rice plants can then be sequentially flooded and maintained at right amount of water similar to the transplanted rice (Rao et al., 2007). In Asia, many farmers had shifted from transplanting to direct-seeding due to lesser labor cost during crop establishment; availability of new, short maturing varieties; and accessibility of herbicides (Pandey and Velasco, 2002; Ampong-Nyarko and De Datta, 1991). The shifting to direct-seeding, however, had resulted in the increase of dominance and abundance of weed species that are well adapted to varying conditions in the field like *Echinochloa glabrescens* Munro ex Hook. f., *Ischaemum rugosum* Salisb., *Cyperus difformis* L., and *Fimbristylis miliacea* (L.) Vahl. (Tomita et al., 2003; Casimero 2008; Rao et al., 2007; Chauhan and Johnson, 2010). In unfavorable rainfed lowland rice farming where water is not supplied through controlled irrigation, but rather through frequent rains during the growing season, growth and development of weeds are greatly favored especially during fluctuations of moisture level due to uneven rainfall patterns. Under uncontrolled condition, growth of weeds can significantly reduce yield of rainfed rice from 51 to 74% (Ampong-Nyarko and De Datta, 1991).

Hand weeding and herbicide application are two of the most commonly used weed management techniques by Filipino farmers. Other weed control techniques include use of clean seeds, good land preparation, good water management, and use of mechanical weeder (Donayre et al., 2014; Moody et al., 1997; Estorninos and Moody, 1982; Navarez et al., 1981). Many farmers favor the use of hand weeding because it is immediately available and practically applicable in areas where workers are abundant. Other farmers, on the other hand, use herbicides because it requires less labor, easily applied, and shows immediate results.

Understanding the effects of weed control interventions on weed population dynamics is very helpful in predicting the ecological changes in the field (Moody, 1996). It also helps refine the control interventions to prevent weed shifts and complexity on weed management. Effects of hand weeding and herbicide control on weeds and yield of rice have been known in irrigated lowland rice (Ihsan et al., 2014; Ehsanullah et al., 2014). In direct wet-seeded rice planted under rainfed conditions, however, these aspects are still yet to be known. This study hypothesized that hand weeding and herbicide interventions affect the diversity, abundance, and dominance of weeds in direct wet-seeded rice under rainfed conditions.

Materials and Methods

Field Plot Preparation and Crop Husbandry

Two experimental trials were conducted at Philippine Rice Research Institute of the Department of Agriculture (DA-PhilRice) in Cansilayan, Murcia, Negros Occidental under Silay soil series (fine loamy, mixed, isohyperthermic, *Aquic Tropudalfs*) (Collado et al., 2014). The first experiment was conducted from June to October 2011 coinciding the wet season with 8.41 mm mean rainfall (Figure 1), 26.3 °C mean temperature, and 91.16% relative humidity. The second experiment was implemented from December 2011 to March 2012 coinciding with dry season with 3.12 mm mean rainfall, 26.23 °C mean temperature, and 88.4% mean relative humidity. The experimental field area was plowed once with carabao-drawn moldboard plow, harrowed twice with hand tractor-rotavator machine, and leveled once with carabao-drawn wooden plank. After thorough leveling, a 100 m^2 plot size was prepared for each treatment. Pre-germinated seeds of PSB Rc10 (registered class seed) were broadcasted simultaneously at seeding rate of 60 kg ha^{-1}. Growing rice plants were nourished with 46 kg N ha^{-1}, 11 kg P ha^{-1}, and 11 kg K ha^{-1} at 20-25 (DAS) for the first dose; 46 kg N ha^{-1}, 9 kg P ha^{-1}, and 9 kg K ha^{-1} at 40 - 45 DAS for the second dose. All plants in each plot depended solely on rainwater.

Experimental Treatments

Experimental treatments included unweeded (T1), hand weeding alone (T2), pre-emergence herbicide + handweeding (T3), and post-emergence herbicide + handweeding (T4). Pre-emergence herbicide, using pretilachlor at 450 g a.i. ha^{-1}, was applied at 3 DAS and post-emergence, using bispyribac-sodium at 31.65 g a.i. ha^{-1} at 8 DAS. Pretilachlor and bispyribac-sodium were selected in this experiment as these herbicides are commonly used by farmers against weeds of direct-seeded rice under rainfed conditions (Donayre et al., 2014). Meanwhile, rate and time of applications were based on recommendations of PhilRice (2001). Except for T1, follow-up hand weedings were supplemented in T2, T3, and T4 based on weed control action indicator (WCAI). WCAI is a tool for checking whether additional weed control (either by hand weeding or herbicide application) is needed after initial implementation of weed management strategies (Paller et al., 2001; PhilRice, 2001). It uses relative weed height (RWH) and relative weed cover (RWC) in the field as basis for implementing another cycle of control measure. The tool recommends additional weed control if the RWH and RWC were >20% and >5% at 15 DAS; and >30% and >5% at 30 and 45 DAS. RWH was calculated by dividing the mean height of all weeds (regardless of species and

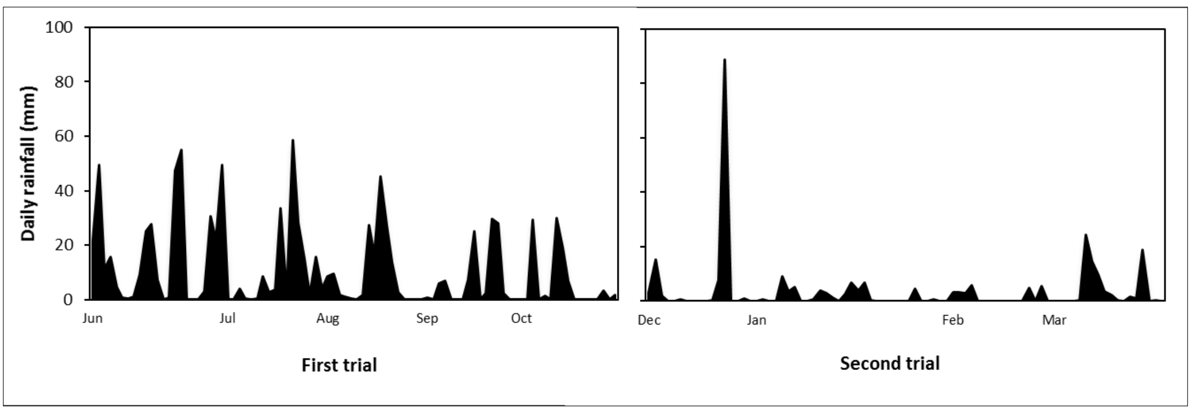


Figure 1. Rainfall patterns during the conduct of the study at PhilRice Negros (Source: PhilRice Negros Agromet Station, Cansilayan, Murcia, Philippines).

growth stages) over the mean height of rice plants per m^2 sample area. The RWC, on the other hand, was visually measured from sampled areas covered by weeds (regardless of species and growth stages). In this experiment, hand weeding technique was used as supplementary control to all treatments requiring this activity.

Data Gathered

Weed community was observed in each plot using three quadrats (0.5 m x 0.5 m) per treatment at 15, 30, and 45 DAS. Weeds inside quadrats were collected for identification, counting, and weighing of biomass. Weed community was determined based on diversity, abundance, and dominance. Diversity of weeds in each treatment was calculated using the Shannon-Weiner's Diversity Index while the abundance of weeds was measured through weed density (plants m^{-2}) and weed biomass (g m^{-2}) (Nkoa et al., 2015; Booth et al., 2003; Moody, 1987). Dominance of weed species, on the other hand, was calculated based on summed-dominance ratio (SDR) as shown in the formula below (Wibawa et al., 2009):

$$SDR\ of\ a\ species = \frac{Relative\ density + Relative\ frequency + Relative\ dominance}{3}$$

where:

$$Relative\ density\ of\ a\ species = \frac{Absolute\ density\ of\ a\ species\ in\ all\ quadrats}{Total\ absolute\ densities\ of\ all\ weed\ species\ in\ all\ quadrats}$$

$$Relative\ frequency\ of\ a\ species = \frac{Absolute\ frequency\ of\ a\ species}{Total\ of\ all\ absolute\ frequencies\ of\ all\ weed\ species}$$

$$Frequency\ abundance\ of\ a\ species = Absolute\ frequency \times Average\ abundance$$

Yield per plot was determined by harvesting the matured grains of rice within a 5 m x 2 m crop cut area. Cut panicles were placed inside nylon sacks then sun-dried for three days. After sun drying, filled and unfilled grains were separated from branches and other dried parts of the plant. Moisture content and weight of filled grains from each plot were measured. Yield in grams per 10 m^2 were then converted into kilograms per hectare after adjusting the grain moisture content at 14%. Weed control cost of each treatment was also computed based on the cost, volume sprayed, time, and number of work days spent for herbicide application and hand weeding.

Experimental Design and Analysis

Each experiment was arranged in RCBD with four replications. All the data were subjected to ANOVA using STAR 201. Data on weed diversities, densities, and biomasses from the two experimental trials were pooled as prior analysis showed no significant interaction between trial and treatments. The data together with summed dominance ratios at 15, 30, and 45 DAS were further subjected to cluster analysis using the SAS 9.1.3. Meanwhile, data on yield were separately analyzed due to interaction between trial and treatments. All means were compared using Fisher's LSD at 5% level of significance.

Results and Discussion

Weed Diversity

Species richness describes the number of species present in an area while evenness describes whether a weed community is dominated by one, a few, or equal number of species. Unweeded plots (T1) had the most diverse weed species at 15, 30, and 45 DAS. Plots in T2 had highest species richness (H= 0.78) and evenness (E= 0.76) at 15 days after seeding (DAS) (Figure 2). Low species richness (H=0.42) and evenness (E=0.35) in T1 was observed due to dominance of one weed species as had been shown in the next discussions. Meanwhile, plots treated with herbicides aided with hand weeding (HW) had zero species richness and evenness at 15 DAS. At 30 DAS, mean values of species richness in T3 (H= 1.38) and T4 (H= 1.27) were significantly the same in T1 (H= 1.40) based on Fisher's LSD. Furthermore, species evenness in T2 (E= 0.71) was also the same in T3 (E= 0.77) and T4 (0.67) except in T1 (E= 0.91). Species richness and evenness were lowest in T4. At 45 DAS, species richness in T2 and T3 were significantly comparable. Low diversity of weeds was observed in T4. The findings suggest that planting rice plants without doing weed control or implementing less effective control interventions could result in severe infestations by numerous weed species. Effect of hand weeding alone on weed diversity is almost the same as without doing weed control. This means that doing hand weeding alone is not a good weed control option in direct-seeded rice under rainfed conditions. Although the use of herbicide + hand weeding resulted in lesser infestations of different weed species, it caused another weed species to dominate throughout the growth stages of rice.

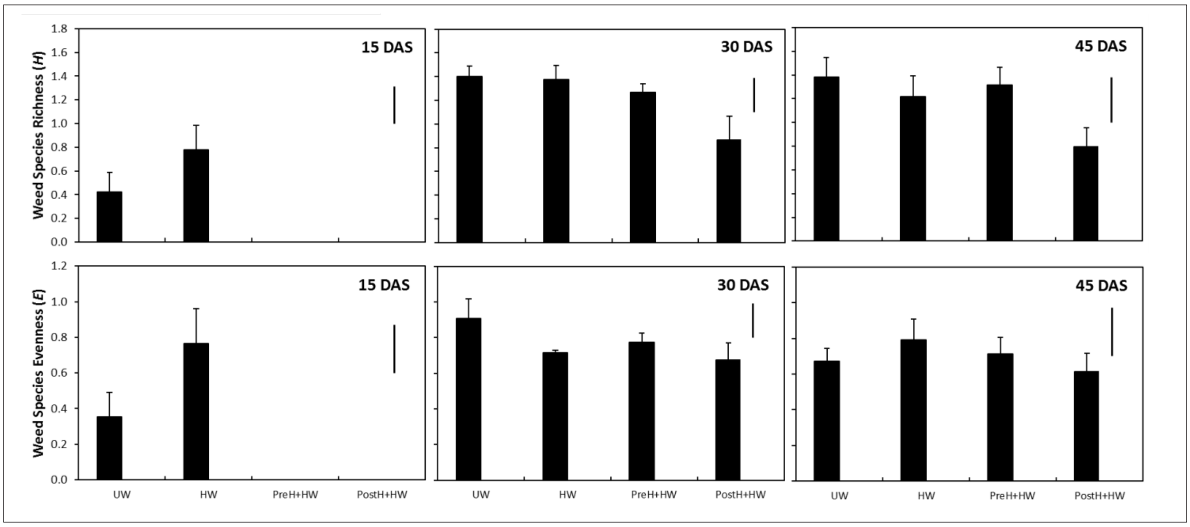


Figure 2. Diversity of weeds as influenced by different treatments (T1 = unweeded, T2 = hand weeding alone, T3 = pre-emergence herbicide + hand weeding, T4 = post-emergence herbicide + hand weeding; error bars are + SE of the means; vertical bars are LSD values at 5% level of significance).

Weed Abundance and Dominance

Studying the abundance and distribution of weeds helps assess the efficacy and efficiency of a single or combined weed control technique. It also helps assess how a certain weed population or species changes over time in response to control interventions. Fourteen weed species were infesting and growing with direct-seeded rice planted under rainfed conditions. Of the 14 common weed species, four of these belonged to grasses *Echinochloa colona* (L.) Link (ECHCO), *Ischaemum rugosum* Salisb. (ISCRU), *Leptochloa chinensis* (L.) Nees (LEFCH), and *Paspalum distichum* L. (PASDI); four belonged to sedges *Cyperus* spp. (CYP sp) = *C. difformis* L. and *C. iria* L., *Fimbristylis* spp. (FIM sp) = *F. miliacea* (L.) Vahl. and *F. dichotoma* (L.) Vahl.; and six belonged to broadleaves *Eclipta prostrata* (L.) L. (ECLAL), *Hydrolea zeylanica* (L.) Vahl. (HYMZE), *Ludwigia* spp. (LUD sp.) = *L. hyssopifolia* (G. Don) Exell, and *L. octovalvis* (Jacq.) Raven, *Monochoria vaginalis* (Burm.f.) C. Presl. (MOOVA), and *Sphenoclea zeylanica* Gaertn (SPDZE). Most of these weed species were also encountered by Donayre et al. (2014), Sanusan et al. (2010), Tomita et al. (2003), and Estorninos and Moody (1982) when they studied the ecology and management of weeds in rainfed rice ecosystem.

Unweeded plots (T1) from the day of seeding until harvest had the highest densities and biomasses of weeds followed by T2 (Tables 1 and 2). Plots treated with pre-emergence and post-emergence herbicides aided with hand weeding had the least densities and biomasses of weeds. At 15 DAS, the total density and biomass of weeds in T1 plots were 197.1 plants m^{-2} and 13.2g m^{-2}, respectively. Weeds in T2 had density values of 56.4 plants m^{-2} and biomass of 11.4g m^{-2}. T3 and T4 had zero values of weed densities and biomasses. CYP sp., LUD sp., MOOVA, and SPDZE were among the weed species observed in T1 and T2 plots.

At 30 DAS, the total density of weeds in T1 increased to 251.2 plants m^{-2} while 93.6 plants m^{-2} in T2. Weed densities in T3 and T4 also increased from 0 to 42 and 52.4 plants m^{-2}, respectively. Weed densities in herbicide-treated plots, however, were lower compared with T1 and T2. LEFCH, CYP sp., FIM sp., and LUD sp. were the most abundant weeds in T1 and T2 plots while PASDI and LEFCH in T3 and T4. Same trend was observed on weed abundance based on biomass (Table 2). Biomasses of weeds were highest in T1 (85.4g m^{-2}) followed by T2 (79.4g m^{-2}). T3 and T4 had lower biomass of weeds weighing at 26 and 23.5g m^{-2}, respectively. CYP sp. and LEFCH in T1; CYP sp., in T2; PASDI in T3; and LEFCH in T4 were the most abundant weeds in terms of biomass.

At 45 DAS, the total density of weeds in T1 was 226.3 plants m^{-2} while 110.5 plants m^{-2} in T2. Species of LUD sp., FIM sp., CYP sp., PASDI, and LEFCH were the most abundant in these treatments. Least number of weeds was observed in herbicide- treated plots. PASDI and LEFCH was the most abundant weed species in these plots.

Total biomass of weeds in T1 was 411.9 plants m^{-2} while 43.9, 59 and 50.3g m^{-2} in T2, T3, and T4, respectively. CYP sp. had the heaviest biomass in T1; MOOVA, CYP sp., and LEFCH in T2; CYP sp., PASDI, and LEFCH in T3; and PASDI and LEFCH in T3 and T4, respectively.

Combining all the means of densities and biomasses of weeds at 15, 30, and 45 DAS through

Table 1. Density of weeds as influenced by hand weeding and herbicide applications.

Treatments	Weed Density m^{-2}											Total
	Grasses				Sedges		Broadleaves					
	ECHCO	ISCRU	LEFCH	PASDI	CYP sp.	FIM sp.	ECLAL	HYMZE	LUD sp.	MOOVA	SPDZE	
15 DAS												
T1	0	0	0	0.3	71.2	0	0	0	61.6	63.6	0.4	197.1
T2	0	0	0	0.3	13.6	0	0	0	12.8	29.8	0.0	56.4
T3	0	0	0	0	0	0	0	0	0	0	0	0
T4	0	0	0	0	0	0	0	0	0	0	0	0
LSD	0	0	0	0.4	74.8	0	0	0	80.7	45.9	0.8	69.3
30 DAS												
T1	0	0	49.7	11.7	82.2	55.9	1.2	5.8	36.8	5.8	2.2	251.2
T2	0	0.5	9.1	2.9	21.5	31.3	0	4.2	18.9	1.5	3.8	93.6
T3	0	4.2	1.4	22.8	1.9	3.1	0	2.9	4.0	0.1	1.6	42.0
T4	1.3	0	37.9	6.0	5.4	0.0	0	0	1.9	0	0.0	52.4
LSD	1.2	2.3	36.4	14.8	53.8	42.0	1.1	10.3	38.5	6.3	3.2	130.5
45 DAS												
T1	0.1	2.3	29.1	28.4	49.1	65.5	0	9.0	37.5	2.0	3.1	226.3
T2	0	0	25.2	5.8	30.8	27.4	0	2.8	17.3	0.3	0.8	110.5
T3	0.7	2.1	1.4	12.0	1.1	1.5	0	1.2	1.4	0	0.7	22.1
T4	0	0	19.8	3.0	2.8	0	0.6	0	1.0	0	0	27.0
LSD	1.8	3.7	31.3	23.5	33.2	64.9	0.8	9.4	32.8	2.0	2.6	76.1

T1 = unweeded, T2 = hand weeding alone, T3 = pre-emergence herbicide + hand weeding, T4 = post-emergence herbicide + hand weeding; Grasses {*Echinochloa colona* (ECHCO), *Ischaemum rugosum* (ISCRU), *Leptochloa chinensis* (LEFCH), and *Paspalum distichum* (PASDI)}; Sedges {[*Cyperus* spp. (CYP sp) = *C. difformis* and *C. iria*], [*Fimbristylis* spp. (FIM sp. = *F. miliacea* and *F. dichotoma*] }; Broadleaves {*Eclipta prostrata* (ECLAL), *Hydrolea zeylanica* (HYMZE), [*Ludwigia* spp. (LUD sp.) = L. *hyssopifolia* and L. *octovalvis*], *Monochoria vaginalis* (MOOVA), and *Sphenoclea zeylanica* (SPDZE)}; mean values exceeding the LSD values are not significantly different at 5% level of significance.

Table 2. Biomass of weeds as influenced by hand weeding and herbicide applications.

Treatments	Weed Biomass (g m^{-2})											Total
	Grasses				Sedges		Broadleaves					
	ECHCO	ISCRU	LEFCH	PASDI	Cyp sp.	Fim sp	ECLAL	HYMZE	Lud sp.	MOOVA	SPDZE	
15 DAS												
T1	0	0	0	2.6	5.1	0	0	0	4.9	0.5	0.1	13.2
T2	0	0	0	2.6	3.8	0	0	0	4.5	0.5	0.0	11.4
T3	0	0	0	0	0	0	0	0	0	0	0	0
T4	0	0	0	0	0	0	0	0	0	0	0	0
LSD	0	0	0	1.3	1.7	0	0	0	1.5	0.0	0.2	4.7
30 DAS												
T1	0	0.0	13.3	1.9	43.9	4.5	0.1	1.6	7.9	7.4	4.9	85.4
T2	0	0.6	7.1	8.1	38.0	6.0	0	3.0	5.8	7.6	3.1	79.4
T3	0	2.5	0.6	11.6	2.1	2.1	0	3.5	2.5	0.5	0.5	26.0
T4	0.3	0	16.4	4.0	1.6	0.0	0	0.0	1.3	0	0	23.5
LSD	0.2	1.5	14.8	9.9	20.1	5.9	0	4.3	4.3	9.5	7.6	42.0
45 DAS												
T1	16.6	3.1	53.0	40.4	198.1	26.5	0	7.6	24.8	23.4	17.9	411.4
T2	0	0	9.5	2.5	9.5	5.4	0	2.5	3.8	10.3	0.5	43.9
T3	6.6	1.9	9.8	12.4	14.1	1.9	0	1.3	2.8	0	8.4	59.0
T4	0	0	24.6	14.0	9.8	0	0.6	0	1.3	0	0	50.3
LSD	29.7	4.9	33.4	31.9	62.2	19.8	1.0	6.7	13.7	25.4	24.3	84.9

Mean values exceeding the LSD values are not significantly different at 5% level of significance.

cluster analysis showed that annual sedges (*C. difformis* and *C. iria*) were the most abundant weeds in T1 and T2 plots (Figure 3). Grasses, particularly PASDI (perennial) and LEFCH (annual/perennial), were the most abundant weeds in T3 and T4. Further analysis of the summed-dominance ratio of each weed species also revealed that T1 was mainly dominated by CYP sp.; T2 by CYP sp., LEFCH, FIM sp., and LUD sp.; T3 by PASDI; and T4 by LEFCH (Figure 4).

The dominance of FIM sp., CYP sp., LUD sp., and LEFCH in unweeded plots can be attributed to their rapid germination and growth on top of soil surfaces at minimal moisture contents in the field. In an ecological study done by Chauhan and Johnson (2009a), it was discovered that soil surface-sown seeds of *C. iria*, *C. difformis*, and *F. miliacea* under saturated condition had higher percentages of seedling emergence (86.7, 55.0, and 54.7%) than when buried at ≥1cm depths. They also found that seedling emergence of the three-weed species under saturated condition had no significant differences when sown in aerobic condition. Their findings had similar results in separate studies on *Leptochloa chinensis* (Chauhan and Johnson, 2008), *Ludwigia hyssopifolia* (Chauhan and Johnson, 2009b), and *F. miliacea* (Begum et al., 2006). Furthermore, the dominance of FIM sp., CYP sp., LUD sp., and LEFCH can also be explained in their abilities to survive in changing field conditions. In the study of Chauhan and Abugho (2013) on the effect of water stress on *L. chinensis* and rice, for example, weed survived the levels of soil water content (12.5, 25, 50, 75, and 100%) as compared to rice that only survived at 50 to 100% field capacities. Outnumbering other weed species by production of viable seeds and growing seedlings in high-volume could also be another attribution to their dominance. According to Galinato et al. (1999), *L. chinensis* can

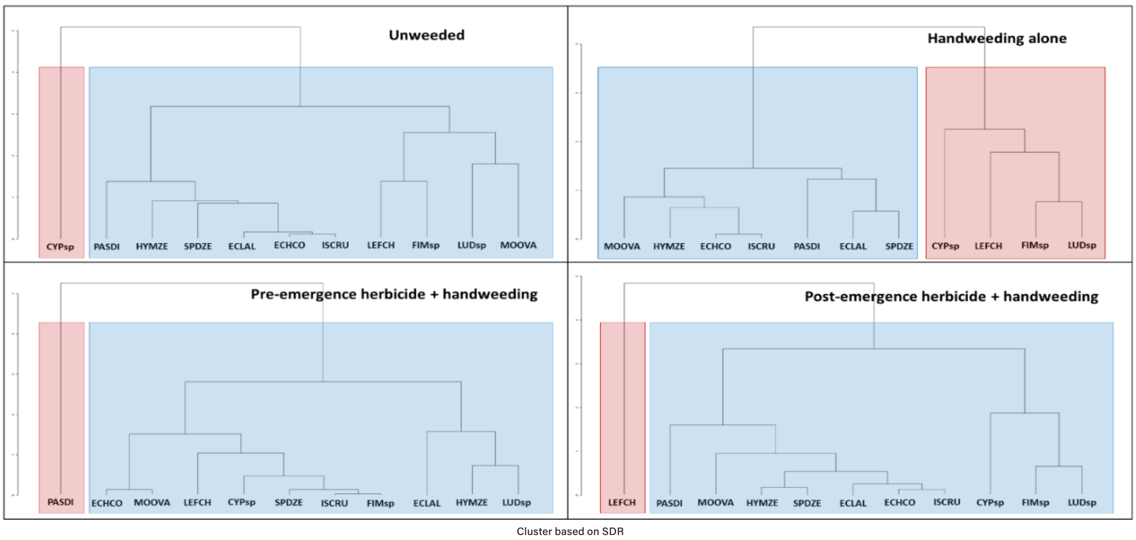


Figure 3. Dendograms of abundant weeds based on density and biomass.

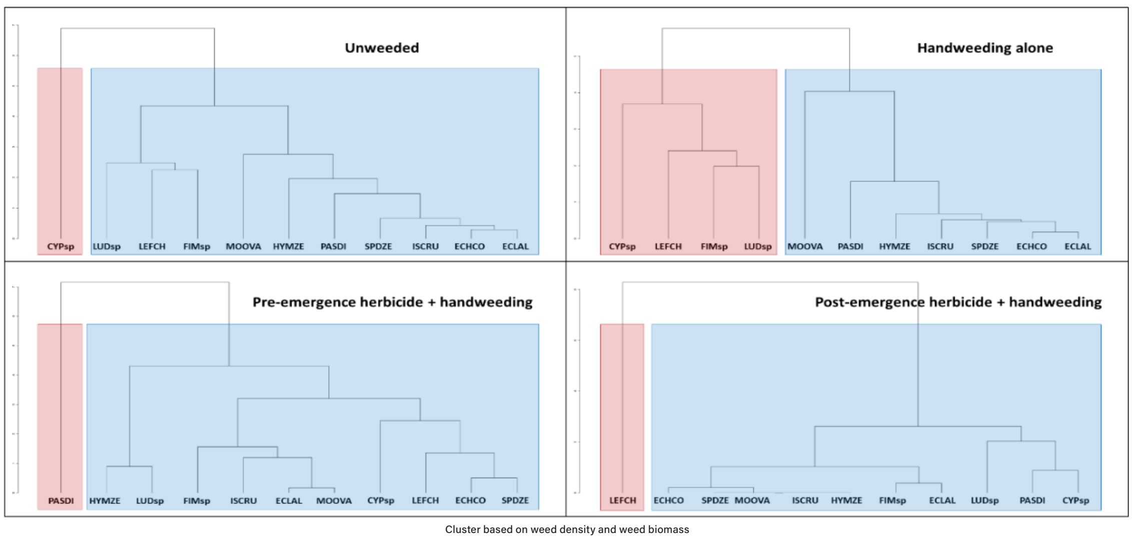


Figure 4. Dendograms of dominant weeds based on summed-dominance ratios.

produce a mean of 27,000 seeds plant^{-1} while *C. iria*, and *F. miliacea* by as much as 4,000 and 10,000 seeds plant^{-1}, respectively.

The dominance of *P. distichum* under pre-emergence herbicide treatment supplemented with hand weeding can be attributed to the escape of its buried-stolons during the time of herbicide application. Stolons of *P. distichum* are modified above-ground stems that produce roots in the nodes and later creep into the ground to become independent plants (Ampong-Nyarko and De Datta, 1991; Moody et al., 2014). Likewise, the supplementation of hand weeding might have aggravated the regeneration and multiplication of the stolons into new developing *P. distichum* seedlings. These attributions may also explain the dominance of *L. chinensis* in plots treated with post-emergence treatment supplemented with hand weeding. *L. chinensis*, like *P. distichum*, is also an annual grass that does not only propagate by seeds but also through stem fragments. Stem fragments of the weed, which were cut into pieces and buried during land preparation, had escaped from the toxic effect of bispyribac-sodium used as post-emergence herbicide in this experiment. In studying the efficacies of different herbicides under dry-seeded field condition, Awan et al. (2015) reported that bispyribac-sodium did not effectively control the density and biomass of *L. chinensis* when used as post-emergence at 14 and 22 days after seeding. Similar findings were also reported by Abeysekara and Wickrama (2005) in their study on wet-seeded rice.

Yield of Direct-Seeded Rice

Direct-seeded rice in T1 plots had the lowest grain yield among treatments in both trials (1,311.8 and 651.1 kg ha^{-1}) (Table 3). In T2 plots, grain yields were 2,886.9 kg ha^{-1} in the first trial and 1,939.2 kg ha^{-1} in the second trial, which is a 120 and 66.4% increase over the yield in T1. On the other hand, rice plants in plots treated with T3 yielded 3,288 and 1,289 kg ha^{-1}; a 150.7 and 49.5% increase over the yield in T1 while 13.9 and 0% increase over the yield in T2. In plots treated with T4, grain yields were 3,874.9 and 1,448.2 kg ha^{-1}; a 195.4 and 55% increase over the yield in T1 while 34.4 and 0% increase over the yield obtained in T2. Plots in T2 had the highest weed control expense (PhP 2,384.5) during the first trial but the least cost in the second trial. Meanwhile, plots treated with T4 had lower weed control cost (PhP 970.4) than T3 (PhP 3,288). Both herbicide aided with hand weedings had higher weed control costs than hand weeding alone during the second trial. Lower yield and higher weed control costs in herbicide and hand weeded plots during the second trial were attributed to the occurrence of prolonged drought at 50 DAS until harvest.

Manual weeding is effective against different kinds of weeds especially if it is properly and timely done with good water control. Filipino farmers rely on this technique because it is easy to employ and requires less labor in small rice fields (Donayre et al., 2014). Results of this study, however, suggest that using hand weeding alone for DWSR under rainfed conditions is less effective and could result in more growth and diverse weed species. Using it alone could also result in lower yield and higher weed control costs due to repeated hand weeding. Meanwhile, spraying herbicides is more effective in suppressing weed growth than hand weeding. However, continuous use of single herbicide will likely cause a change in the predominating weed species in an area (Mercado, 1983). The results of this study showed that combining herbicide with hand weeding was more effective in minimizing weed growth and improving rice yield than hand weeding alone. However, the data showed the combining the two resulted in the dominance of perennial weed species. Thus, to achieve sustainable weed control for DWSR, continuous use of the same herbicide with the same amount and timing of application is not recommended as this practice may lead to invasion, dominance, and development of resistance by one or more species, which could become a big problem in the next cropping seasons.

Table 3. Yield of direct-seeded rice as influenced by different treatments.

Treatments	Grain Yield (kg ha^{-1})		Weed Control Cost (PhP ha^{-1})	
	First Trial	Second Trial	First Trial	Second Trial
T1	1,311.8^{c}	651.1^{b}	-	-
T2	2,886.9^{b}	1,939.2^{a}	2,384.5	4,706.6
T3	3,288.0^{ab}	1,289.1^{a}	1,156.4	5,079.5
T4	3,874.9^{a}	1,448.2^{a}	970.4	4,893.5

Means with the same letters are not significantly different at 5% level of significance.

Conclusion

Herbicide and hand weeding showed effects on managing weed population and rice yield in direct wet-seeded rice under rainfed conditions. Hand weeding alone resulted in the dominance of *Cyperus* spp., *L. chinensis*, *Fimbristylis* spp., and *Ludwigia* spp. while the application of pre-emergence herbicide + hand weeding and post-emergence herbicide + hand weeding resulted in the dominances of *P. distichum* and *L. chinensis*, respectively. Hand weeding alone resulted in less yield and higher weed control cost while use of herbicides + hand weeding resulted in higher yield at least weed control costs. These findings could help explain or predict the possible outcomes (weed diversity and abundance) when weed control is not implemented, or done through hand weeding alone or a combination of hand weeding with herbicides. The findings could also help improve the weed control strategies against different weeds of direct wet-seeded rice under unfavorable rainfed conditions.

Literature Cited

Abeysekara ASK, Wickrama UB (2005) Control of *Leptochloa chinensis* (L.) Nees in wet-seeded rice fields in Sri Lanka. *In* Rice is life: Scientific perspectives for the 21th century. Proceedings of the World Rice Research Conference (pp 215-217). Japan: Tokyo and Tsukuba

Ampong-Nyarko K, De Datta SK (1991) A handbook for weed control in rice. Philippines: International Rice Research Institute

Awan TH, Sta Cruz P, Chauhan BS (2015) Efficacy and economics of different herbicides, their weed species selectivity, and the productivity of mechanized dry-seeded rice. Crop Protection **78**: 239-246

Begum M, Juraimi AS, Amartalingam R, Bin Man A, Bin Syed Rastans SO (2006) The effects of sowing depth and flooding on the emergence, survival, and growth of *Fimbristylis miliacea* (L.) Vahl. Weed Biology and Management **6**: 157-164

Booth BD, Murphy SD, Swanton CJ (2003) Weed ecology in natural and agricultural systems. UK: CABI Publishing, Oxon

Casimero MC, Bakar B, Man A (2008) Sustainable weed management in rice in Asia: A regional perspective. Proceedings of the 39th Anniversary and Annual Scientific Conference of the Pest Management of the Philippines, Palawan, Philippines

Chauhan BS, Abugho SB (2013) Effect of water stress on the growth and development of *Amaranthus spinosus*, *Leptochloa chinensis*, and Rice. American Journal of Plant Sciences **4**: 989-998

Chauhan BS, Johnson DE (2008) Germination ecology of Chinese sprangletop (*Leptochloa chinensis*) in the Philippines. Weed Science **56**: 820-825

Chauhan BS, Johnson DE (2009a) Ecological studies on *Cyperus difformis*, *Cyperus iria* and *Fimbristylis miliacea*: Three troublesome annual sedge weeds of rice. Annals of Applied Biology **155**: 103-112

Chauhan BS, Johnson DE (2009b) *Ludwigia hyssopifolia* emergence and growth as affected by light, burial depth and water management. Crop Protection **28**: 887-890

Chauhan BS, Johnson DE (2010) The role of seed ecology in improving weed management strategies in the tropics. Advances in Agronomy **105**: 221-262

Donayre DKM, Endino CA, Seville CU, Ciocon IMG (2014) Major weeds and farmers' weed management practices in rainfed ricefields of Negros, Philippines. Asia Life Sciences **23**(1): 137-148

Ehsanullah SAA, Ashraf U, Rafiq H, Tanveer M, Khan I (2014) Effect of sowing dates and weed control methods on weed infestations, growth and yield of direct-seeded rice. Philippine Agriculturist **97**(3): 307-312

Estorninos LE, Moody K (1982) Farmers' weed control practices in rainfed wetland rice (*Oryza sativa*) growing areas in Iloilo, Philippines. Philippine Journal of Weed Science **9**: 18-28

Galinato MI, Moody K, Piggin CM (1999) Upland rice weeds of South and Southeast Asia. Philippines: International Rice Research Institute

Ihsan MZ, Khaliq A, Matloob A, El-Nakhlawy FA, Ahmed RA, Daur I, Aslam Z (2014) Influence of herbicides applied alone or supplemented with manual weeding on weed growth, rice yield and grain quality in direct-seeded rice (*Oryza sativa* L.). Philippine Agriculturist **97**(4): 395-402

Mackill DJ, Coffman WR, Garrity DP (1996) Rainfed lowland rice improvement. Philippines: International Rice Research Institute

Mercado BL (1983) Interactions between herbicide use and the weed flora of upland and rainfed crops. *In* Walter H (Ed.). Weed Management in the Philippines: Report of Seminars (pp 152-159). Germany: Josef Margraf, Oberwiesentr. Stuttgart

Moody K (1987) Weeds: generating populations, field sampling, and data analysis. *In* IRRI (Ed.). Crop Loss Assessment in Rice (pp 75-86). Philippines: International Rice Research Institute

Moody K (1996) Weed community dynamics in ricefields. *In* Naylor R (Ed.). Herbicides in Asian Rice: Transitions in Weed Management (pp 27-36). Palo Alto (California) Institute for International Studies, Stanford University and Manila Philippines: International Rice Research Institute

Moody K, Munroe CE, Lubigan RT, Paller Jr EC, Barcial PM, Fabro LE, Janiya JD, Magsino GL (2014) Major weeds of the Philippines (2nd Ed). Philippines: University of the Philippines Los Baños

Navarez DC, Estaño DB, Moody K (1981) Preliminary evaluation of farmers' weed control practices in Cagayan, Philippines. Philippine Journal Weed Science **8**: 49-55

Nkoa R, Owen MDK, Swanton CJ (2015) Weed abundance, distribution, diversity, and community analyses. Weed Science Special Issue: 64-90

Paller EC, Ramirez AHM, Malenab ET (2001) Weed management in grain corn: Comparing calendared treatments and use of weed control action indicators (WCAI). Philippine Journal of Crop Science **27**(1): 9-12

Pandey S, Velasco L (2002) Economics of direct seeding in Asia: patterns of adoption and research priorities. *In* Pandey S, Mortimer M, Wade L, Tuong TP, Lopez K, Hardy B (Eds.). Direct seeding: Research issues and opportunities. Proceedings of the International Workshop on Direct Seeding in Asian Rice Systems: Strategic Research Issues and Opportunities (pp 3-14) Thailand: Bangkok

PhilRice [Philippine Rice Research Institute] (2001) Management options for rice field weeds. Philippines: Philippine Rice Research Institute

PSA [Philippine Statistics Authority] (2014) Major crop statistics of the Philippines (9th Edition). Quezon City, Metro Manila, Philippines. Retrieved from https://psa.gov.ph/content/selected-statistics-agriculture (accessed May 5, 2015)

PSA [Philippine Statistics Authority] (2017) Selected Statistics Agriculture. Quezon City, Metro Manila, Philippines Retrieved from https://psa.gov.ph/content/selected-statistics-agriculture (accessed June 5, 2018)

PSA [Philippine Statistics Authority] (2019) Palay and corn quarterly bulletin (October to December 2018). Volume 3, No. 2. Quezon City, Metro Manila, Philippines. Retrieved from https://psa.gov.ph/content/selected-statistics-agriculture (accessed June 6, 2020)

Rao AN, Johnson DE, Sivaprasad B, Ladha JK, Mortimer AM (2007) Weed management in direct-seeded rice. Advances in Agronomy **69**: 153-255

Sanusan S, Polthanee A, Audebert A, Seripong S, Mouret J (2010) Suppressing weeds in direct-seeded lowland rainfed rice: Effect of cutting dates and timing of fertilizer application. Crop Protection **29**: 927-935

Tomita S, Nawata E, Kono Y, Inamura T, Nagata Y, Noichana C, Sributta A (2003a) Impact of direct dry-seeding on rainfed paddy vegetation in North-East Thailand. Weed Biology and Management **3**(2): 68-76

Tomita S, Nawata E, Kono Y, Inamura T, Nagata Y, Noichana C, Sributta A (2003b) Differences in weed vegetation in response to cultivating methods and water conditions in rainfed paddy fields in North-East Thailand. Weed Biology and Management **3**(2): 117-126

Wibawa W, Mohamad R, Juraimi AS, Omar D, Mohayidin MG (2009) Weed efficacy and short term weed dynamic impact of three non-selective herbicides in immature oil palm plantation. International Journal of Agriculture and Biology **11**: 145-150

FULL PAPER

PHOSPHORUS STATUS IN SOILS FORMING IN THE PYROCLAST DEPOSITS FROM THE 1991 PLINIAN ERUPTION OF MT. PINATUBO, PHILIPPINES

Michelle C. Quimbo[1], Pierre Delmelle[2], Pearl B. Sanchez[3], and Alain Bernard[4]

[1]Philippine Rice Research Institute, Science City of Muñoz, Nueva Ecija, Philippines, [2]Université Catholique de Louvain, Ottignies-Louvain-la-Neuve, Belgium, [3]University of the Philippines Los Baños, Laguna, Philippines, [4]Université Libre de Bruxelles, Belgium

*Corresponding Author: mcquimbo@philrice.gov.ph

Abstract

Phosphorus (P) is usually a limiting nutrient in mature volcanic Andisols. However, the addition of fresh volcanic pyroclasts on these soils can act as a source of plant-available P (P_{avail}). This study focused on the impact of the early stages of weathering and soil formation of the pyroclast (tephra and lahar) deposits derived from the 1991 Mt. Pinatubo eruption on the current P status of cultivated and non-cultivated soils. The total (P_{total}) and P_{avail} status of the new soil developing from the pyroclast deposits (MS) in the forest, grassland, and rice paddy were compared to their corresponding ~500-yr buried soils (BS). The generally lower P_{total} and P_{avail} values in the BS compared with the MS reflect the gradual loss of apatite during chemical weathering. Furthermore, the higher P retention measured in the BS compared with the MS may reflect the small buildup of active Al and Fe in short-range order and amorphous secondary minerals (i.e., allophanes/imogolite and ferrihydrite) and Al/Fe-organic matter complexes. These minerals can bind P and make it less available for plant use. The current P contents in the MS (22 - 212 mg kg^{-1}) and pyroclast layers (55 - 258 mg kg^{-1}) of the cultivated and non-cultivated soils contain ample bioavailable P to support the requirement of plants, especially for high-value crops such as rice.

Keywords: *Apatite, Lahar, Pyroclast, Phosphorus Retention, Tephra, Weathering.*

Introduction

Phosphorus (P), next to nitrogen (N), is one of the most limiting essential nutrients in soils as it is typically strongly bound to secondary iron oxides; thus, occurs in small bioavailable concentrations (Smith et al., 2015; Blaskó, 2011). It is involved in photosynthesis and other key physiological and biochemical processes in plants (Pansu and Gautheyrou, 2006; Blaskó, 2011). Plants take up P from the soil solution primarily in the monovalent form, i.e., HPO_4^{2-}; the other ionic species $H_2PO_4^-$ and PO_4^{3-} usually occur in minor amounts at typical soil pH values between 5 and 6 (Roy et al., 2006). The primary source of P in soils is P mineral weathering and organic matter mineralization (Blaskó, 2011; Uchida, 2000). Phosphate bioavailability decreases with increasing soil development due to the immobilization of P into organic matter, precipitation in secondary minerals (i.e., Ca-, Fe-, and Al-phosphates), and adsorption to secondary Fe oxides (Pierzynski et al., 2000; Smith et al., 2015). Adsorption of P on variable charge minerals such as ferrihydrite, goethite, and allophanes is favored in acidic conditions as these constituents develop a positive electrical charge. The adsorption is specific, making P nearly immobile; thereby, reducing its availability to plants. With time, adsorbed phosphates may be occluded within the structure of Fe- and Al-oxyhydroxides, becoming completely inaccessible (Nanzyo et al., 1993; Parfitt, 1980).

Tropical soils usually contain low P reserves due to a higher degree of mineral weathering, faster P mineralization from organic matter, and greater P fixation to secondary Al/Fe-oxyhydroxides (Dabin, 1980). Most of the bioavailable P comes from organic matter recycling. Hence, crop production in these regions requires supplemental fertilization to alleviate P deficiency and increase yields (National Research Council, 1993). Volcanic soils are also often limited in P due to the presence of short-range order (SRO) and amorphous minerals such as allophanes, imogolite, ferrihydrite, and Al/Fe-organic complexes. These compounds have high anion exchange capacities and often develop a positive surface charge; thereby, enhancing strong P adsorption (Dahlgren et al., 2004; Shoji and Takahashi, 2002). Therefore, soil P fertility and plant use efficiency of P fertilizers in mature volcanic soils are usually very low (Shoji and Takahashi, 2002).

Most volcanic soils develop on extrusive fragmented magmatic rocks (pyroclasts) (Dahlgren et al., 2004). The P content of extrusive magmatic rocks (from basalt to rhyolite) varies roughly in the range of 0.1 to 1 vol.% (Deer et al., 1992). Phosphorus is typically encountered in primary magmatic minerals in the form of apatite [$Ca_5(PO_4)_3$(F,Cl,OH] (Nanzyo et al., 1997). In volcanic soils, apatite weathering is the main source of plant-available P (Dahlgren et al., 2004; Nanzyo and Yamasaki, 1998) and has been shown to contribute to the rapid revegetation of volcanic ash soils when N is present (Shoji and Takahashi, 2002). A fresh deposit of tephra (< 2 - 64 mm-sized fragmented pyroclasts) on an existing volcanic soil can act as a new source of P and temporarily alleviate P limitation in the soil (Nanzyo et al., 1997; Engelstad et al., 1974).

In 1991, the eruption of Mt. Pinatubo blanketed a surface area of approximately 2000 km^2 with approximately 5 km^3 (dense rock equivalent) of dacitic tephra (Melosantos et al.1996; Newhall and Punongbayan, 1996). The cumulative volume of lahar deposited from 1991 to 1993 is ~1.9 km^3 covering an area of ~770 km^2 (Punongbayan et al., 1993). Most of the soils that received dense rock equivalent deposits (i.e., tephra and lahar) were agricultural soils grown to rice, sugarcane, corn, vegetables, and root crops (Herrera, 1992; Rantucci, 1994).

Pyroclastic materials are known to be rich in nutrient elements from its mineral constituents and therefore, upon weathering their deposits may act as a fresh source of bioavailable P. In a tropical volcanic region, studies dealing with the P release and availability from pyroclast materials during the early stages of soil development and its impact on the buried former soils are scarce. This study (1) determined the total P and plant-available P contents in soils developed from the 26-yr Mt. Pinatubo pyroclast (i.e., tephra and lahar) deposits; (2) compared these values with those found in the former soils buried by the 1991 volcanic deposits; and (3) evaluated the influence of pedogenesis and varying land uses on total P content, plant-available P, and phosphate retention.

Materials and Methods

General Characteristics of the Study Sites and Field Soil Sampling

The study was conducted in the provinces of Pampanga (Porac and Floridablanca municipalities) in the east and southeast, respectively; Tarlac (Bamban municipality) in the northeast; and Zambales (San Marcelino municipality), in the southwest of Mt. Pinatubo in Central Luzon, Philippines (Figure 1). Sampling sites were selected based on the type of pyroclastic material (ash, pumice, lahar) deposited and land use. Five locations for soil sampling were chosen in the provinces of Pampanga (Porac, Floridablanca), Tarlac (Bamban), and Zambales (San Marcelino) in Central Luzon, Philippines. The selected sites in Pampanga and Tarlac were affected by ashfall while the site in Zambales is buried by lahar deposit during the 1991 Mt. Pinatubo eruption due to its proximity to the volcano (Bautista, 1996).

The general site description (i.e., location, altitude, slope, distance from the crater) and the photograph of a representative soil profile at each site are shown in Figure 2. The sampling sites vary according to land use, altitude, slope, type, and thickness of the pyroclastic deposit. Two adjacent soil profiles, 20 - 50 m apart, were collected for each of the five study sites to serve as pseudo-replicates. Uncultivated soils affected by tephra were collected from [P1] forest (Fo-Ash; Bamban, Tarlac; P1-a, P1-b), [P4] grassland located at high altitude (Gr-HA-Ash; Porac, Pampanga; P4-a, P4-b), and [P3] grassland located in low altitude (Gr-LA-Ash; Floridablanca, Pampanga; P3-a, P3-b). Two soils were collected in agricultural (cultivated) soils grown to paddy rice: one affected with ash [P2] (IR-Ash; Bamban, Tarlac; P2-a, P2-b) and another with lahar [P5] (IR-Lahar; San Marcelino, Zambales; P5-a, P5-b). The depth of the soil profiles ranges from ~40 to 90 cm. The soil profiles from P1 and P5 sites were collected on April 13, 2018, and those from P2, P3, and P4 on September 19-21, 2017.

The soil profiles showed the presence of a modern soil (MS horizon) from the 1991 Mt. Pinatubo pyroclastic deposit, while the buried soil (BS horizon) developed from the previous volcanic deposit emplaced ~500 years ago (Newhall and Punongbayan, 1996).

Soil Physical and Chemical Analysis

The samples were air-dried, crushed, and passed through a 2 mm sieve. All the chemical analyses were conducted on the fine-earth fraction < 2 mm (bulk) of the soil horizons (MS and BS) and pyroclast layers (i.e., ash, pumice, lahar) of each soil profile. Ash and pumice are collectively termed as tephra.

The particle-size distribution was determined through ultrasonic and Na-saturated resin dispersion to quantify the wt.% of sand, silt, and clay (Rouiller et al., 1972). Total organic C (wt.%) was done following the method of Pansu and Gautheyrou (2006). The total element analysis (Ca, Mg, Na, K) expressed in wt.% was determined using the method of Chao and Sanzolone (1992). Subsequently, the TRB was calculated for both the soil horizons and tephra layer in comparison with the pristine 1991 tephra deposit to estimate the degree of weathering (Herbillon, 1989; Delvaux et al., 1989).

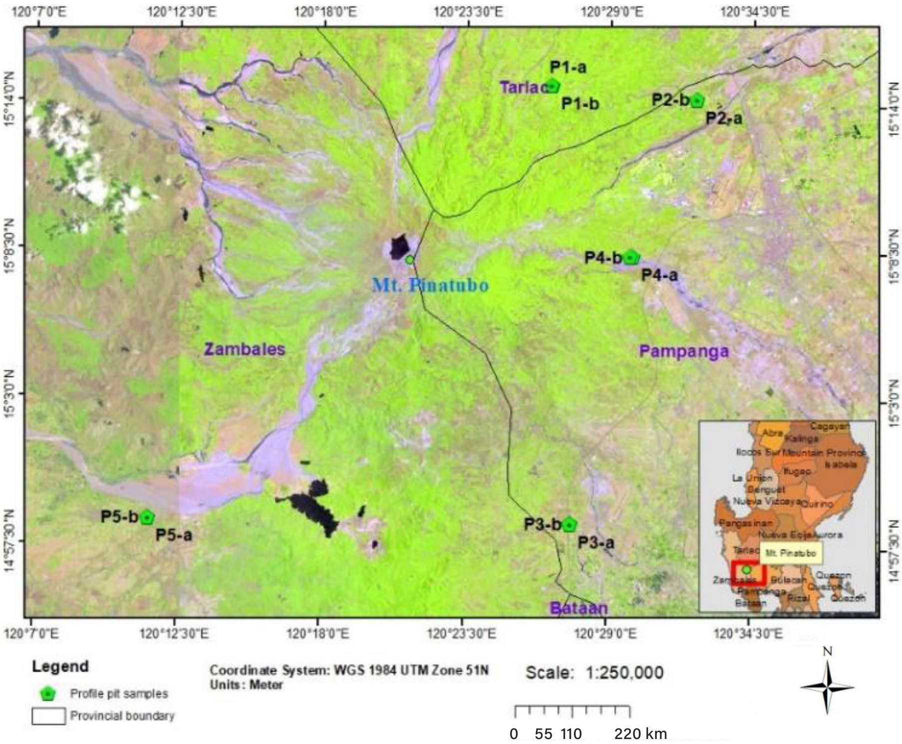
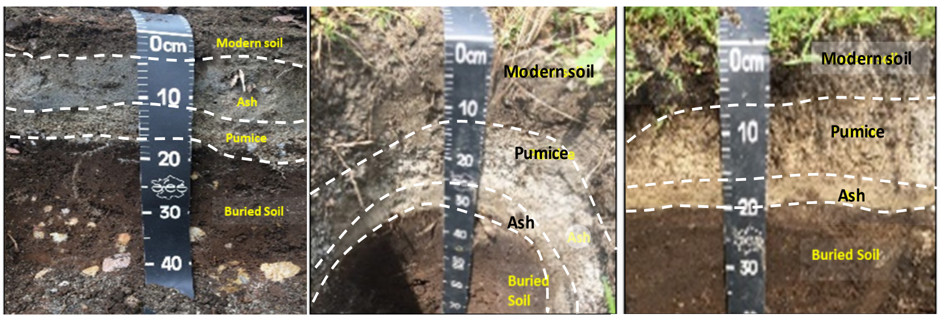


Figure 1. Location map of the study sites in Central Luzon, Philippines showing its proximity to Mt. Pinatubo volcano. Two soil profile pits were collected each from the five study sites with varying land uses (green dotted pentagons). P1-a and P1-b are ash affected-forest soil profiles (Fo-Ash; Bamban, Tarlac); P2-a and P2-b, ash affected-paddy (irrigated) rice soil profiles (IR-Ash; Bamban, Tarlac); P3-a and P3-b, ash-affected grassland soil profiles located in low altitude (Gr-LA-Ash; Floridablanca, Pampanga); P4-a and P4-b, ash affected-grassland soil profiles located in high altitude (Gr-HA-Ash; Porac, Pampanga); P5-a and P5-b, paddy rice-lahar affected soils (IR-Lahar; San Marcelino, Zambales).

Non-cultivated soils

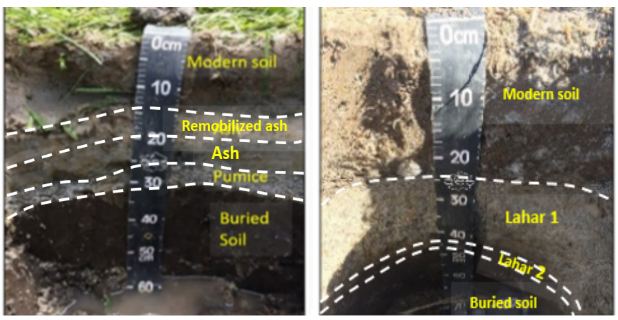


Land Use: Forest (P1-a; Fo-Ash)
Pyroclast depth: 17 cm
Alt: 503 m.a.s.l
Slope: 5-9 %
Dist. from Mt. Pinatubo crater: 15 km NE
Location: Bamban, Tarlac

Land Use: Grassland in high altitude
(P4-b; Gr-HA-Ash)
Pyroclast depth: 33 cm
Alt: 286 m.a.s.l
Slope: 5-9 %
Dist. from Mt. Pinatubo crater: 16 km E
Location: Porac, Pampanga

Land Use: Grassland in low altitude
(P3-a; Gr-LA-Ash)
Pyroclast depth: 18 cm
Alt: 46 m.a.s.l
Slope: 0-4 %
Dist. from Mt. Pinatubo crater: 22 km SE
Location: Floridablanca, Pampanga

Cultivated soils



Land Use: Irrigated Rice (P2-b; IR-ASH)
Pyroclast depth: 31 cm
Alt: 105 m.a.s.l
Slope: 0-4 %
Dist. from Mt. Pinatubo crater: 23 km NE
Location: Bamban, Tarlac

Land Use: Irrigated Rice (P5-b; IR-Lahar)
Pyroclast depth: 37 cm
Alt: 45 m.a.s.l
Slope: 0-4 %
Dist. from Mt. Pinatubo crater: 25 km SW
Location: San Marcelino, Zambales

Figure 2. Photograph of representative soil profiles from non-cultivated (forest, grassland) ash-affected soils and cultivated (paddy rice) ash and lahar-affected soils from Tarlac, Pampanga, and Zambales, Philippines. Alt: altitude, Dist: distance, E: east, SE: southeast; NE: northeast, SW: southwest.

The oxalate-extracted Si, Al, and Fe (Si_o, Al_o, Fe_o) contents were measured based on the method of Blakemore et al. (1981) to determine the (i) Al and Fe in organic complexes, (ii) Fe in SRO (hydr)oxides (i.e., ferrihydrite), (iii) Al and Si in SRO aluminosilicates (i.e., allophane/imogolite) (Dahlgren et al., 1997). The dithionite citrate bicarbonate (DCB)-extractable ($_d$) and Na-pyrophosphate ($_p$) extractable Fe and Al (Fe_d, Fe_p, Al_p) were extracted following the methods of Mehra and Jackson (1960) and Bascomb (1968), respectively. The DCB is a selective dissolution extractant for organically complexed, non-crystalline hydrous oxides, amorphous aluminosilicates, and "free" (amorphous and crystalline) forms of Fe that is not tied up in the lattice of primary minerals and which has been weathered and released to the soil solution. The Na-pyrophosphate selectively extracts organically bound forms of Fe and Al indicating the abundance of organo-metallic complexes (Wada, 1989). Allophane/imogolite and ferrihydrite contents were estimated from Si_o and Fe_o (Dahlgren et al., 2004). All the elements were measured by Inductively Coupled Plasma-Atomic Emission Spectrometer (ICP-AES), ICAP 6000 Series.

Total P Analysis. Total P (Pt_{otal}, mg kg^{-1}) is the sum of all forms of P in the soil, i.e., organic, inorganic, occluded, and plant-available P (Pansu and Gautheyrou, 2006). The P_{total} in the soil and pyroclasts was carried out through loss on ignition at 1,000 °C followed by borate fusion and dissolution of fusion beads in 10% nitric acid (HNO_3) (Chao and Sanzolone, 1992).

Plant-available P (Modified Bray P2 Method). The P_{avail} extraction method by Bray and Kurtz (1945) was based on solubilization of P compound in acid followed by the action of fluoride anion to reduce the activity of the Al^{3+}, Fe^{3+}, and Ca^{2+} cations by forming complexes with the latter. It measures P_{avail} in adsorbed and acid-soluble phosphate forms. It provides an estimate of the relative bioavailability of inorganic ortho-phosphate (PO_4-P) in soils in acid to neutral pH (Dewis and Freitas, 1970). Five grams of soil or pyroclast sample was treated with 35 ml Bray solution (0.03 M NH_4F + 0.1 M HCl; pH 1.5), agitated for 5 min, and then filtered. The hydrochloric acid (HCl) and ammonium fluoride (NH_4F) removes easily acid-soluble forms of P, largely Ca phosphates. The NH_4F dissolves Al and Fe phosphate precipitates by forcing complexation with the metal ions under acidic conditions. The P_{avail} in the extract was determined using ICP-AES and expressed in mg kg^{-1}. The P_{avail} of the 1991 Mt. Pinatubo ash deposit that was collected few months after the eruption (September, 1991) at the western side of Mt. Pinatubo by Prof. Alain Bernard of Université Libre de Bruxelles, Belgium was also analyzed. As the samples originated from recently deposited volcanic materials, the P extracted from the soil using the Bray P2 method would represent the P_{avail} released from calcium apatite. The contribution of P from dacite glass dissolution, if there is any, may not be significant. The mean P content of dacite glass is 1,100 mg kg^{-1} (n=3) but the dissolution rate is very slow, i.e., 1 x 10^{-9} mol m^{-2} s^{-1} at pH 4 (25°C) (Wolff-Boenisch et al., 2004) compared to that of natural apatite, which immediately dissolves at pH 4 (25 °C), i.e., 1 x $10^{-0.003}$ mol m^{-2} s^{-1} (Harouiya et al., 2007).

Phosphate retention (P_{ret}). The P_{ret} method proposed by Blakemore et al. (1981) uses the equilibration of a soil sample with a solution containing soluble P, and measurement of phosphate remaining in solution (Eq. 1). A 2-g bulk sample was mixed with 10 mL P-retention solution for 24 h. The P-retention solution was prepared by mixing 4.40 g potassium dihydrogen phosphate (KH_2PO_4), 16.4 g anhydrous sodium acetate (CH_3COONa), and 11.5 mL glacial acetic acid in 1 L distilled water. The mixture was centrifuged at 2000 rpm for 15 minutes. An aliquot of the supernatant was analyzed using the ICP-AES.

$$P_{ret}\,(\%) = \frac{\text{Initial P}}{\text{concentration}} - \frac{\text{P remaining in}}{\text{sample solution}} \qquad \text{Eq. 1}$$

Where 'P_{ret}'is the P retained in the sample after equilibration with the 'initial P concentration' of 100 mg kg^{-1} P solution expressed in percent; 'P remaining in the sample solution' is the measured P in the extract after 24 hours of shaking.

Results

Phosphorus Contents of The Modern Soil and Pyroclast Deposit

The contents of P_{total}, P_{avail}, P_{avail} to P_{total} ratio (P_{avail}/P_{total}), and P_{ret} of the soil horizons and pyroclast layers of the soil profiles varying in land use are shown in Table 1.

Fo-Ash (P1-a, P1-b). In the two soil profiles, the MS horizon, ash, and pumice layers contain comparable quantities of P_{total}, ranging from 574 to 853 mg kg^{-1}. The P_{avail} content in the MS horizon of P1-a and P1-b soil profiles differ by ~one order of magnitude (92 and 212 mg kg^{-1}, respectively). The ash and pumice layers contain 104 to 199 mg kg^{-1} P_{avail}. The P_{avail}/P_{total} ratio of the MS horizon, ash, and pumice layers range from 0.16 to 0.26 for the two soil profiles. The MS horizon has a P_{ret} value of 4.23 and 8.62% in the P1-a and P1-b soil profiles, respectively. The ash and pumice layers from both soil profiles did not retain any P.

IR-Ash (P2-a, P2-b). The P_{total} content in the MS horizon of the P2-a and P2-b is (528 and 547 mg kg^{-1}), respectively. The P_{total} content measured for the remobilized ash, ash, and pumice layers varies

Table 1. Phosphorus contents along with soil profile depth of the different land-use types in selected sites of Tarlac, Pampanga, and Zambales.

Profile Code	Depth		Horizon/Layer	P_{total}		P_{avail}		P_{avail}/P_{total}		Pretention	
	a	b		a	b	a	b	a	b	a	b
	cm			mg kg^{-1}		mg kg^{-1}		mg kg^{-1}		%	
[b]tephra (1991)				715		354		0.5		-	-
[c]Sep 1991 Ash				-		61	83			-	-
Fo-Ash (P1)	0-3	0-4	Modern soil	673	853	92	212	0.14	0.25	4.23	8.62
	3-11	4-13	Ash	746	752	121	199	0.16	0.26	0.00	0.00
	11-17	13-25	Pumice	745	574	134	104	0.18	0.18	0.00	0.00
	17-40	25-40	Buried soil	330	376	4	5	0.01	0.01	26.06	21.55
IR-Ash (P2)	0-14	0-15	Modern soil	528	547	78	87	0.15	0.15	11.79	15.97
	14-25	15-20	Remobilized ash	472	537	202	201	0.43	0.37	7.26	5.56
	25-32	20-25	Ash	727	796	248	258	0.34	0.32	0.73	0.00
	32-38	25-31	Pumice	454	492	55	88	0.12	0.18	0.92	0.00
	38-39	-	Ash	749	-	206	-	0.28	-	4.89	-
	39-90	31-55	Buried soil	241	250	26	22	0.11	0.09	12.21	3.26
Gr-LA-Ash (P3)	0-7	0-6	Modern soil	600	700	72	62	0.12	0.09	0.00	0.00
	7-16	6-14	Pumice	701	500	62	55	0.09	0.11	0.00	0.00
	16-20	14-18	Ash	717	666	163	180	0.23	0.27	4.31	1.88
	20-37	18-35	Buried soil	444	414	37	18	0.08	0.04	3.49	2.23
Gr-HA-Ash (P4)	0-13	0-12	Modern soil	620	742	131	166	0.21	0.22	0.00	4.51
	13-22	12-26	Pumice	500	490	71	55	0.11	0.11	0.00	0.00
	22-27	26-33	Ash	751	710	232	228	0.32	0.32	0.00	0.00
	27-50	33-73	Buried soil	104	217	1	2	0.01	0.01	10.10	13.59
IR-Lahar (P5)	0-18	0-24	Modern soil	233	470	22	90	0.19	0.19	7.23	10.21
	18-34	24-42	Lahar 1	494	631	62	68	0.11	0.11	0	1.86
	34-37	42-45	Lahar 2	546	542	115	116	0.21	0.21	2.53	0.91
	37-50	45-65	Buried soil	683	741	139	132	0.18	0.18	16.22	10.95

[a] Two pseudo-replicate soil profiles for each sampling site; [b] P contents of 1991 Mt. Pinatubo fresh tephra (Nanzyo et al., 1997); [c] P_{avail} content of September 1991 Mt. Pinatubo ash (sample donated by Prof. Alain Bernard, ULB, Belgium).

between 454 and 796 mg kg^{-1}. The P_{avail} content of the MS horizon (78 and 87 mg kg^{-1} in P2-a and P2-b, respectively) is two to three times lower than the remobilized ash and ash layers (202-258 mg kg^{-1}). The pumice layer has 55 and 88 mg kg^{-1} P_{avail} in the P2-a and P2-b soil profiles, respectively. The P_{avail}/P_{total} of the MS horizon and pumice layer for both soil profiles range from 0.12 to 0.18, which is significantly lower than the ratio values inferred for the remobilized ash and ash layers (P_{avail}/P_{total} = 0.28-0.43). The MS horizon retained 11.79 and 15.79% P in the P2-a and P2-b soil profiles, respectively which is two times higher than the P_{ret} in the remobilized ash layer (7.26% in P2-a and 5.56% in P2-b). The ash and pumice layers have P_{ret} values ranging from 0.73 to 4.89%.

Gr-LA-Ash (P3-a, P3-b). The P_{total} content in the MS horizon and pyroclast layers of the two soil profiles, P3-a and P3-b are comparable and range from 500 to 717 mg kg^{-1}. The P_{avail} contents of the MS horizon and pumice layer in the two soil profiles also fall in the same range of values (55 - 72 mg kg^{-1}). In contrast, P_{avail} in the ash layer is threefold higher, i.e., 163 and 180 mg kg^{-1} in P3-a and P3-b soil profiles, respectively. Accordingly, the P_{avail}/P_{total} ratio in the MS horizon and pumice layers (0.09-0.12) is lower than in the ash layer (0.23 - 0.27). The MS horizons and pumice layers do not retain P, whereas P_{ret} in the ash layer amounts to ~4.3 and 1.9% in the P3-a and P3-b soil profiles, respectively.

Gr-HA-Ash (P4-a, P4-b). The P_{total} content of the MS horizon and pyroclast layers ranges from 490 to 751 mg kg^{-1}. The P_{avail} content of the MS horizon in the P4-a and P4-b soil profiles (131 and 166 mg kg^{-1}, respectively) is significantly higher than that of the pumice layer (71 mg kg^{-1} in P4-a and 55 mg kg^{-1} in P4-b), but lower than the ash layer (232 in P4-a and 228 in P4-b mg kg^{-1}). The P_{avail}/P_{total} ratio in the P4-a and P4-b soil profiles is higher in the MS horizon (0.21 and 0.22, respectively) and ash layer (0.31 and 0.32, respectively) in comparison to the pumice layer (0.14 and 0.11, respectively). The MS horizon of the P4-a soil profile does not retain P, but the P4-b soil profile retains a small quantity of P, i.e., 4.5%. Phosphorus retention is not observed in the pumice and ash layers.

IR-Lahar (P5-a, P5-b). The P_{total} content in the MS horizon of P5-a and P5-b soil profiles varies by ~twofold (233 and 470 mg kg^{-1}, respectively). Compared to the lahar layers (494 mg kg^{-1}, P5-b, and 631 mg kg^{-1}, P5-b), the MS horizon has a lower P_{total}. Similarly, the P_{avail} content between the MS horizon in P5-a (22 mg kg^{-1}) and P5-b (90 mg kg^{-1}) soil profiles varies by as much as three times. The lahar 1 layer has ~two times lower P_{avail} content, i.e., 62 and 68 mg kg^{-1} in P5-a and P5-b soil profiles, respectively, compared with the lahar 2 layer, i.e., 115 and 116 mg kg^{-1}, respectively. Consequently, the P_{avail}/P_{total} ratio of the lahar 1 layer (i.e., 0.12 and 0.11 in P5-a and P-b profiles, respectively) is ~two times lower than that of lahar 2 layer (i.e., 0.21 for both soil profiles), whereas the MS horizon has a more variable P_{avail}/P_{total} ratio (i.e., 0.09 and 0.19 in P5-a and P-b profiles, respectively). Phosphorus retention in the MS horizon of P5-a and P5-b soil profiles is 7.2 and 10.2%, respectively. The lahar 1 and lahar 2 layers have lower P_{ret} values ranging from 0 to 2.5% for the two soil profiles.

Phosphorus Contents of the Buried Soils

Fo-Ash (P1-a, P1-b). The P_{total} content of the BS horizon is 330 in the P1-a and 376 mg kg^{-1} in the P1-b soil profile. The P_{avail} content is 4 and 5 mg kg^{-1}, respectively. The P_{avail}/P_{total} ratio is very low (~0.01) for this horizon. The P_{ret} values for P1-a and P1-b soil profiles are 26.1 and 21.6%, respectively.

IR-Ash (P2-a, P2-b). The BS horizon in the IR-Ash soil contains 241-250 mg kg^{-1} P_{total}. The P_{avail} content is 26 mg kg^{-1} in P2-a and 22 mg kg^{-1} in P2-b. The P_{avail}/P_{total} ratio in the P2-a and P2-b soil profile is 0.11 and 0.09, respectively, and the P_{ret} is 12.2 and 3.3%, respectively.

Gr-LA-Ash (P3-a, P3-b). The BS horizon of the P3-a and P3-b soil profiles has a P_{total} content of 414 and 444 mg kg^{-1}, respectively, and P_{avail} content of 37 and 18 mg kg^{-1}, respectively. The P_{avail}/P_{total} is 0.08 in the P3-a and 0.04 in the P3-b soil profile. The P_{ret} values are low, i.e., 3.5% (P3-a) and 2.2% (P3-b).

Gr-HA-Ash (P4-a, P4-b). The P_{total} content in the P4-a and P4-b soil profiles is 104 and 217 mg kg^{-1}, respectively. The BS horizon has only 1 mg kg^{-1} P_{avail} content in the P4-a and 2 mg kg^{-1} in the P4-b soil profile. The P_{avail}/P_{total} is also very low, only ~0.01 in both soil profiles. The P_{ret} in the P4-a and P4-b soil profiles is 10.1 and 13.6%, respectively.

IR-Lahar (P5-a, P5-b). The BS horizon has 683 and 741 mg kg^{-1} P_{total} in the P5-a and P5-b soil profiles, respectively. Comparable P_{avail} contents were measured in the P5-a and P5-b (139 and 132 mg kg^{-1}), respectively. The P_{avail}/P_{total} is 0.20 (P5-a) and 0.18 (P5-b). The P_{ret} in the P5-a and P5-b soil profiles are 16.2 and 11.0%, respectively.

Discussion

For each land-use type, the P_{total} and P_{avail} contents and P_{ret} differ between the two soils that were sampled. For example, the MS of the two IR-Lahar soils differs markedly in terms of their P_{total} and P_{avail} contents (Table 1). This may be attributed to heterogeneities in the composition of the pyroclast parent material, horizon thickness, volume of crop cover, and biomass restitution. Reyes and Neue (1991) reported that the physical and chemical characteristics of the 1991 lahar materials from Mt. Pinatubo vary due to mixing and sedimentation processes involving various proportions of fresh pyroclasts, lithics, and former sediments (including soils). In most cases, differences among the soil profile types emerge despite the intra-site heterogeneities.

Total Phosphorus Content

Phosphorus in soils occurs in both inorganic and organic forms. The proportions of inorganic and organic P vary depending on soil type and weathering degree, but in general inorganic P amounts to 35 - 70% of P_{total}, with the rest corresponding to organic P (Sharpley, 1995; Mishra et al., 2017). Due to the propensity of volcanic soils to accumulate organic matter, organically bound P constitutes often an important pool (Shoji and Takahashi, 2002). The lowest and highest P_{total} contents measured in the MS correspond to the IR-lahar (233-470 mg kg^{-1}) and Fo-Ash (673-853 mg kg^{-1}) soils, respectively (Table 1). These values compare with the P_{total} content measured in the soils developed on the ash from the 1883 eruption of Krakatoa volcano in Indonesia (413 - 710 mg kg^{-1}; Schlesinger et al., 1998). Gudmundsson et al. (2014) reported a higher total P (1671 - 1902 mg kg^{-1}) in the first 20 cm of non-cultivated Silandic Andisols in Iceland. Similarly, higher total P contents were found in variously developed Andisols from Chile (993 and 3,469 mg kg^{-1}; Escudey et al., 2001). Shoji et al. (1993) indicated that the total P content in 25 Andisol pedons from various districts of Japan ranges from ~1000 to 3900 mg kg^{-1}. The relatively low P_{total} concentrations in the MS reflect the early stage of weathering and the low organic matter accumulation.

The most important factors influencing the status of P in Andisols are chemical weathering, biocycling, and fertilization (Shoji et al., 1993; Dahlgren et al., 2004). Unweathered tephra contains a significant amount of P, which tends to increase with the tephra Si content (Nanzyo et al., 1997; Nanzyo et al., 2003). Phosphorus in tephra reflects largely the presence of apatite of magmatic origin (Schlesinger et al., 1998; Nanzyo et al., 2003). Although apatite has a moderate solubility, chemical weathering of apatite in tephra is an important source of P for plants and microbes (Nanzyo et al., 2010; Nanzyo and Kanno, 2018). Several studies highlighted the occurrence of apatite as a minor mineral phase in the 1991 Mt. Pinatubo tephra deposit (Bernard et al., 1996; Nanzyo et al., 1997; Castillo and Punongbayan, 1996). A range of P_{total} content has been reported for the 1991 Pinatubo fresh tephra 'tephra$_{(1991)}$', i.e., 715 - 916 mg kg^{-1} (Bernard et al., 1996; Castillo and Punongbayan, 1996; Nanzyo et al., 1997). Thus, P_{total} is generally lower by 2 - 67% (Table 1) in the MS than in the tephra$_{(1991)}$, except for Fo-Ash/a (853 mg kg^{-1}) and Gr-HA-Ash/a (742 mg kg^{-1}) soils, which fall within the above range of values.

Except in IR-Lahar/a,b, Gr-LA-Ash/a and Fo-Ash/a), the P_{total} content of the MS horizon is similar or higher than that of its parent material (C horizon; i.e., ash, pumice, or lahar deposit immediately underlying the MS horizon) (Table 1). The net gain or loss of P in a non-cultivated soil during pedogenesis will depend on the relative importance of various processes such as weathering, mineralization, immobilization, adsorption, and fertilizer addition as summarized by the following equation:

In the absence of other processes, the dissolution of apatite (and possibly P occurring in the tephra's glassy component) during chemical weathering of the tephra should reduce P_{total} in the soil (Nanzyo et al., 2010). As weathering is normally more pronounced in the surface horizons, lower P_{total} values are expected in the MS samples than in the C layer. Our results showed that there is no massive difference between the topsoil (MS) and the subsurface layers (C), except in the case of IR-Lahar. This is probably due to a combination of factors, including organic matter accumulation (and hence P) in the surface horizon and heterogeneity in the texturally different parent material (i.e., a layer of ash, a layer of pumice). The ratio of P_{total} in the C horizon to that of tephra$_{(1991)}$ is systematically less than one except for Fo-Ash soil (Figure 3). This supports the idea that chemical weathering has removed some of the P from the soil's parent material. Although weathering also affects the MS, the uptake of P by plants and its incorporation

$$\text{leachable P} + \text{available P} = \text{mineralization} + \text{weathering} + \text{fertilizer addition} - \text{immobilization} - \text{adsorption} \qquad \textbf{Eq. 2}$$

where *leachable P* is the P in organic, inorganic (i.e., primary and secondary minerals), and occluded forms (i.e., Fe/Al-(hydr)oxides); available P is the solution P that is available for plant uptake; mineralization is the P released from organic matter mediated by microorganisms; weathering is the P released from the dissolution of primary and secondary minerals; fertilizer addition is the outside P fertilizer source added in cultivated soils; immobilization is the intake of P by microorganisms; adsorption is the fixation of P in the surfaces of Al/Fe (hydr)oxides and secondary minerals.

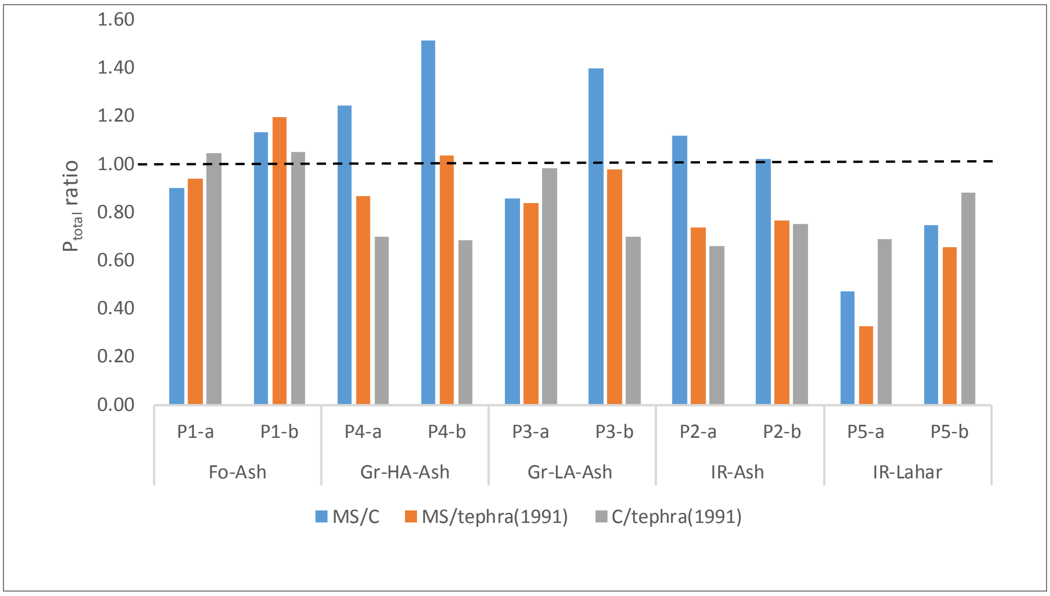


Figure 3. Total P content ratio of the modern soils to its tephra parent material or C horizon [MS/C]; modern soil to the fresh tephra [MS/tephra$_{(1991)}$]; and C horizon to the fresh 1991 tephra [C/tephra$_{(1991)}$] of Fo-Ash (P1-a, P1-b; Tarlac province), IR-Ash (P2-a, P2-b; Tarlac province), Gr-LA-Ash (P3-a, P3-b; Pampanga province), Gr-HA-Ash (P4-a, P4-b; Pampanga province) and IR-Lahar (P5-a, P5-b; Zambales province) soil profiles. 'tephra $_{(1991)}$' P_{total} value adapted from Nanzyo et al. (1997).

into organic forms reduce the net removal of P from modern soils. The latter process could be responsible for the maintenance of the P_{total} levels in the MS horizon of Fo-Ash soil.

The lowest P_{total} contents in the MS were measured for the IR-Ash (528 - 547 mg kg^{-1}) and IR-Lahar (233 - 470 mg kg^{-1}) profiles, which both support rice cultivation. Rice has been cultivated on these soils for 13 years (2005-2017) and 12 years (2006-2017), respectively. The removal, after harvesting, of threshed rice straws and grains containing appreciable amounts of P has the effect of eliminating P from the soil; thus, decreasing its P_{total} content. While the application of inorganic P fertilizer (~26 kg ha^{-1} cropping $season^{-1}$) to the IR-Ash soil limits the decline in total P, the IR-Lahar soil does not receive any P additions (except in 2006). This probably explains its low P_{total} content. Flooding and drainage of paddy soils during the growing season were also noted to increase P losses compared with other soils (Sharpley, 1995; Duxbury and Perverly, 1978).

In all but the IR-Lahar soil, the P_{total} content of the BS is systematically lower (1.4 to 6.0 times) than that of the MS. This is further supported by comparing the means of the two sample groups, which revealed a statistically significant difference (t-test, P = 0.018). Total P in the BS soil is also lower than the values measured in the pyroclast materials that overlay it (Table 1). The BS derived from pyroclasts, which was deposited by the previous Plinian eruption of Mt. Pinatubo about ~500 years ago (Newhall and Punongbayan, 1996), could not be sampled but according to Pallister et al. (1996), it is dacitic in composition and its mineral assemblage resembles that of the 1991 eruption products. Thus, one can reasonably assume that the P_{total} content was more or less in the same range as that of the 1991 eruption products. This implies that the comparatively depleted P_{total} values in the BS samples reflect the gradual loss of P due to apatite dissolution during chemical weathering. Although the BS always exhibits a significantly stronger capacity to retain P than the MS (Table 1 except in IR-Ash/b profile), P adsorption on secondary mineral constituents (and possibly alumino-organic complexes) was probably not very efficient throughout ~500 years of soil development. Also, organic matter accumulation is limited in the BS, preventing the build-up of a significant organic P pool. As a result, the BS experienced a net loss of P and a reduction in P_{total}.

The BS with the highest P_{total} content corresponds to the IR-Lahar (P_{total} = 683 - 741 mg kg^{-1}). In contrast to the other BS samples, total P in this soil is on par with the values found in the MS (P_{total} = 528 - 853 mg kg^{-1}), suggesting weak weathering and/or retention of P in organic compounds and adsorbed forms. The organic carbon content of the IR-Lahar's BS is low (0.89 - 1.18 wt.%; not shown) and compares with the other buried soils. Therefore, the accumulation of organic P is probably not responsible for the elevated P_{total} value. The Si_o content of the BS (0.10 - 0.11 wt.%; not shown) from the IR-Lahar profile is ~2 to 5 times higher than in the other BS. Moreover, the Al_o content associated with SRO compounds is 2 to 3-fold higher than the other BS (0.26-0.30 wt.%; not shown) except for Fo-Ash soil. This suggests the presence of reactive surfaces onto which P can bind. The low pH values measured for the IR-Lahar's BS would favor weathering reactions. The Si_o and Al_o contents are typical of weakly weathered and poorly developed soils (Shoji et al., 1993). The high P_{total} content of the BS soil from the IR-Lahar profile cannot yet be fully explained.

Available Phosphorus Content

In soils developed on volcanic pyroclasts, bioavailable P originates from the chemical weathering of primary phosphorus-bearing minerals such as apatite (Dahlgren et al., 2004; Nanzyo and Yamasaki, 1998). Thus, appreciable amounts of P may be available in young volcanic soils due to rapid weathering of apatite, and low P retention due to low concentrations of active Al and Fe. Different types of acid solutions and methods have been used to evaluate plant-available P in fresh tephra and volcanic soils, i.e., Bray P2, Truog, Mehlich No. 3, Olsen, anion exchange resins (Pansu and Gautheyrou, 2006; Uchida, 2000). While the absolute values may slightly differ between methods, acid-extractable P in the Pinatubo tephra (72 mg kg^{-1}, Table 1) is within the range of values (~18 - 350 mg kg^{-1}) reported by Nanzyo et al. (1997) for tephra varying in composition from basalt to rhyolite. However, they reported a much higher content of P_{avail} (i.e., ~350 mg kg^{-1}) for Mt. Pinatubo's ash, although their P_{total} value compares well with our results. Available P for the ash specimen is also 2.8 - 3.6 times lower than in the C horizon of the Fo-ash, IR-Ash, Gr-LA-Ash, and Gr-HA-Ash soil profiles. These observations suggest that the P_{avail} measurement for the fresh ash sample is not representative; therefore, this value was not used for the rest of the discussion. By referring to Nanzyo et al.'s (1997) analyses, the P_{avail}/P_{total} ratio in the $tephra_{(1991)}$ is ~0.5.

In the cases of the Fo-Ash, IR-Ash, and IR-Lahar/a soil profiles, there is less P_{avail} in the MS than in the ashy C horizon (Table 1). Recalling that the availability of P is dictated mainly by apatite in the primary mineral assemblage of the soil parent material, a reduced P_{avail} content in the soil points to the consumption of apatite through weathering. In support of this, Table 1 indicates that the P_{avail}/P_{total} ratio in the MS and pyroclast deposits is lower than that of $tephra_{(1991)}$.

The evolution of the P_{avail}/P_{total} ratio with depth differs between the five soil profiles (Table 1). For the Fo-Ash, Gr-LA-Ash, and IR-Lahar soils, the MS horizon and C horizon display roughly similar P_{avail}/P_{ratio} ratio values, suggesting commonalities of weathering conditions. In contrast, in the IR-Ash, the P_{avail}/P_{ratio} ratio is lower (more than two times) in the MS than in the ash (C horizon) situated immediately beneath it. This may reflect a more intense dissolution of apatite in the surface soil. An opposite situation is found for the Gr-HA-Ash soil profile. A plausible explanation for this behavior is that the pumice layer beneath the MS does not represent the parent material. The final phase of the 1991 eruption of Mt. Pinatubo produced fine-grained ash and this material fell over the area where the Gr-HA-Ash soil was sampled (Melosantos et al., 1996). The original P_{avail} and P_{total} contents of the pumice deposit are not known but could depart from that of the fresh ash from which the present-day MS has developed. The weathering may proceed at different rates in the pumice and ash materials due to differences in the hydrology of the deposits. For example, the dissolution of apatite may be enhanced in a fine-textured compared with a coarse-textured material due to greater specific surface area values and higher microporosity allowing water retention in the former. Nanzyo et al. (1997) showed that the fine size fraction of ash produced higher P_{avail} values than the course one. In IR-Ash soil, the difference in P_{avail}/P_{total} ratios in the MS and the underlying ash layer could have arisen due to the heterogeneous nature of the latter. This ash layer consists of remobilized ash materials (which may also contain eroded soil) carried by flood; hence, additional P_{avail} could come from this eroded soil materials and runoff water.

The P_{avail}/P_{total} ratio of the BS in the five soil profiles is always lower (by a factor of 2.5 to 50) than that of the $tephra_{(1991)}$ (Table 1), mirroring the significantly reduced P_{avail} contents measured in the BS samples, a likely consequence of chemical weathering and apatite dissolution. For the Fo-Ash and Gr-HA-Ash soils, P_{avail}/P_{total} ratio is at least an order of magnitude lower in the BS than in the MS. Again, this result points to more advanced weathering in the ~500 years old BS. A similar pattern is observed in the Gr-LA-Ash and IR-Ash profiles, but the differences in the P_{avail}/P_{total} ratios between the buried and surface modern soil are less pronounced. In contrast, the P_{avail}/P_{total} ratio of the BS in the IR-Lahar/a (IR-Lahar/b) profile is higher than (similar to) that of the corresponding MS. It is also higher than the ratio values found for the BS from the four other profiles. High P_{avail} may be linked to elevated apatite content in the parent material and/ or weak weathering. The second possibility would be compatible with the high P_{total} value measured for the BS.

Generally, the P_{avail} content of the MS in each soil profile (22 - 212 mg kg^{-1}; Table 1) is above the critical limit for P deficiency, i.e., P_{avail} < 10 mg kg^{-1} (USDA-NRCS, 1994). The P_{avail} values are also above those reported by Collado et al. (2013) for different soils from the Zambales province (P_{avail} < 10 - 15 mg kg^{-1}) measured prior to the 1991 eruption. Thus, the addition of tephra material can provide a significant amount of plant-available P during the early stage of weathering. The pyroclast layers in all the soil profiles also have sufficient contents of P_{avail} (55 - 258 mg kg^{-1}; Table 1).

Phosphorus Retention

Phosphorus retention is less than 20% in all samples (Table 1). Except in the IR-Ash soil, the BS always exhibits a higher P_{ret} than the MS. The ash, pumice, and lahar materials have low P_{ret} varying between ~0 and 4.3%. Phosphorus retention measures the quantity of P that can be held in the soil due to precipitation and/or adsorption on mineral and organic matter surfaces (Mishra et al, 2017; Satti et al., 2007). As weathering is responsible for the formation of SRO minerals such as allophanes, imogolite, and ferrihydrite in volcanic soils, P_{ret} has been shown to increase with the degree of weathering (Shoji et al., 1993). Allophanes, imogolite, and Al/ Fe-(hydr) oxides have the ability to strongly adsorb P (as phosphate) through ligand-exchange and/or precipitation mechanisms (Parfitt, 1980; Nanzyo, 1988).

Young volcanic soils have low P_{ret} due to low contents of active Al and Fe, i.e., Al and Fe present in allophanes, hydr(oxides), and Al-Fe-organo complexes (Nanzyo et al., 1997). Volcanic soil formation is typically driven by the rapid dissolution of the glassy component of tephra and the release of large quantities of Si, Al, and Fe. As a result, the soil solution becomes supersaturated and poorly crystalline phases such as allophanes and ferrihydrite precipitate (Dahlgren et al., 1993; Ugolini and Dahglren, 2002). Aluminum and Fe can also form complexes with organic matter. The secondary constituents, in particular allophane and alumino-organic complexes, interact strongly with the P that gradually dissolves from apatite, eventually retaining it almost irreversibly (Takahashi and Dahlgren, 2016; Dalgren et al., 1997). As a consequence, P availability decreases with increasing soil development.

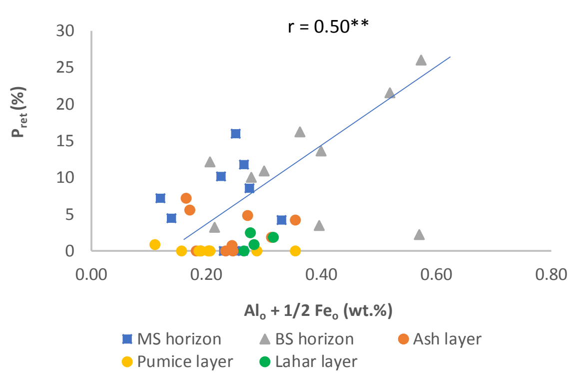


Figure 4. Plot graph of P retention vs. Al_o + ½ Fe_o in the soil horizons and pyroclast layers of Fo-Ash (P1-a, P1-b; Tarlac), IR-Ash (P2-a, P2-b; Tarlac), Gr-LA-Ash (P3-a, P3-b; Pampanga), Gr-HA-Ash (P4-a, P4-b; Pampanga) and IR-Lahar (P5-a, P5-b; Zambales) soil profiles.

In Figure 5[a-b], the P_{ret} values obtained for the MS and BS of each soil are plotted against the corresponding total reserve in bases (TRB) and Fe_d/Fe_t, i.e., weathering indices. Assuming a homogeneous composition of the parent material, a low TRB indicates higher weathering and vice-versa with Fe_d/Fe_t. For P_{ret} values at least a few percent, Figure 5a suggests an inverse relationship between P_{ret} and TRB ($r = 0.77$, $p<0.001$). Furthermore, the P_{ret} of MS and BS showed a positive relationship with Fe_d/Fe_t ($r = 0.78$, $p<0.001$) (Fig. 5b). These results agree with the view that the capacity of volcanic soil to retain P increases with weathering (Shoji et al., 1993; Dahlgren et al., 2004).

There is no relationship between P_{ret} and Fe_o-Fe_p (data not shown). The Fe_o-Fe_p gives a measure of Fe in poorly crystalline phases such as ferrihydrite (Schaetzl and Anderson, 2005). This might be due to the low formation of Fe (hydr)oxide in both the MS and BS horizons. Furthermore, ferrihydrite interacts preferentially with dissolved silica and humic substances (Dahlgren et al., 2004; Schwertmann, 1988).

The positive relationship between P_{ret} and Al_p + Fe_p ($r = 0.88$, $p<0.001$; Fig. 6) in the soil horizons and pyroclast layers shows the influence of Al/Fe-organic complexes on their capacity to retain P. The Al and Fe fractions extracted by Na-pyrophosphate are those adsorbed in organic complexes (Wada, 1989). As soil organic matter, Al, and Fe build up with the progression of weathering, the formation of Al/Fe-organo complexes also increases especially in the soil horizons. The P ions bind to the Fe/Al-(hydr) oxide surfaces by interacting with OH^- and/or OH^{2+} groups; thus, they can fix P and temporarily reduce its availability for plant uptake (Mishra et al., 2017).

Overall, the results indicate that even if small, the accumulation of SRO minerals, particularly

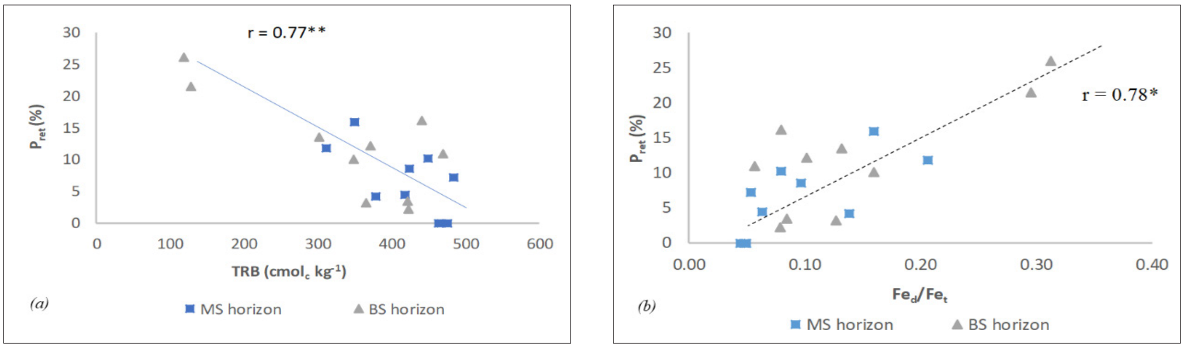


Figure 5. Plot graphs of P retention vs. (a) TRB and (b) Fe_d/Fe_t in the soil horizons of Fo-Ash (P1-a, P1-b; Tarlac), IR-Ash (P2-a, P2-b; Tarlac), Gr-LA-Ash (P3-a, P3-b; Pampanga), Gr-HA-Ash (P4-a, P4-b; Pampanga) and IR-Lahar (P5-a, P5-b; Zambales) soil profiles.

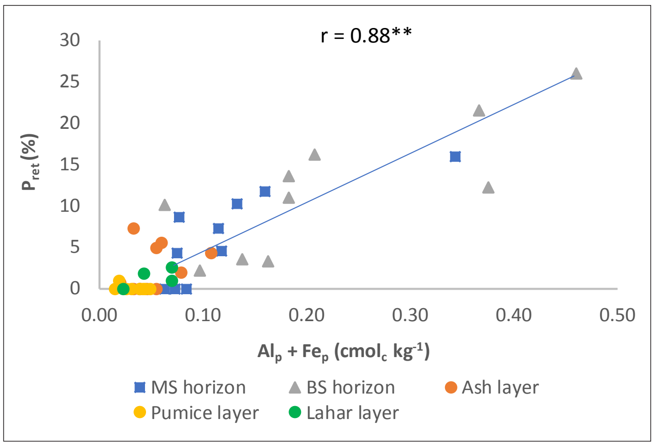


Figure 6. Plot graph of P retention vs. [Al_p + Fe_p] in the soil horizons and pyroclast layers of Fo-Ash (P1-a, P1-b; Tarlac), IR-Ash (P2-a, P2-b; Tarlac), Gr-LA-Ash (P3-a, P3-b; Pampanga), Gr-HA-Ash (P4-a, P4-b; Pampanga) and IR-Lahar (P5-a, P5-b; Zambales) soil profiles.

allophanes and imogolite, and soil organic matter in response to weathering in the poorly developed MS and BS enhances the capacity of the young soils to retain P significantly. Based on an in-situ weathering experiment involving the tephra from the 1980 eruption of Mt. St. Helens, USA, Dahlgren et al. (1997) reached a similar conclusion. They noticed that 10 years of tephra weathering in a subalpine forest led to a sevenfold increase in P retention. The data obtained by this study highlight a similar effect.

Conclusion

Assessment of the P status in the pyroclast-affected cultivated and non-cultivated soils 26 years after deposition showed that the P_{total} and P_{avail} contents in the developing modern soils are probably high enough to support the plants' P requirement. The pyroclast deposit from the 1991 Mt. Pinatubo eruption acts as a ready source of plant-available P during the early stages of weathering. This is due to the dissolution of P-bearing minerals, particularly apatite. The P retention (< 20%) in the modern soils is low due to the small contents of active Al and Fe from Al/Fe-(oxyhydr)oxides, SRO minerals, and Al/Fe-organic complexes. This indicates further that modern soils (including the partially weathered pyroclast deposits) across the different land uses have a low degree of weathering and are weakly developed. As such they still contain a significant reserve of plant-available P.

Some of the factors that influence the chemical weathering of pyroclasts and the P status in cultivated and non-cultivated young volcanic soils are the composition and heterogeneity of the pyroclast deposits (i.e., type, thickness, grain size, presence of eroded sediments), and the kind of land use and management (i.e., volume of crop cover, biomass restitution, and removal, fertilization, drainage, runoff). In cultivated soils grown to rice, P availability and contents can be controlled by various mechanisms such as the intensity of crop production, biomass recycling (i.e., P removal from harvested grains and biomass, restitution), fertilization, and water drainage in addition to chemical weathering. The continuous crop cultivation and partial crop removal in the rice soils affected by ash and lahar are possible causal factors for their lower P_{total} and P_{avail} contents compared with the forest and grassland soils covered by ash.

The generally lower P_{total} and P_{avail} values in the buried compared with the modern soils, except for IR-Lahar, reflect the gradual loss of P with time due to apatite dissolution during chemical weathering. Higher P retention is observed in the ~500-yr buried soils than in the modern soils due to the small build-up of active Al and Fe in SRO minerals (i.e., allophanes and imogolite) and Al/Fe-organic matter complexes in the course of pedogenesis. Moreover, the buried soils have a significantly higher net loss of P, i.e., P_{total} and P_{avail} (except for IR-Lahar), due to a lower rate of P fixation as the secondary materials (i.e., allophane, imogolite, Al/Fe-organic matter complexes) occurred in low quantities. The organic P pool is also low as the deposition of pyroclast deposit has impeded the addition of organic matter from biomass restitution in the buried soils.

Acknowledgment

The authors would like to thank the Académie De Recherche et D'Enseignement Supérieur (ARES) in the framework of the Commission Universitaire pour Le Developpement (CUD) in Belgium for funding this PhD research. The research was conducted through the collaboration of the Earth and Life Institute Environmental Sciences, University Catholique de Louvain (UCLouvain), University of the Philippines Los Baños (UPLB), Université Libre de Bruxelles (ULB), and Philippine Institute of Volcanology and Seismology (PHILVOCS). We would also like to thank the jury members of this dissertation, Prof. Sophie Opfergelt (UCLouvain), Prof. Rodrigo Badayos (UPLB), Prof. Marnik Vanclooster (UCLouvain), Prof. Erlinda Paterno (UPLB), and Prof. Pompe Sta. Cruz (UPLB) for their valuable inputs to improve the quality of the paper.

Literature Cited

Bautista CB (1996) The Mount Pinatubo disaster and the people of Central Luzon. *In* Newhall CG and Punongbayan RS (Eds). Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology, Quezon City. Hongkong: University of Washington Press

Bernard A, Knittel U, Weber B, Weis D, Albrecht A, Hattori K, Oles D (1996) Petrology and geochemistry of the 1991 eruption products of Mount Pinatubo. *In* Newhall C and Punongbayan RS. (Eds.), Fire and Mud, Eruptions, and Lahars of Mount Pinatubo, Philippines (pp 767-797). USA: Univ. Washington Press

Blakemore LC, Searle PL, Daly BK (1981) Methods for chemical analysis of soils. New Zealand: Department of Scientific and Industrial Research.

Blaskó L (2011) Soil Science. Debreceni Egyetem. Agrár- és Gazdálkodástudományok Centruma

Bray RH, Kurtz LT (1945) Determination of total organic and available forms of P in soils. Soil Sci. **59**:39

Castillo PR, Punongbayan RS (1996) Petrology and Sr, Nd, and Pb Isotopic Geochemistry. *In* Newhall RS, Christopher G., Punongbayan RS. (Eds.). Fire and Mud (pp 799-805). Philippine Institute of Volcanology and Seismology, Quezon City. UK: University of Washington Press

Chao TT, Sanzolone RF (1992) Decomposition techniques. Journal of Geochemical Exploration **44:** 65-106

Collado WB, Monteza RM, Dollentas RT, De Dios JLD, Torre JP, Bibar JE, Badayos, RB, Soliman, AE (2013) Simplified Keys to Soil Series - Zambales. Soil Series Guidebook. Philippines: Philippine Rice Research Institute

Dabin B (1980) Phosphorus deficiency in tropical soils as a constraint on agricultural output. *In* Soil-related Constraints to Food Production in the Tropics (pp 217-232). Philippines: Los Baños, Laguna

Dahlgren RA, Dragoo JP, Ugolini FC (1997) Weathering of Mt. St. Helens tephra under a cryic-udic climatic regime. Soil Science Society of America Journal **61**: 1519-1525

Dahlgren RA, Saigusa M, Ugolini FC (2004) Nature, properties, and management of volcanic soils. Advances in Agronomy **82**: 113-182

Deer WA, Howie RA, Zussman J (1992) An introduction to the Rock-forming Minerals. (2nd ed). England: Longman Scientific and Technical, Essex

Delvaux B, Herbillon AJ, Vielvoye L (1989) Characterization of a weathering sequence of soils derived from volcanic ash in Cameroon. Taxonomic, mineralogical and agronomic implications. Geoderma **45**: 375–388

Duxbury JM, JH Peverly (1978) Nitrogen and phosphorus losses from organic soils. Journal of Environmental Quality **7**: 566-570

Engelstad OP, Jugsujinda A, De Datta SK (1974) Response by flooded rice to phosphate rocks varying in citrate solubility. Soil Science Society of America Proceedings **38**: 524-529

Escudey M, Galindo G, Foerster JE, Briceño MA, Díaz P, Chang AC (2001) Chemical forms of phosphorus of volcanic ash derived soils in Chile. Communications in Soil Science and Plant Analysis **32**: 601-616

Gudmundsson T, Gudmundsson ST, Thorvaldsson G (2014) Soil phosphorus fractionation in Icelandic long-term grassland field experiments. Icelandic Agricultural Sciences **27**(1): 81-94

Harouiya N, Chaïrat C, Köhler SJ, Gout R, Oelkers EH (2007) The dissolution kinetics and apparent solubility of natural apatite in closed reactors at temperatures from 5 to 50 °C and pH from 1 to 6. Chemical Geology **244**(3-4): 554-568

Herrera IO (1992) Mt. Pinatubo R and D program of the Department of Agriculture-Region III. *In* Proceedings of the symposium on sustainable agricultural development of Mt. Pinatubo-affected areas. November 5-6, 1992. Philippines: University of the Philippines

Herbillon AJ (1989) Chemical estimation of weatherable minerals present in the diagnostic horizons of low activity clay soils. 8th International Soil Classification Workshop 1986

Mehra OP, Jackson ML (1960) Iron oxides removal from soils and clays by dithionite-citrate system buffered with sodium bicarbonate. Proceeding of 7th National Conference Clay Minerals, Washington

Melosantos MOP, Solidum RU, Scott WE, Quiambao RB, Umbal JV, Rodolfo KS, Tubianosa BS, Delos Reyes PJ, Alonso RA, Ruelo H (1996) Tephra falls of the 1991 eruptions of Mount Pinatubo. *In* CG Newhall and Punongbayan RS (Eds.). Fire and Mud. Eruptions and Lahar of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology, Quezon City. Hongkong: University of Washington Press

Mishra G, Debnath S, Rawat D (2017) Managing phosphorus in terrestrial ecosystem: A review. European Journal of Biological Research **7**(3): 255-270

Nanzyo M, Yamasaki S (1998) Phosphorus-bearing mineral in fresh, andesite and rhyolite tephras in the northern part of Japan. Phosphorus Research Bulletin **8**: 95-100

Nanzyo M, Kanno H (2018) Role of inorganic soil constituents in selected topics. *In* Inorganic Constituents in Soil (pp 136-176). Singapore: Springer

Nanzyo M, Dahlgren R, Shoji S (1993) Chemical characteristics of volcanic ash soils. *In* Shoji S, Nanzyo M, Dahlgren R (Eds.). Volcanic Ash Soils. Genesis, Properties, and Utilization. Developments in Soil Science 21. Amsterdam: Elsevier

Nanzyo M, Takahashi T, Sato A, Shoji S, Yamada I (1997) Dilute acid-soluble phosphorus in fresh air-borne tephras and fixation with an increase in active aluminum and iron. Soil Science and Plant Nutrition **43**(4): 839-848

Nanzyo M, Yamasaki S, Honma T (2011) Changes in content of trace and ultratrace elements with an increase in noncrystalline minerals in volcanic ash soils of Japan. Clay Science **12** : 25-32

Nanzyo M, Kanno H, Takahashi T (2010) Organic carbon accumulation in Andosols: (3) Occurrence of apatite and biotite in young and matured volcanic ash soils, and discussions on nutrient supply for ecosystems. Journal of Integrated Field Science **7**: 73-77

National Research Council (1993) Soil and Water Quality: An Agenda for Agriculture. USA: The National Academies Press

Newhall CG, Punongbayan RS (1996) Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology, Quezon City. UK: University of Washington Press

Pallister JS, Hoblitt RP, Meeker GP, Knight RJ, Siems DF (1996) Magma mixing at Mount Pinatubo: Petrographic and chemical evidence from the 1991 deposits. *In* Newhall CG and Punongbayan RS (Eds.). Fire and Mud. Eruptions and Lahar of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology, Quezon City. UK: University of Washington Press

Pansu M, Gautheyrou J (2006) Handbook of Soil Analysis: Mineralogical, Organic and Inorganic methods. New York: Springer

Parfitt RL (1980) Chemical properties of variable charge soils. *In* Theng, BKG (Ed.). Soils with Variable Charge (pp 167-193). New Zealand: New Zealand Society of Soil Science

Pierzynski M, Sims JT, Vance GF (2000) Soil phosphorus and environmental quality. *In* Soils and Environmental Quality (pp 155-207). USA: CRC Press, Boca Raton

Punongbayan RS, Tungol NM, Arboleda RA, DelosReyes PJ, Isada M, Martinez ML, Melosantos MLP, Puertollano J, Regalado TM, Solidum RU, Tubianosa BS, Umbal J V, Alfonso RA, Remotique CT (1993) Impacts of the 1993 lahars and long-term lahar hazards and risks around Pinatubo volcano. PHIVOLCS Internal Report, Quezon City

Rantucci G (1994) Geological Disasters in the Philippines: The July 1990 earthquake and the June 1991 eruption of Mount Pinatubo - Description. Effects and lessons learned. Report in cooperation with PHILVOLCS, Rome: Italian Ministry of Foreign Affairs, Directorate-General for Development Cooperation

Reyes RY, Neue HU (1991) Characterization of the volcanic ejecta from Mount Pinatubo and its impact on rice production. Philippine Journal of Crop Science **16:**(2) 69-73

Roy RN, Finck A, Blair G, Tandon H (2006) Plant nutrition for food security: A guide for integrated nutrient management. FAO Fertilizer and Plant Nutrition Bulletin **16**: 21

Rouiller J, Burtin G, Souchier B (1972) La dispersion des sols dans l'analyse granulométrique. Méthode utilisant les résines échangeuses d'ions. ENSAIA Nancy **14**: 194-205

Satti P, Mazzarino MJ, Roselli L, Crego P (2007) Factors affecting soil P dynamics in temperate volcanic soils of southern Argentina. Geoderma 2007 **139**: 229-240

Schaetzl R, Anderson S (2005) Soils: Genesis and Geomorphology. USA: Cambridge University Press

Schwertmann U (1988) Occurrence and formation of iron oxides in various paleoenvironments. *In* Stucki JW (Ed.). Iron in Soils and Clay Minerals (pp 267-308). USA: Reidel, Norwell, MA

Schlesinger WH, Bruijnzeel LA, Bush MB, Klein EM, Mace KA, Raikes JA, Whittaker RJ (1998) The biogeochemistry of phosphorus after the first century of soil development on Rakata Island, Krakatau, Indonesia. Biogeochemistry **40**(1): 37-55

Sharpley AN (1995) Soil phosphorus dynamics: Agronomic and environmental impacts. Ecological Engineering **5:** 261-279

Shoji S, Takahashi T (2002) Environmental and agricultural significance of volcanic ash soils. Global Environmental Research-English Edition **6**(2): 113-135

Shoji S, Nanzyo M, Dahlgren R (1993) Volcanic ash soils. Genesis, properties, and utilization. Developments in Soil Science 21. Amsterdam: Elsevier

Smith P, Cotrufo MF, Rumpel C, Paustian K, Kuikman PJ, Elliott JA, Scholes MC (2015) Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. Soil Discussion **1:** 665-685

Uchida R (2000) Essential nutrients for plant growth: Nutrient functions and deficiency symptoms. *In* Silva R, Uchida JA (Eds.). Plant Nutrient Management in Hawaii's Soils, Approaches for Tropical and Subtropical Agriculture (pp 31-55). Hawaii: College of Tropical Agriculture and Human Resources

USDA-NRCS (1994) Soil Phosphorus: Soil Quality Kit- Guides for Educators. United States Department of Agriculture: Natural Resources Conservation Service (pp 1-6). Retrieved from http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053254.pdf (accessed August 24, 2020)

Wada K (1989) Allophane and imogolite. *In* JB Dixon and SB Weed (Eds.). Minerals in Soil Environments (2nd edn) USA: Soil Sci. Soc. Am

Wolff-Boenisch D, Gislason S, Oelkers E, Putnis C (2004) The dissolution rates of natural glasses as a function of their composition at pH 4 and 10. 6, and temperatures from 25 to 74 ° C. Geochimica et Cosmochimica Acta **68**(23): 4843-4858

SOIL MICROBIAL FUNCTIONAL DIVERSITY IN CONTINUOUSLY FERTILIZED IRRIGATED LOWLAND RICE ECOSYSTEM

Paul John M. Pangilinan[1], Florida C. Garcia[1], Roel R. Suralta[2], Jennifer T. Niones[2], Editha V. Evangelista[2], Maria Auxilia T. Siringan[3], Wilfredo B. Collado[2], and Jayvee A. Cruz[2]

[1]Central Luzon State University, Science City of Muñoz, Nueva Ecija, Philippines,
[2]Philippine Rice Research Institute, Science City of Muñoz, Nueva Ecija, Philippines, [3]Microbiological Research Services Laboratory, Natural Sciences Research Institute, University of the Philippines, Diliman, Quezon City, Philippines,
*Corresponding Author: jayveeacruz@gmail.com

Abstract

This study assessed soil microbial functional diversity in the long-term fertility trials under irrigated lowland rice ecosystem; examined the community-level physiological profile of soil microbial communities using BiOLOG EcoPlate analysis; and determined the correlation between soil microbial functional diversity and indigenous soil nutrient supply. The sole carbon utilization patterns (SCUPs) of soil microbial communities showed that the microbial communities under fertilized treatment have higher functional diversity and metabolic proficiency in utilizing a wide array of carbon sources than the unfertilized treatment. Positive correlation between microbial functional diversity and pH and negative correlation between soil organic matter and functional diversity were observed. Microbial functional diversity was not affected by long term inorganic fertilization in irrigated lowland rice systems. Hence, fertilization rates with +N-P-K Site-Specific Nutrient Management (SSNM) indicates that there is a balanced fertilization of the macro-nutrients NPK needed in that particular area.

Keywords: *Average Well Color Development, Biolog Ecoplate, Lowland Rice Ecosystem, Microbial Functional Diversity.*

Introduction

Soil has the most diverse and important assemblage of organisms that represents a significant reservoir of biodiversity. It is assumed to be directly responsible for soil ecosystem processes especially nutrient cycling and organic matter decomposition (Wardle et al., 1999; Heemsbergen et al., 2004; Bardgett and van der Puten, 2014; Soliveres et al., 2016). Soil quality is strongly affected by microbe mediated processes which function is relative to diversity. Diversity is not just a simple response variable to the constant changes in soil micro and macro-habitats but also a predictor of ecosystem functioning (Cardinale et al., 2006; Balvanera et al., 2013). Biodiversity performs ecosystem services beyond production, it also performs key processes that sustain natural processes and ecosystem functions. Therefore, the persistence of these key processes depends upon the maintenance of microbial functional diversity.

Soil microbes are highly sensitive to external disturbances. Fertilization and other agricultural activity strongly alter the community structure and diversity of soil microorganisms (Allison et al., 2008; Hartmann et al., 2015; Su et al., 2015) and in turn significantly influence a wide range of soil biological processes (Sinsabaugh et al., 2008). Based on this external sensitivity, soil microbial communities have been widely used as an indicator of soil quality and ecosystem functioning (Bastida et al., 2016; Loeppmann et al., 2016).

Demand for soil productivity is expected to increase from agricultural use to meet the increasing requirement for food and bioenergy (Ort et al., 2015). Understanding the biological dynamics of managed soils in relevance to ecosystem functionality is critical to accurately assess the future agroecosystem response to global changes. The capacity of the soil to produce sufficient raw materials may be improved and sustained with long-term anthropological interventions. Conventional farming practices influence soil quality and microbial functional composition by altering the quality of plant residues and the spatial distribution of nutrients (Christensen, 1996). Interventions of natural processes such as fertilization are considered necessary to maximize agricultural productivity. Margins to further increase and sustain crop yield may directly influence the trade-offs of ecosystem services. To ensure that soils can cope with external perturbations, an "underground revolution" occurs, which determines how the indigenous soil biological system and the diversity of functions operate under intensive agroecosystem management (Bender et al., 2016).

Agricultural land management is one of the most significant anthropogenic activities that greatly alters soil characteristics including physical, chemical, and biological properties (Jangid et al., 2008). Conventional management systems influence soil microorganisms and the soil microbial processes by altering the quantity and quality of plant residues entering the soil and their spatial distribution through changes in nutrients and inputs (Christensen, 1996). Fertilization influences soil microbial composition, growth, and metabolism (Broeckling et al., 2008). Paddy soils are routinely fertilized to improve soil nutrition and to optimize crop production just as different groups of microorganisms vary in their ability to adapt to the various soil nutrient conditions.

Long-term fertilization experiments involving conventional practices can be manipulated to modify soils in a particular manner. Studies in this area also contributed significantly to existing knowledge about the evolution and development of soil fertility and crop productivity. However, if conventional practices are not properly managed, these can have adverse environmental consequences greatly affecting the ability of soil microbial communities to effectively respond to any perturbations (Schionning et al., 2004).

Maintaining an area with good soil fertility is part of keeping the plants healthy and ensuring abundant harvest, which can be achieved through fertilizer application. However, over-fertilization can decrease growth and leave plants weak and vulnerable to pests and diseases. Balanced fertilization is one key to attain good soil fertility status for sustainable high yields, which can be assessed through soil microbial community evaluation. In this study, we examined the functional diversity, richness, and evenness in terms of *in-vitro* sole carbon source utilization of soil microbial communities under long-term soil fertility experiment in intensively- irrigated lowland rice systems. This will possibly serve as an indicator of balanced fertilization and available energy sources of the area.

Materials and Methods

Soil Sample Collection

Soil samples were collected from the Long-term Fertility Experiment (LTFE) at the Philippine Rice Research Institute-Central Experiment Station of the Department of Agriculture (DA-PhilRice), Maligaya, Science City of Muñoz, Nueva Ecija. The experiment was initiated in the mid-to-late 1960s and is still an ongoing research.

During the time of sampling, LTFE was planted with NSIC Rc 160 irrigated lowland rice variety. The soil samples were collected from plots either with no N-P-K fertilization or +N-P-K Site-Specific Nutrient Management (SSNM) for nitrogen. The soil samples were collected from each plot at the post-harvest stage of rice. Soil samples were placed in clear sterile plastic containers and then transported to the laboratory.

Determination of Soil Microbial Functional Diversity

BiOLOG EcoPlate analysis was used to assess the substrate utilization pattern (CSUP) of soil microbial communities. Analysis was conducted at the Microbiological Research Services Laboratory, National Science Research Institute in the University of the Philippines, Diliman, Quezon City.

Preparation of soil samples for BiOLOG EcoPlate analysis. By means of aseptic technique, 10 g of fresh soil sample was added to 90 mL of 0.1% peptone water. The soil suspension was manually shaken. Residual soil samples were air dried for subsequent soil chemical analysis.

Serial dilution and BiOLOG EcoPlate inoculation. Ten mL of the soil suspension was transferred to a sterile glass bottle containing 90 mL 0.1% peptone water, and serially diluted up to 10^{-3} dilution. The 10^{-2} dilution was used to inoculate the BiOLOG EcoPlate. Supernatant at 150 µL was dispensed to each well of the EcoPlate.

Incubation and reading of BiOLOG EcoPlate color development. The plates were incubated (25˚C) for seven days and color development was recorded every 24 h with an automated plate reader. Data were collected using MicroLog 4.01 software. Optical density (OD) expressed as the absorbance value of each well of the microplate was obtained. OD of each well was corrected by subtracting the OD of the control well to the OD of each well. Microbial carbon utilization was expressed as average well color development and computed using the formula;

Equation 1 $$AWCD = \frac{1}{31}\sum_{i=1}^{31} \quad OD_{(i,j,t)}$$

Determination of functional diversity index using biolog ecoplate data. Soil microbial functional diversity was computed using the data that was generated from the BiOLOG EcoPlate analysis. Microbial diversity index was computed using the Shannon (*H'*), Simpson's (*D*), and Pielou or Evenness (*E*) index, which defines functional richness, dominance, and evenness, respectively. Soil microbial functional diversity was computed using the following formula;

Shannon index (H')

Equation 2 $$H' = -\sum_{i=1}^{n} p_i(Inp_i)$$

Simpson's index (1-D)

Equation 3 $$1 - D = 1 - \frac{\sum_{i=1}^{n} n_i(n_i - 1)}{N(N-1)}$$

Pielou/Evenness index (E)

Equation 4 $$E = \frac{H}{In(N)}$$

Where, p_i is the ratio of the corrected absorbance value of each well to the sum of the absorbance value of all the wells, n_i corrected absorbance value of carbon sources, and N is the total number of carbon sources.

Curve integration approach

Metabolic activity through the 7-day incubation period was quantified using curve integrated approach using the area under the kinetic curve and Reimann's sum.

Area Under the Kinetic Curve. Numerical integration method was used to approximate the integral area under the kinetic curve of sole carbon source utilization, which was computed using the formula (Guckert et al., 1997; Haack et al., 1995; Gauch et al., 1997);

Equation 5 $$A_{ik} = \frac{1}{2}\sum_{j=1}^{j=n-1} \left[t_{(j+1)} - t_j\right] \bullet \left[OD_{ikt_{(j+1)}} + OD_{ikt_{(j)}}\right]$$

Where, A_{ik} is the area under the curve, $OD_{ikt(j+1)}$ and $OD_{ikt(j)}$ is the absorbance reading of each well at time t.

Reimann's Sum. The weighted average of the optical density of each time point and an approximation of the area under the curve with time were computed using the formula (Mayr et al., 1999);

Equation 6 $$S_i = \frac{1}{T} \bullet \left[\left(\frac{x_i + x_0}{2} \times \frac{t_i - t_0}{2}\right) + \left(\frac{x_2 + x_0}{2} \times \frac{t_2 - t_0}{2}\right) + \cdots + \left(\frac{x_s + x_0}{2} \times \frac{t_s - t_0}{2}\right)\right]$$

Where, S_i is the Reimann's sum, T is the total incubation time (hr), x_i is the absorbance reading at each time point (t) and t_i is the time of the reading.

Chemical Characterization of Soils

Soil samples were analyzed for pH and organic matter (OM) content. Chemicals were analyzed at the Soil and Plant Tissue Analysis Laboratory, College of Agriculture, Central Luzon State University.

Statistical Analysis

Significant differences between fertilization treatments were analyzed using an independent sample t-test.

Results and Discussion

Community Level Physiological Profiling

Results showed that the average well color development (AWCD) curve of the fertilized and unfertilized treatment follows a sigmoid curve (Figure 1a). The fertilized curve is higher relevant to the unfertilized curve. The highest rate of AWCD for both of the treatments was recorded at the 48-h incubation period, which then followed a decreasing trend with time (Figure 1b).

All results were based on the 120-h incubation period. The average well color development was significantly higher in the fertilized treatment than in unfertilized treatment. AWCD is the sum value of all the optical densities of the 31 carbon substrates in the EcoPlate. Curve integrated approach using the area under the kinetic curve (AUKC) and Reimann's sum were employed. AUCK and Reimann's sum are kinetic measures to quantify the metabolic activity of microbial communities within the seven-day

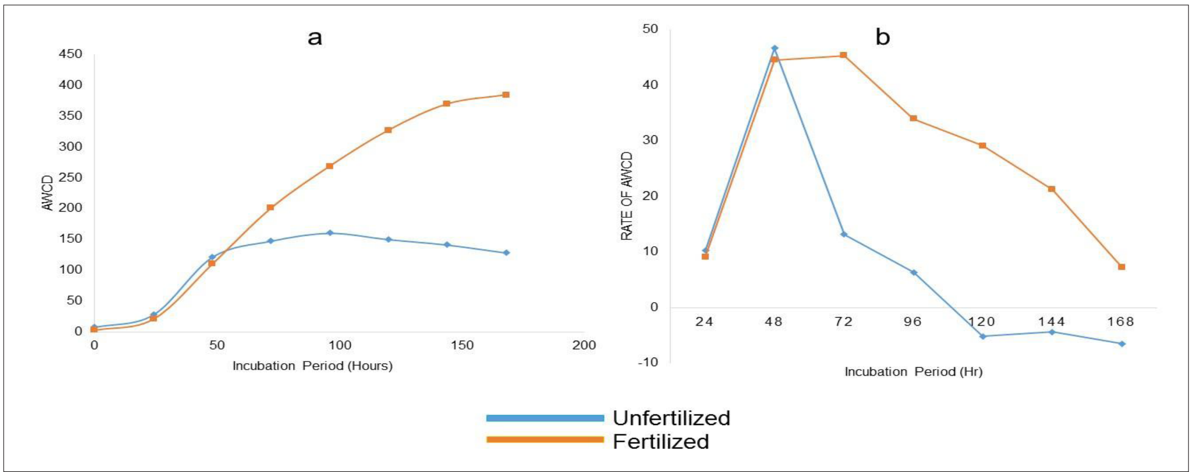


Figure 1. (a) AWCD and (b) rate of AWCD of metabolized carbon substrates in BiOLOG EcoPlates based on 168-h incubation.

incubation period. Independent sample *t*-test revealed that the AUKC and Reimann's sum of the fertilized treatment were significantly higher relevant to the unfertilized treatment (Table 1).

Table 1. Average Well Color Development (AWCD) and Curve integrated variables (Reimann's sum and area under the kinetic curve) of the fertilized and unfertilized treated soils representing relative degree of sole carbon source utilization.

Treatment	AWCD	Reimann's Sum	Area Under the Kinetic Curve
Unfertilized	150.41^{b}	116.76^{b}	19616.3^{b}
Fertilized	327.17^{a}	213.27^{a}	35829.5^{a}

Means within a column followed by the same letter are not significant at 0.05% level of significance.

Microbial activity in each microplate was expressed as AWCD. It is relevant to sole-carbon source utilization patterns of microbial communities determined by the overall color development in the EcoPlate. It represents the overall metabolic activity of microbial communities and estimates the degree of microbial functional diversity based on physiological parameters (Thuithaisong et al., 2010).

The decreasing trend indicates that microbial communities were utilizing the carbon substrate present in the EcoPlate. Slower rate of AWCD implies that microbial communities were able to utilize a wide array of carbon substrates in the EcoPlate while a rapid decline indicates that fewer substrates are metabolized. Carbon substrate utilization showed that addition of the recommended amount of fertilizer required for the crop based on morphological symptoms modified the metabolic profile of microbial communities (Kong et al., 2006).

Sole-Carbon Source Utilization in The Fertilized and Unfertilized Treatments

Carbon substrates were grouped into carbon guilds (Weber and Legge, 2009). There was a higher utilization of amino acids, polymers, and amine/amides in the unfertilized treatment. However, utilization of carboxylic acid and carbohydrates were similar for both treatments (Figure 2).

Utilization of carbon substrates were expressed as percentage per carbon guild to show the kind of carbon substrates mostly utilized by the microbial communities. The functional composition of microbial communities is relevant to the available energy sources in the environment. It has been established that upon the addition of simple inorganic substances to the soil (Sun et al., 2004), it significantly affects the metabolic activity of soil microbial communities by changing the functional composition of microbial communities metabolize the readily available energy sources (Fierer and Jackson, 2006; Hartmann et al., 2015; Zhalnina et al., 2015).

PCA and Bidimensional Biplot Analyses of Sole-Carbon Source Utilization

Principal components were analyzed to show the similarities and/or differences of microbial communities on the basis of sole-carbon source utilization patterns. The assumption is that points that are close to each other are similar and those that are distant are different. PC1 accounts for 51.37% of the total variance while PC2 accounts for 11.34% (Figure 3). Points were differentiated into three distinct clusters; each was differentiated along the two principal axes. Bidimensional biplot analysis showed that the separation of points in the PCA plot was attributed to the differences in carbon utilization. The varying degree and direction of carbon substrate in the biplot indicates the variability in carbon utilization (Figure 4).

Functional Diversity Indices of Soil Microbial Communities

Diversity indices were computed to determine the functional diversity of soil microbial communities in terms of carbon source utilization patterns. The

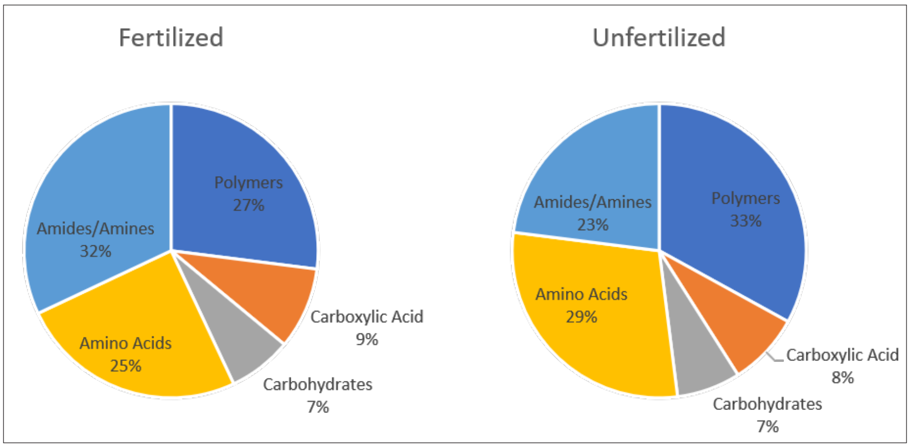


Figure 2. Percentage sole-carbon source utilization per carbon guilds at 120-h incubation period.

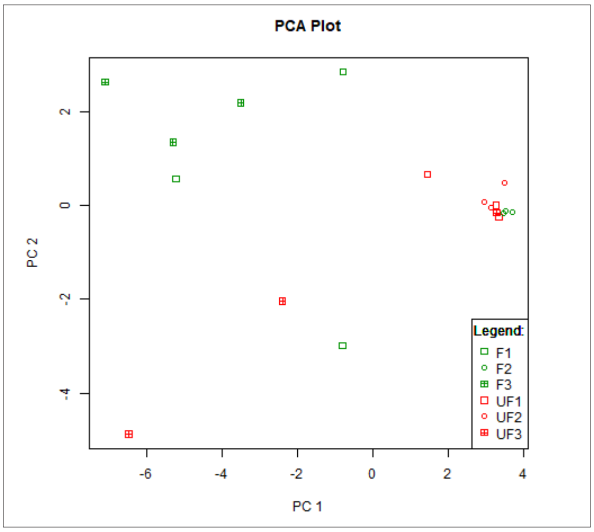


Figure 3. PCA analysis of sole-carbon source utilization of corrected optical density of the fertilized (F) and unfertilized (UF) plots.

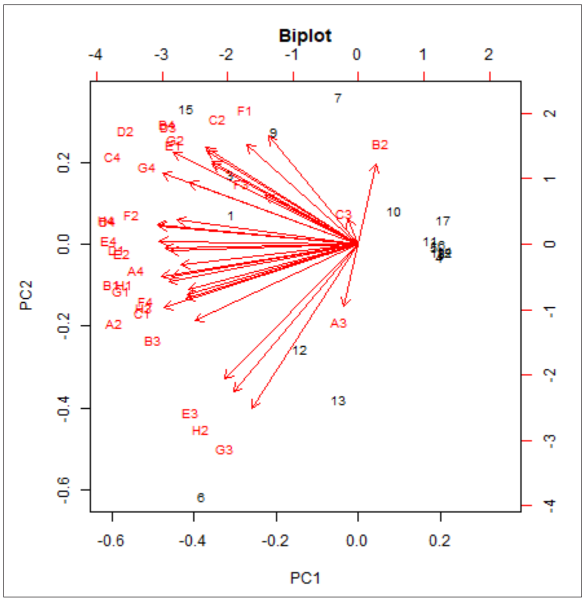


Figure 4. Bidimensional biplot analysis of sole-carbon source utilization of corrected optical density of the fertilized (F) and unfertilized (UF) treated soils. A2: β-Methyl-D-Glucoside; A2: D-Galacturonic Acid γ-Lactone ; A3: L-Arginine; B1: Pyruvic Acid Methyl Ester; B2: D-Xylose; B3: D-Galacturonic Acid; B4: L-Asparagine; C1: Tween 40; C2: i-Erythritol; C3: 2-Hydroxy Benzoic Acid; C4: L-Phenylalanine; D1: Tween 80; D2: D-Mannitol; D3: 4-Hydroxy Benzoic Acid; D4: L-Serine; E1: α -Cyclodextrin; E2: N-Acetyl-D-Glucosamine; E3: γ -Hydroxybutyric Acid; E4: L-Threonine; F1: Glycogen; F2: D-Glucosaminic Acid; F3: Itaconic Acid; F4: Glycyl-L-Glutamic Acid; G1: D-Cellobiose; G2: Glucose-1-Phosphate; G3: α -Ketobutyric Acid; G4: Phenylethyl-amine; H1: α -D-Lactose; H2: D,L- α -Glycerol Phosphate; H3: D-Mallic Acid; H4: Putescine.

corrected optical density for the 120-h incubation period was used for the computation. Table 2 shows the diversity index of the fertilized and unfertilized treatments. There were no significant differences between the functional diversity indices of microbial communities between the fertilized and unfertilized plots as expressed as Shannon and Simpson's index. This suggests that species richness and evenness have no significant effect on the differentiation of soil microbial functional diversity under long-term inorganic fertilization. However, significant differences between the evenness index of the fertilized and unfertilized treatments were observed, which suggest that differentiation on soil functional diversity occurs at the level of differential carbon utilization and is independent on species diversity.

Table 2. Functional diversity indices of soil microbial communities under long-term fertilized and unfertilized treatments base on 120-h incubation period for 31 sole carbon substrates of EcoPlate.

Treatment	Shannon (h)	Simpson's			Evenness (e)
		D	1-D	1/D	
Unfertilized	2.29[a]	0.1306[a]	0.8694[a]	8.1927[a]	0.6656[b]
Fertilized	2.78[a]	0.1230[a]	0.8770[a]	7.6564[a]	0.8104[a]

Means within a column followed by the same letter are not significant at 0.05% level of significance.

Correlation Analysis

The chemical analyses of soil samples were correlated with microbial diversity indices (Table 3). Pearson's moment of correlation reveals moderately negative correlation between organic matter and diversity indices, indicating that microbial metabolic activity and microbial functionality have an inverse relationship with organic matter content. However, there was a strong correlation between pH and diversity index.

Zhang et al. (2016) reported that anthropogenic addition of chemical fertilizers and manure can affect soil microorganisms by supplying nutrients and indirectly altering soil pH. This is due to the great influence of pH on the chemical properties of the soil and the relative availability and reactivity of mineral and organic substances present in the soil. It has been well established that lower soil pH favors fungal communities. BiOLOG EcoPlate results account for bacterial communities only because fungi cannot reduce tetrazolium dye.

Table 3. Correlation coefficients (Pearson moment of correlation) between diversity indices and soil organic matter (OM) and pH.

Functional Diversity Index	%OM	pH
Shannon Index (H')	-0.4625*	0.3097**
Simpson's Index (1-D)	-0.4479*	0.2779**
Evenness Index (E)	-0.2569**	0.0522**

*, significant; **, highly significant

According to Fakruddin and Mannan (2013), the use of sole carbon source utilization patterns or community level physiological profiling in describing microbial functional communities offer a fast, highly reproducible technique that covers a wide spectrum of possible microbial specimens. However, the major disadvantages of using this method include: result only represents the cultivable fraction of microbial communities; fast-growing organisms are favored; bias to those organisms that are able to effectively utilize the available carbon sources; and sensitivity to inoculum density.

Conclusion

Microbial functional diversity was not affected by long term inorganic fertilization in irrigated lowland rice systems. However, the differentiation on soil functional diversity was affected by long term inorganic fertilization at the level of differential carbon utilization and was independent on species diversity.

The functional composition of microbial communities is relevant to the available energy sources in the area. Hence, it can be concluded that the long-term experiment area at DA-PhilRice CES still has a good soil fertility status. Understanding the importance of microbial biomass, activity, and diversity is a good indicator of balanced fertilization (N, P, and K) in the area, which is important in promoting and enhancing rice crop growth and production.

Literature Cited

Allison SD, Czimczik CI, Treseder KK (2008) Microbial activity and soil respiration under nitrogen addition in Alaskan boreal forest. Global Change Biology **14**: 1156-1168

Balvanera P, Siddique I, Dee L, Paquette A, Isbell F, Gonzalez A, Griffin JN (2013) Linking biodiversity and ecosystem services: Current uncertainties and the necessary next steps. BioScience **6**: 49-57

Bardgett RD, Van Der Putten WH (2014) Belowground biodiversity and ecosystem functioning. Nature **515**: 505-511

Bastida F, Torres If, Moreno JL, Baldrian P, Ondoño S, Ruiz-Navarro A, Hernandez T, Richnow HH, Starke R, Garcia C, Jehmlich N (2016) The active microbial diversity drives ecosystem multifunctionality and is physiologically related to carbon availability in Mediterranean semi-arid soils. Molecular Ecology **25**: 4660-4673

Bender SF, Wagg C, Van Der Heijden MG (2016) An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. Trends in Ecology and Evolution **31**: 440-452

Broeckling, CD, Broz AK, Bergelson J, Manterm DK, Vivanco JM (2008) Root exudates regulate soil fungal community composition and diversity. Applied and Environmental Microbiology **74:** 738-744

Cardinale BJ, Srivastava DS, Duffy JE, Wright JP, Downing AL, Sankaran M, Jouseau C (2006) Effects of biodiversity on the functioning of trophic groups and ecosystems. Nature **443**: 989-992

Christensen BT (1996) Matching measurable soil organic matter fractions with conceptual pools in simulation models of carbon turnover: Revision of model structure. *In* Powlson DS, Smith JU, Smith P (Eds.), Evaluation of Soil Organic Matter Models Using Existing Long-term Data Sets. Global Environmental Change (pp 143-160) Berlin: Springer Verlag

Fakruddin M, Mannan K (2013) Methods for analyzing diversity of microbial communities in natural environments. Ceylon Journal of Science (Biological Sciences) **42**(1): 19-33

Fierer N, Jackson RB (2006) The diversity and biogeography of soil bacterial communities. Proceedings of the National Academy of Sciences of the United States of America **103**: 626-631

Gauch HG, Whittaker RH, Wentworth TR (1997) A comparative study of reciprocal and other ordination techniques. Journal of Ecology **65**: 157-174

Guckert SB, Carr GS, Johnson TD, Hamm BG, Davidson DH, Yumagai Y (1997) Community analysis by biolog: Curve integration for statistical analysis of activated sludge microbial habitats. Journal of Microbiological Methods **27**: 183-197

Haack SK, Garchow H, Klug M, Forney L (1995) Analysis of factors affecting the accuracy, reproducibility and interpretation of microbial community carbon source utilization patterns. Applied and Environmental Microbiology **61**: 1458-1468

Hartmann M, Frey B, Mayer J, Mäder P, Widmer F (2015) Distinct soil microbial diversity under long-term organic and conventional farming. ISME Journal **9**: 1177-1194

Heemsbergen DA, Berg MP, Loreau M, Van Hal Jr, Faber JH, Verhoef HA (2004) Biodiversity effect on soil processes explained by interspecific functional dissimilarity. Science **306**: 1019-1020

Jangid K, Williams MA, Franzluebbers AJ, Sanderlin JS, Reeves H (2008) Relative impacts of land use, management intensity and fertilization upon soil microbial community structure in agricultural system. Soil Biology and Biochemistry **40:** 2843-2853

Kong WD, Zhu YG, Fu BJ, Marschner P, He JZ (2006) The veterinary antibiotic oxytetracycline and Cu influence functional diversity of the soil microbial community. Environmental Pollution **143**: 129-137

Loeppmann S, Blagodatskaya E, Pausch J, Kuzyakov Y (2016) Substrate quality affects kinetics and catalytic efficiency of exo-enzymes in rhizosphere and detritusphere. Soil Biology and Biochemistry **92**: 111-118

Mayr C, Winding A, Hendrisen NB (1999) Community level physiological profile of soil bacteria unaffected by extraction method. Journal of Microbiological Methods **36**: 29-33

Ort DR, Merchant SS, Alric J, Barkan A, Blankenship RE, Bock R, Croce R, Hanson MR, Hibberd JM, Long SP, Moore TA, Moroney J, Niyogi KK, Parry MA, Peralta-Yahya PP, Prince RC, Redding KE, Spadling MH, Van Wijk KJ, Vermaas WF, Von Caemmerer S, Weber AP, Yeates TO, Yuan JS and Zhu XG (2015) Redesigning photosynthesis to sustainably meet global food and bioenergy demand. Proceedings of the National Academy of Sciences of the United States of America **112**: 8529-8536

Schionning P, Elmholt S, Christensen BT (2004) Soil quality management concepts and terms. *In* Schjønning P, Elmholt S, Christensen BT (Eds.). Managing Soil Quality, Challenges in Modern Agriculture (pp 1-15). UK: CAB International

Sinsabaugh RL, Lauber CL, Weintraub MN, Ahmed B, Allison SD, Crenshaw C, Zeglin LH (2008) Stoichiometry of soil enzyme activity at global scale. Ecology Letters **11**: 1252-1264

Soliveres S, Van Der Plas F, Manning P, Prati D, Gossner MM, Renner SC, Alt F, Arndt H, Baumgartner V, Binkenstein J, Birkhofer K, Blaser S, Blüthgen N, Boch S, Böhm S, Börschig C, Buscot F, Diekötter T, Heinze J, Hölzel N, Jung K, Klaus VH, Kleinebecker T, Klemmer S, Krauss J, Lange M, Morris EK, Müller J, Oelmann Y, Overmann J, Pašalić E, Rillig MC, Schaefer HM, Schloter M, Schmitt B, Schöning I, Schrumpf M, Sikorski J, Socher SA, Solly EF, Sonnemann I, Sorkau E, Steckel J, Steffan-Dewenter I, Stempfhuber B, Tschapka M, Türke M, Venter PC, Weiner CN, Weisser WW, Werner M, Westphal C, Wilcke W, Wolters V, Wubet T, Wurst S, Fischer M, Allan E (2016) Biodiversity at multiple trophic levels is needed for ecosystem multifunctionality. Nature **536**: 456-459

Su JQ, Ding LJ, Xue K, Yao HY, Quensen J, Bai SJ, Wei WX, Wu JS, Zhou J, Tiedje JM, Zhu YG (2015) Long-term balanced fertilization increases the soil microbial functional diversity in a phosphorus-limited paddy soil. Molecular Ecology **24**: 136-150

Sun HY, Deng SP, Raun WR (2004) Bacterial community structure and diversity in a century-old-manure-treated agroecosystem. Applied and Environmental Microbiology **70**: 5868-5874

Thuithaisong C, Parkpian P, Shipin O, Shreshtha R, Naklang K (2010) Comparison of microbial diversity of paddy soils in sustainable organic farming. International Journal of Environmental and Rural Development **1**: 152-157

Wardle DA, Bonner KI, Baker GM, Yeatas GW, Nicholson KS, Bardgett RD, Watson RN, Ghani A (1999) The plant removals in perennial grassland: Vegetation dynamics, decomposers, soil biodiversity, and ecosystem properties. Ecological Monographs **69**:535-568

Weber K, Legge R (2009) One-dimensional metric for tracking bacterial community divergence using sole carbon source utilization patterns. Journal of Microbiological Methods **79**: 55-61

Zhalnina K, Dias R, De Quadros PD, Davis-Richardson A, Camargo FA, Clark IM, Mcgrath SP, Hirsch PR, Triplett EW (2015) Soil pH determines microbial diversity and composition in the park grass experiment. Microbial Ecology **69**: 395-406

Zhang C, Liu G, Xue S, Wang G (2016) Soil bacterial community dynamics reflects changes in plant community and soil properties during the second succession of abandoned farmland in the loess plateau. Soil Biology and Biochemistry **97**: 40-49

FULL PAPER

EFFECTS OF RICE HUSK BIOCHAR APPLICATION UNDER DIFFERENT WATER MANAGEMENT ON GRAIN YIELD, SOIL PROPERTIES, AND WATER PRODUCTIVITY IN RICE

Kristine Samoy-Pascual*, Filomena S. Grospe, Alaissa T. Remocal, and Ricardo F. Orge

Philippine Rice Research Institute, Science City of Muñoz, 3119 Nueva Ecija, Philippines
*Corresponding Author: kcsamoy@gmail.com

Abstract

Empirical data on the combined effects of biochar application and alternate wetting and drying (AWD) technique on water productivity (WP) in rice are limited. Thus, this study evaluated the WP of rice and the soil physico-chemical properties through rice husk biochar application under different water management in sandy clay loam in farmers' field. Biochar was applied every dry season at different rates (0, 2, 5, and 10 t ha^{-1}) under AWD and modified continuous flooding (MCF) for two years. Application of rice husk biochar did not affect the water use (WU) and WP of rice relative to the control. The soil water holding capacity also did not significantly improve with the addition of biochar. Significant reduction of WU was influenced only by AWD while the grain yield did not vary with MCF. The low WU and high grain yield under AWD resulted in high water savings and WP. The first application of biochar reduced the bulk density (BD) of the soil relative to the control while further addition of biochar did not change the BD among treatments. Significant reduction in the soil organic carbon (SOC) relative to MCF was observed in AWD. Further study is recommended to determine the extent of changes on the amount of SOC with continuous practice of AWD.

Keywords: *Alternate Wetting and Drying, Rice-Husk Biochar, Soil Organic Carbon, Water Savings, Water Productivity.*

Introduction

Rice is the largest consumer of fresh water in agriculture. With the increasing demand for food, efficient water use in rice cultivation is necessary to sustain food production. However, there is an increasing water scarcity globally that threatens food security. By 2025, it is estimated that 15 - 20 million of irrigated rice will suffer from water shortage in Asia (Tuong and Bouman, 2003). According to Webster and Lee-Huu (2003) as cited by Rola et al. (2015), per capita water availability has been declining over the years in the Philippines. Several reasons for this include the rapid increase in population and urbanization that have caused conflicting demands for domestic, agricultural, and industrial purposes. The declining availability of water is also worsened by the degradation of watersheds (Rola and Franciso, 2004; Rola et al., 2015). To cope with water scarcity, several water-saving techniques (WSTs) were developed to save irrigation water for rice cultivation (Bouman et al., 2007). However, alternative ways to improve WSTs are needed to achieve higher water savings and cope with the ever-increasing threat of water shortage.

Alternate wetting and drying (AWD) is a water-saving technology that involves the periodic draining and re-flooding of rice fields. In contrast, the conventional farmers' practice of continuous flooding the soil consumes a substantial amount of water due to losses from seepage, percolation, run-off, and evaporation. With AWD, water consumption is reduced by 25% (Siopongco et al., 2013). Its benefits call for continued development by adding more value to the technique to further improve the water productivity of rice.

Rice husk is one of the by-products of the rice milling industries, which is becoming an important source of energy generation through gasification and pyrolysis (Phonphuak and Chindaprasirt, 2105; Saeid and Chojnacka, 2019). The by- and co-product of these processes is called biochar - a porous carbonaceous solid produced from heating under limited or absence of oxygen (Haefele et al., 2011; Boateng et al., 2015). Biochar is a potential material for soil amelioration to improve crop productivity and enhance carbon sequestration in soils (Lehmann et al., 2006; Verheijen et al., 2009). However, the large volume of biochar produced from any commercial gasification plants could pose a problem in the environment in terms of waste disposal. Thus, it is important to assess the benefits of biochar to address the problem. Reported benefits of biochar include the improvement of soil fertility due to its capacity to retain inorganic nutrients in the soil with high pH value and carbon-nitrogen ratio (Lee et al., 2013). Biochar application also improves soil aggregation and structure owing to its high surface area that enhances soil moisture retention. The improved water retention in soils is commonly observed in coarse-textured or sandy soils with large amounts of macropores (Verma et al., 2014). While most of the researches on biochar application were carried out on non-paddy soil using woods as biochar feedstock (Asai et al., 2009; Mukherjee et al., 2014; Pandit et al., 2018), there is still limited information on rice husk biochar and its effect on paddy soil, which requires different management, especially on water. Moreover, AWD and biochar application studies are mostly conducted under on-station or controlled environment. Thus, experiments in farmers' fields are needed.

In this study, it was hypothesized that combining the AWD technique and application of rice husk biochar in sandy clay loam soil can improve the soil physicochemical properties and grain yield in rice while enhancing further the water productivity. This study quantitatively assessed the effects of AWD technique in soil amended with rice-husk biochar. Its effects on the soil physical and chemical properties, water productivity, and agronomic performance in paddy rice were determined under field condition.

Materials and Methods

Field Location and Experimental Set-up

Field experiments were conducted in a farmer's field located at Barangay Sta. Clara, Cuyapo (15°80 N, 120°69 E), Nueva Ecija for two dry (December - April) and two wet (June - October) seasons from 2018 to 2019. The soil in Cuyapo is sandy clay loam with 21% clay, 23% silt, and 56% sand (Table 1). The experiment was laid out in a split-plot design with water management and rate of biochar as treatments in three replicates. The main treatment comprised alternate-wetting and drying (AWD) and modified continuous flooding (MCF) soil condition. AWD set-up was irrigated only when the perched water table reached -15 cm below the soil surface during dry season (DS) and -20 cm during wet season (WS). MCF set-up was irrigated at 5 cm every two days. The subplot was the rate of rice husk biochar consisted of 2, 5, 10 t ha^{-1}. A control treatment was also included with no biochar. The biochar was derived from carbonizing rice husks using an open-type carbonizer (Orge and Abon, 2012). Each subplot measured 2.5 m x 2 m while each main plot was separated by 0.5 m canal to minimize seepage during irrigation. The rice husk biochar was thoroughly mixed during the last harrowing based on treatments applied a day before transplanting.

Table 1. Soil properties of the experimental site in Brgy. Sta. Clara, Cuyapo, Nueva Ecija.

Parameters	Values
Soil texture	sandy-clay loam
Clay (%)	20.6
Sand (%)	56.3
Silt (%)	23.0
pH (H_2O)	7.8
Organic carbon (g kg^{-1})	18.7
Total nitrogen (g kg^{-1})	3.7
Potassium (g kg^{-1})	0.0
Bulk density (g cm^{-3})	1.3

Crop Management Practices

Crop management practices were based on the PalayCheck® System for Irrigated Lowland Rice (PhilRice, 2007). Twenty-day old seedlings of NSIC Rc 160 were transplanted from a *dapog* seedbed to the main field. A total of 120 and 90 kg ha^{-1} of N fertilizers were applied during DS and WS, respectively. N was applied in three equal splits during basal application (0 DAT), topdressing in the mid-tillering and the panicle initiation stage. Phosphorus and potassium were applied each at 40 kg ha^{-1} as basal in both seasons. A complete fertilizer (14-14-14) was used for basal application and urea (46-0-0) for topdressing. Table 2 shows the details of the field management practices of the field experiments.

Data Gathering and Measurements

Field water tubes were used as observation wells to monitor the perched water level in AWD. The perforated tube was installed at 15 and 20 cm below the soil surface during DS and WS, respectively. During irrigation, a calibrated flow meter was used to measure the irrigation input per plot. Irrigation came from a water pumped in an open canal near the farm. At crop maturity, crop cut samples were harvested at 5 m^2 area of each plot. The samples were threshed, cleaned, dried, and weighed. The moisture content of the grains was measured using a digital moisture meter, and grain yield was computed based on 14% moisture content. Rainfall was obtained from the rain gauge installed near the experimental plot. The total water input was computed as the sum of the irrigation and rainfall. Water productivity was determined as the ratio of the grain yield over the total water use.

Soil samples (0 - 10 cm depth) were obtained in each treatment plot for the analysis of bulk density (BD), soil organic carbon (SOC), potassium (K), and soil pH following the standard protocol. Soil samplings were conducted 1 - 3 days after harvest in each season. The SOC was determined using Walkey-Black method (Walkey and Black, 1934) while the soil K used the ammonium acetate method (Peter, 2013). The soil pH was measured in the supernatant suspension using distilled water with 1:1 ratio. The soil water holding capacity (WHC) was determined from soil samples from each treatment plot at harvest during the dry season when biochar was applied following a modified procedure of Priha and Smolander (1997). Soil samples were saturated in water for at least 2 hours while the saturated soil was allowed to drain in a humid enclosure until no gravimetric water was observed. Expressed in percentage, soil WHC was computed as the ratio of the mass of the water contained in the saturated soil and mass of the saturated soil.

Statistical Analysis

Analysis of variance (ANOVA) was conducted using a split-plot design, in which water management (W) was treated as the whole-plot factor and biochar rate (B) as the split-plot factor in randomized complete block design with three replications in a season. Significant differences among treatments were analyzed using Least Significant Difference at 5% level of probability. All data were analyzed using an open software Statistical Tool for Agricultural Research, implemented in the R statistical package (IRRI, 2013).

Results and Discussion

Effects on Soil Physical and Chemical Properties

The effect of biochar in the soil has been widely reported to improve the soil quality for crop production (Ding et al., 2016). In this study, the first biochar application significantly affected ($P < 0.05$) the bulk density of the soil but further addition did not change among treatments. The bulk density of the soil with biochar decreased by 17 - 23% relative to the control after the first application (Figure 1a). These values were within the range of reported reduction of bulk density in most soils with biochar applied relative to no biochar (Blanco-Canqui, 2017). The small reductions in soil bulk density can be associated with agronomic benefits such as the promotion of plant root elongation and root density (Verheijen et al., 2009; Grable and Siemer, 1968; Thompson et al., 1987). However, the magnitude of changes in bulk density associated with biochar

Table 2. Crop management practices during the four-season field experiment in Brgy. Sta. Clara, Cuyapo, Nueva Ecija.

Variables	2018 DS	2018 WS	2019 DS	2019 WS
Plowing date	Feb. 2	July 5	Jan. 9	June 20
Seeding rate, kg ha^{-1}	40	40	40	40
No. seedlings hill^{-1}	2-3	2-3	2-3	2-3
Distance, cm	20 x 20	20 x 20	20 x 20	20 x 20
Transplanting date	March 7	July 9	Jan. 15	July 2
Harvesting date	June 22	Oct. 19	April 30	Oct. 11
Pesticide/herbicide (P/H)	Nominee/ Rodenticide	Rodenticide	Rodenticide	None
Date P/H application	March 21-22 May 18	July 17/23 July 18/July 30	Jan. 19/30 Jan. 19	None
Pesticide/herbicide application	Nominee/ Rodenticide	Rodenticide	Rodenticide	None
Total N (kg N ha^{-1})	120	90	120	90
Total K (kg K_2O ha^{-1})	40	40	40	40
total P (kg P_2O5 ha^{-1})	40	40	40	40

DS - dry season; WS - wet season

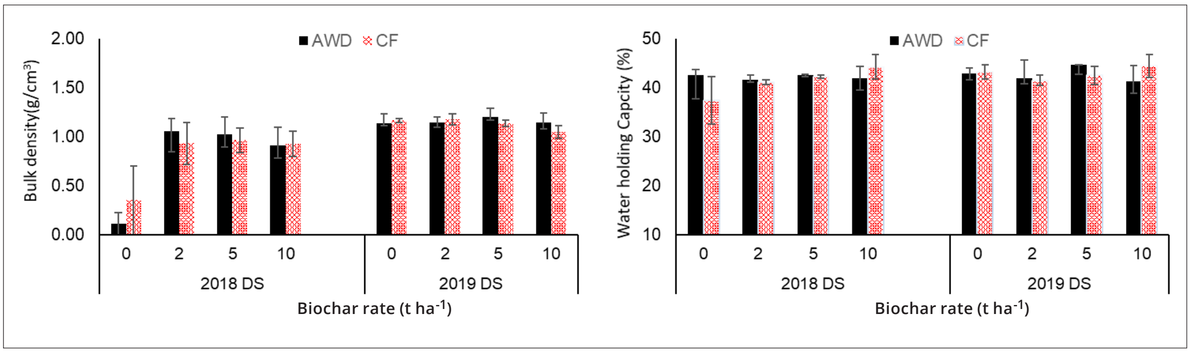


Figure 1. (a) Bulk density and (b) water holding capacity of the soil under different water management and rate of biochar.

application can also vary with the soil properties and biochar rate applied (Blanco-Canqui, 2017). In terms of WHC, there were no significant effects of biochar application on the soil regardless of water management. However, when the rate of biochar was increased, WHC also slightly increased by 10 - 18% compared with the control after the first application under MCF (Figure 1b). The previous report showed that applying biochar increases the WHC of the soil by improving the overall soil porosity and increasing soil water content (Abukar, 2019; Batista et al., 2018). This is because organic amendment generally increases the amount of organic matter that could improve the water retention in the soil (Sohi et al., 2009) by improving soil aggregates. Hudson (1994) reported a positive correlation (r =0.79) between organic matter and WHC in sandy soils. However, relative to MCF, this was not evident under AWD in our study, wherein no changes were observed on the WHC of soil with biochar relative to the control. The result can be attributed to the significantly ($P<0.05$) lower SOC in AWD relative to MCF after first application (Table 3). The SOC under AWD was reduced by 53% relative to MCF regardless of biochar rate. This is consistent with the previous report showing reduced SOC and ecosystem carbon loss with water savings such as intermittent soil drying, drainage or AWD (Yang et al., 2020; Hooijer et al., 2010). According to Yang et al. (2020), changes in soil moisture content caused by the change in irrigation mode have an impact on SOC and its active components. They also added that combining the water-saving technique with biochar significantly increased SOC. However, result of our study showed otherwise. There were no significant combined effects of water and biochar on SOC, which could be attributed to the application rate of biochar used in our study. Rate was lower in this study than the previous work, in which effect of increased SOC with biochar was evident at 40 t ha^{-1}. Despite the reduced SOC in AWD, continuous practice of AWD tended to increase SOC after the second application but the magnitude was still below the level of SOC of MCF (Table 3). As this study was conducted only for two years, the extent to which the amount of SOC will increase or stabilize with continuous practice of AWD must be further evaluated. In a water-intensive rice production system, water-saving techniques such as AWD should reduce soil carbon loss, provide savings, and reduce greenhouse gas emissions. In terms of soil K, there was a significant ($P <0.05$) reduction of K at 2 t ha^{-1} rate of biochar relative to the control regardless of water management on the first year of application (Table 4). Soil K also tended to increase when the biochar rate increases up to 10 t ha^{-1} but showed no significant differences with the control (Table 4). Previous report showed that the efficiency of added K depends on the dynamic equilibrium of soil K, which could be influenced by soil properties including soil type, texture, inherent soil K, and dominant clay minerals (Li et al., 2009). For soil pH, there were no significant changes among treatments and no interacting effect of the treatments (Table 5). This is in contrast to the previous study, which showed that soil pH increases after biochar application (Yuan et al., 2011). However, most of the previous studies were performed on acidic soils with pH lower than the pH of biochar used (Abrishamkesh et al., 2015). In this study, the soil pH without biochar was >7, which is considered alkaline. As a result, the liming effect of biochar had no significant effects even with increasing biochar rate. Combinations of soils and biochars may result in different pH buffering capacities (Mukherjee et al, 2011).

Effects on Grain Yield and Water Productivity

Tables 6 and 7 show the grain yield of rice during DS and WS. Grain yields in 2018 DS were only below 2 t ha^{-1} due to severe stem borer infestation. Under normal condition in Nueva Ecija, reported grain yields of MCF and AWD is at least 6 t ha^{-1} (Sibayan et al., 2018; Corton et al., 2000). Previous reports corroborated our results in 2019 DS, in which grain

Table 3. Seasonal soil organic carbon under different water and biochar rate in Brgy. Sta. Clara, Cuyapo, Nueva Ecija.

Treatments	Soil Organic Carbon (g kg^{-1})				
	2018 DS	2018 WS	2019 DS	2019 WS	Mean
Water (W)					
MCF	22.74^{a}	11.18^{a}	14.51^{a}	15.79^{a}	16.05^{a}
AWD	10.73^{b}	13.25^{a}	15.39^{a}	15.68^{a}	13.76^{a}
Biochar rate (B)					
0	14.36^{a}	12.85^{a}	15.40^{a}	14.96^{a}	14.39^{a}
2	22.34^{a}	10.88^{a}	13.90^{a}	15.87^{a}	15.75^{a}
5	20.20^{a}	12.01^{a}	15.46^{a}	15.50^{a}	15.79^{a}
10	10.06^{a}	13.13^{a}	16.86^{a}	16.62^{a}	14.17^{a}
ANOVA					
W	*	ns	Ns	ns	ns
B	ns	ns	Ns	ns	ns
W x B	ns	ns	Ns	ns	ns

Within a column, different small letters indicate significant treatment differences at *p < 0.05. ns means not significant.

Table 4. Seasonal amount of soil potassium (K) content under different water and biochar rate in Brgy. Sta. Clara, Cuyapo, Nueva Ecija.

Treatments	Soil K (g kg^{-1})				
	2018 DS	2018 WS	2019 DS	2019 WS	Mean
Water (W)					
MCF	0.067^{a}	0.083^{b}	0.074^{a}	0.049^{a}	0.068^{a}
AWD	0.055^{a}	0.096^{a}	0.080^{a}	0.050^{a}	0.070^{a}
Biochar rate (B)					
0	0.059^{a}	0.099^{a}	0.077^{a}	0.049^{ab}	0.071^{a}
2	0.057^{a}	0.077^{c}	0.062^{a}	0.042^{b}	0.060^{b}
5	0.077^{a}	0.093^{b}	0.079^{a}	0.050^{ab}	0.075^{a}
10	0.051^{a}	0.087^{b}	0.091^{a}	0.056^{a}	0.071^{a}
ANOVA					
W	Ns	*	ns	ns	ns
B	Ns	**	ns	*	**
W x B	Ns	ns	ns	ns	ns

Within column, different letters indicate significant treatment differences at *p < 0.05, **p < 0.01; ns- not significant

Table 5. Seasonal soil pH under different water and biochar rate in Brgy. Sta. Clara, Cuyapo, Nueva Ecija.

Treatments	Soil pH				
	2018 DS	2018 WS	2019 DS	2019 WS	Mean
Water (W)					
MCF	7.77^{a}	7.43^{a}	7.48^{a}	7.52^{a}	7.55^{a}
AWD	7.90^{a}	7.54^{a}	7.56^{a}	7.58^{a}	7.65^{a}
Biochar rate (B)					
0	7.92^{a}	7.69^{a}	7.54^{a}	7.61^{a}	7.69^{a}
2	7.93^{a}	7.74^{a}	7.61^{a}	7.67^{a}	7.74^{a}
5	7.59^{a}	7.66^{a}	7.47^{a}	7.56^{a}	7.57^{a}
10	7.91^{a}	7.50^{a}	7.47^{a}	7.48^{a}	7.59^{a}
ANOVA					
W	ns	ns	ns	ns	ns
B	ns	ns	ns	ns	ns
W x B	ns	ns	ns	ns	ns

Within column, different letters indicate significant treatment differences at *p < 0.05; ns- not significant.

Table 6. Grain yield, water use, and water productivity of rice under different water management and biochar rate in dry seasons, 2018-2019.

Treatments	Grain Yields t ha^{-1}		Total Water Use (m^{3} ha^{-1})		Water Productivity (kg grain m^{-3} water)	
	2018 DS[1]	2019 DS	2018 DS	2019 DS	2018 DS	2019 DS
Water management (W)						
MCF	1.30^{a}	7.37^{a}	3060^{a}	18,070^{a}	0.47^{b}	0.44^{a}
AWD	1.42^{a}	7.22^{a}	790^{b}	4,260^{b}	2.10^{a}	1.69^{b}
Biochar rate (B)						
0	1.32^{a}	7.43^{a}	2132^{a}	11,100^{a}	1.16^{a}	1.09^{a}
2	1.42^{a}	7.47^{a}	1815^{a}	11,690^{a}	1.25^{a}	1.09^{a}
5	1.54^{a}	7.35^{a}	1766^{a}	10,850^{a}	1.58^{a}	1.07^{a}
10	1.14^{a}	6.92^{a}	1987^{a}	11,000^{a}	1.16^{a}	1.02^{a}
ANOVA						
W	ns	Ns	*	*	*	**
B	ns	Ns	Ns	ns	ns	Ns
W x B	ns	Ns	Ns	ns	ns	Ns

Yields were infested with stemborer. Means followed by a different letter are not significantly different at *p< 0.05. In the ANOVA, asterisk means * p<0.05; ** p<0.01. ns= not significant.

Table 7. Grain yield, water use, and water productivity of rice under different water management and biochar rate in wet seasons, 2018-2019.

Treatments	Grain Yields t ha^{-1}		Total Water Use (m^3 ha^{-1})		Water Productivity (kg grain m^{-3} water)	
	2018 WS	2019 WS	2018 WS	2019 WS	2018 WS	2019 WS
Water management (W)						
MCF	4.65^a	4.15^a	22,755^a	27,560^a	0.20^a	0.14^a
AWD	4.74^a	3.92^a	22,569^b	26,450^b	0.21^a	0.16^a
Biochar rate (B)						
0	4.42^a	4.07^a	22,720^a	27, 030^a	0.19^a	0.15^a
2	4.70^a	4.10^a	22,656^a	27, 050^a	0.21^a	0.15^a
5	4.73^a	3.90^a	22,627^a	26,970^a	0.21^a	0.15^a
10	4.92^a	4.08^a	22,647^a	26,960^a	0.22^a	0.15^a
ANOVA						
W	ns	ns	*	*	ns	Ns
B	ns	ns	Ns	ns	ns	Ns
W x B	ns	ns	Ns	ns	ns	Ns

Means followed by a different letter are not significantly different at p< 0.05. ns= not significant.

yields varied from 7.2 to 7.4 and from 6.9 to 7.4 t ha^{-1} across water and biochar rates, respectively. In both DS, treatments did not significantly affect the grain yields. Grain yields did not also vary across treatments in WS. Grains yielded 4.6 - 4.7 and 4.4 - 4.9 t ha^{-1} in 2018 WS, and 3.9 - 4.1 and 3.9 - 4.1 t ha^{-1} in 2019 WS across water and biochar rate, respectively. Similar studies showed that yields under AWD usually do not differ with CF or MCF (Pascual et al., 2020; Lampayan et al., 2015). In this study, incorporation and increasing the rate of biochar did not affect the yield of rice relative to the control, although yield advantage on the use of biochar over the control has been reported in rice (Zhang et al., 2012). Soil properties, crop management practices, and biochar feedstock partly explained these variations.

There was a significant effect of the treatments during DS while the effect of biochar rate and its interaction with water management were not significant. The total water use in AWD was reduced by 74 - 76% relative to MCF in all DS (Table 6) regardless of with or without biochar. The irrigation frequency of AWD was 3 - 9 times lower than MCF with 24 - 38 times irrigation events. While in the WS, a significant portion of the total water use (98 - 100%) came from rainfall. The water savings in this study was higher than the reported savings in Central Luzon (Sibayan et al., 2018; Lampayan et al., 2015) because the soil texture of our site is sandy clay loam, which requires frequent irrigation to maintain MCF than heavy clay soil. Water productivity (WP) of AWD was significantly ($P<0.05$) higher by 74% relative to MCF regardless of biochar rate in 2019 DS. However, water productivity was very high in 2018 DS due to the very low yield. In all DS, WP data in this study were above the reported values of WP in the Philippines (Bouman and Tuong, 2000) due to very high level of grain yield but low water input, especially in 2019 DS.

Conclusion

Findings of this study showed that combined effects of rice husk biochar with increasing rate up to 10 t ha^{-1} and AWD technique had no significant interacting effects on SOC, soil pH, K, grain yield, water use, and water productivity in sandy-clay loam soil. Significant reduction of water use was influenced only by the AWD technique, which increased water productivity. The AWD technique also decreased SOC relative to modified continuous flooding. Further study is recommended to determine the extent of changes on the amount of SOC with continuous practice of AWD. Water-saving techniques such as AWD in a water-intensive rice production system should not negatively interfere soil carbon in the long term, which may outweigh the technique's benefits.

Acknowledgment

This study was funded by the Climate Resiliency for Enhanced Agricultural Trade and Efficiency for Rice (CRP-002) program of DA-PhilRice.

Literature Cited

Abukar A (2019) Influence of rice husk biochar on water holding capacity of soil in the savannah ecological zone of Ghana. Turkish Journal of Agriculture-Food Science and Technology **7**(6): 888-891

Abrishamkesh S, Gorji M, Asadi H, Bagheri-Marandi GH, Pourbabaee AA (2015) Effects of rice husk biochar application on the properties of alkaline soil and lentil growth. Plant, Soil and Environment **61**(11): 475-582

Asai H, Samson BK, Stephan HM, Songyikhangsuthor K, Homma K, Kiyono Y, Inoue Y, Shiraiwa T, Horie T (2009) Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. Field Crops Res **111**(1-2): 81-4

Batista EM, Shultz J, Matos TT, Fornari MR, Ferreira TM, Szpoganicz B, de Freitas RA, Mangrich AS (2018) Effect of surface and porosity of biochar on water holding capacity aiming indirectly at preservation of the Amazon biome. Scientific Reports **8**(1): 1-9

Blanco-Canqui H (2017) Biochar and soil physical properties. Soil Science Society of America Journal **81**(4): 687-711

Boateng AA, Garcia-Perez M, Masek O, Brown R, del Campo, B (2015). Biochar production technology. *In* Lehmann J and Joseph S. (Eds.). Biochar for Environmental Management-Science and Technology *(*pp 63-109). New York: Routledge

Bouman BAM, Lampayan RM, Tuong TP (2007) Water Management in Irrigated Rice: Coping with Water Scarcity. Philippines: International Rice Research Institute

Bouman BAM and Tuong TP (2000) Field water management to save water and increase its productivity in irrigated lowland rice. Agric Water Manage **1615**(1): 20

Corton TM, Bajita JB, Gorospe FS, Pamplona RR, Asis CA, Wassmann R, Lantin RS, Buendia LV (2000) Methane emissions from irrigated and intensively managed rice fields in Central Luzon (Philippines). Nutr. Cycl. Agroecosyst. **58**(1-3): 37-53

Ding Y, Liu Y, Liu S, Li Z, Tan X, Huang X, Zeng G, Zhou L, Zheng B (2016) Biochar to improve soil fertility. A review. Agronomy for Sustainable Development **36**(2): 36

Grable AR, Siemer EG (1968) Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potentials, and elongation of corn roots. Soil Science Society of America Journal **32**(2): 180-186

Haefele SM, Konboon Y, Wongboon W, Wmarants S, Maarifat AA, Pfriffer EM, Knoblauch C (2011) Effects and fate of biochar from rice residues in rice-based systems. Field Crop Res **121**(3): 430-440

Hooijer A, Page S, Canadell JG, Silvius M, Kwadijk J, Wosten H, Jauhiainen J (2010) Current and future CO_2 emissions from drained peatlands in Southeast Asia. Biogeosciences Discussion **4**(7): 1505-1514

Hudson BH (1994) Soil organic matter and available water capacity. Journal of Soil and Water Conservation **49**(2):189-194

International Rice Research Institute [IRRI] (2013) Statistical tool for agricultural research. Plant Breeding Genetics and Biotechnology Biometrics and Breeding Informatics. Philippines: Open Source Software.

Lampayan RM, Samoy-Pascual KC, Sibayan EB, Ella VB, Jayag OB, Cabangon R, Bouman BAM (2015) Effects of alternate wetting and drying (AWD) threshold level and plant seedling age on crop performance, water input, and water productivity of transplanted rice in Central Luzon, Philippines. Paddy Water Environ. **13**: 215-227

Lee JW, Hawkinsb L, Day DM (2013) Biochar fertilizer for soil amendment and carbon sequestration. *In* Advanced Biofuels and Bio products (pp 57-68). New York: Springer

Lehmann J, Gaunt J, Rondon M (2006) Bio-char Sequestration in Terrestrial Ecosystems – A Review. Mitig Adapt Strat Glob Change **11**(2): 403-427

Li X, Lu J, Wu L, Chen F (2009) The difference of potassium dynamics between yellowish red soil and yellow cinnamon soil under rapeseed (*Brassica napus* L.)–rice (*Oryza sativa* L.) rotation. Plant Soil **320**:141-151

Mukherjee A, Lal R, Zimmerman AR (2014) Effects of biochar and other amendments on the physical properties and greenhouse gas emissions of an artificially degraded soil. Science of the Total Environment **487**:26-36

Mukherjee A, Zimmerman AR, Harris W (2011). Surface chemistry variations among a series of laboratory-produced biochars. Geoderma **163**(3-4): 247-255

Orge RF, Abon JEO (2012) Design improvement of the PhilRice continuous-type rice hull carbonizer for biochar production towards sustainable agriculture. OIDA International Journal of Sustainable Development **5**(8): 83-96

Pandit NR, Mulder J, Hale SE, Martinsen V, Schmidt HP, Cornelissen G (2018) Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low-input nepalese soil. Science of the total environment **625**: 1380-1389

Pascual KS, Martin EC, Ariola CP (2020) Effects of water and weed management on the weed density, grain yield, and water productivity of wet-seeded rice. Philippine Journal of Science **149** :121-131

Peters J (2013) Laboratory procedures and methods. University of Wisconsin-Extension-Madison Soil Science Department College of Agriculture and Life Sciences. University of Wisconsin-Extension-Madison. https://uwlab.soils.wisc.edu/about-us/lab-procedures-and-methods/

PhilRice [Philippine Rice Research Institute] (2007) Palaycheck® system for irrigated lowland rice. Philippines: PhilRice

Priha O, Smolander A (1997) Microbial biomass and activity in soil and litter under Pinus sylvestris, Picea abies and Betula pendula at originally similar field afforestation sites. Biol. Fertil. Soils **24**(1): 45-51

Phonphuak N, Chindaprasirt P (2015) Types of waste, properties, and durability of pore-forming waste-based fired masonry bricks. *In* Torgal PF, Lourenco PB, Labrincha JA Kumar S, Chindaprasirt P (Eds.). Eco-Efficient Masonry Bricks and Blocks (pp 103-127). India: Woodhead Publishing

Rola AC, Francisco HA (2004) A model of water governance in the Philippines. *In* Rola AC, Francisco HA, Liguton JPT (Eds.). Winning the Water War: Watersheds, Water Policies, and Water Institutions (p 26). Philippines: PIDS and PCAARRD.

Rola A, Pulhin JM, Tabios GQ, Lizada JC, Dayo MH (2015) Challenges of water governance in the Philippine. Philippine Journal of Science **144**: 197-208

Siopongco J, Wassmann R, Sander BO (2013) Alternate wetting and drying in Philippine rice production: feasibility study for a Clean Development Mechanism. Retrieved from http://books.irri.org/ technicalbulletin17_content.pdf (accessed November 18, 2016)

Sibayan EB, Pascual KS, Grospe FS, Casil MED, Tokida T, Padre AT, Minamikawa K (2018) Effects of alternate wetting and drying technique on greenhouse gas emissions from irrigated rice paddy in Central Luzon, Philippines. Soil Science and Plant Nutrition **64**: 39-46

Saeid A, Chojnacka K (2019) Fertlizers: Need for New Strategies. *In* Chandran S, Unni MR, Thomas S (Eds.). Organic Farming (pp 91-116). India: Woodhead Publishing

Sohi S, Loez-Capel E, Krull E, Bol R (2009) Biochar's roles in soil and climate change: A review of research needs. CSIRO Land and Water Science Report **5**(09): 1-57

Thompson PJ, Jansen IJ, Hooks CL (1987) Penetrometer resistance and bulk density as parameters for predicting root system performance in mine soils. Soil Science Society of America Journal **51**(5):1288-1293

Tuong TP, Bouman BAM (2003) Rice production in water scarce environments. *In* Kijne JW, Barker R, Molden, D (Eds.). Water Productivity in Agriculture: Limits and Opportunities for Improvement (pp 53-56). CABI: Wallingford, UK

Verma M, M'hamdi N, Dkhili Z, Brar SK Misra K (2014) Biotransformation of waste biomass into high value biochemical. Springer Science Business Media New York. DOI 10.1007/978-1-4614-8005-1_3

Verheijen FGH, Jeffery S, Bastos AC, Van der veld M, Diafas I (2009) Biochar application to soils - A critical scientific review of effects on soil properties, processes and functions. EUR **24099**:162

Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil science **37**:29-38

Yang S, Chen X, Jiang Z, Ding J, Sun X, Xu J (2020) Effects of biochar application on soil organic carbon composition and enzyme activity in paddy soil under water-saving irrigation. International Journal of Environmental Research and Public Health **17**:333

Yuan J, Xu R, Wang N, Li J (2011) Amendment of acid soils with crop residues and biochars. Pedosphere **21**: 302-308

Zhang A, Bian R, Pan G, Cui L, Hussain Q, Li l, Zheng J, Zheng J, Zhang X, Han X, Yu X (2012) Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: A field study of 2 consecutive rice growing cycles. Field Crops Research **127**: 153-160

FULL PAPER

SCREENING AND SELECTION OF DIFFERENT *Azolla* spp AS POTENTIAL AMELIORANT FOR ACIDIC AND SALINE PADDY SOILS

Evelyn F. Javier, Xarin Xara G. Sto Domingo, Jerome M. Mercado, and Maria Leah A. Sevilla

Agronomy, Soils and Plant Physiology Division, Philippine Rice Research Institute,
Maligaya, Science City of Muñoz, Nueva Ecija 3119
*Corresponding Author: efjavier@philrice.gov.ph

Abstract

A greenhouse experiment was conducted to assess the effect of some *Azolla* spp in the improvement of soil pH and electrical conductivity (EC) of acid and saline paddy soils for rice production. This study hypothesized that *Azolla* spp can correct or reduce acidity and salinity of the paddy soils due to its ability to absorb high amount of iron. Different *Azolla* accession were evaluated under normal, acidic, and saline soil from 2017 to 2019. The *Azolla* spp showed its potential to ameliorate soil salinity and acidity. *Azolla microphylla* 4113 (MI 41133) and *Azolla microphylla* 4114 (MI 4114) performed well in ameliorating acidic and saline soil, respectively; however, these green manures need re-sowing 3 times per cropping system in three years to achieve significant soils EC reduction. Salinity was significantly ameliorated in the third application of *Azolla* after four cropping seasons. The biomass of the different Azolla decreased through time foregoing sporulation. Therefore, there is still a need to optimize the ameliorative potential of the *Azolla* without sacrificing sporulation or growth.

Keywords: *Azolla spp, Ameliorative Potential, Electrical Conductivity, Soil pH*

Introduction

Azolla is a small fast-growing and free-floating fern naturally available on moist soils, ditches, and marshy ponds. This aquatic plant is used as biofertilizers and produces around 300 t of green bio-hectare a year under normal subtropical climate, which is comparable to 800 kg of nitrogen. This fern is mostly used in rice paddy fields because of its ability to fix nitrogen at high rates and low cost (Peters and Mayne, 1974). *Azolla* is used as a biofertilizer for rice crop as it decomposes easily in the soil and makes nitrogen efficiently available to the rice plant (Javier and Tabien, 2003). The quick multiplication rate and rapid decomposing capacity of *Azolla* has become the paramount factor for its use as green manure.

Studies on the use of *Azolla* as an agent for treating water waste are being conducted to determine the efficiency of this technique (Devi et al., 2014). However, researches on the bioremediation of problem soils such as high salinity and acidity level using *Azolla* are limited. In one of the preliminary studies (Sto Domingo et al., 2015), it was observed that *Azolla* has high content of available iron. Vermicompost applied with *Azolla* as substrate also recorded high iron content (Javier et al., 2019). As such, it was hypothesized that *Azolla* can accumulate high iron content approximately averaging at 13,299.32 ppm (Javier et al., 2019), which usually becomes more soluble at low pH. In paddy soils where water can be a natural neutralizer (Ponnamperuma, 1985), acidic aerobic soil when flooded increases its pH while sodic and calcareous soil depress its pH (Ponnamperuma, 1965 and 1972). In cases when water cannot change soil acidity due to its original parent material, acidic paddy soils can affect the growth and yield of rice plants. As such, phytoremediation can be used.

Salinity affects fresh water and soil particularly in arid and semi-arid regions. Ironically, irrigation has resulted in the accumulation of salt with above normal concentrations in the rooting zone of arable land, as high rates of evaporation and transpiration draw soluble salts from deep layers of the soil profile. Permanent solution to soil salinity entails a sound drainage system to manage the rising water table. This cannot be employed on a large scale or vast areas due to cost-intensive management. This can be resolved by planting salt-tolerant crops. Alternatively, phytoremediation can also be considered as a potential mitigating technique. Qadir and Oster (2004) compared remediation of salt-affected soils through chemicals and vegetation. Their study results showed that soil amendment with gypsum reduced 62% of sodicity levels while 52% was lessened through phytoremediation. Halophytes dominate saline soils, which can be salt-excluders, salt includers, or salt-accumulators. These mechanisms, however, are also active in non-halophytes (Breckle, 2002). In flooded soil condition, aquatic plants like *Azolla* and other aquatic weeds can be used in phytoremediation as some studies already showed its potential in soil remediation (Banach et al., 2012) and amelioration (Sufian et al., 2013).

In view of the insufficient information about this topic, this paper described the growth of *Azolla* when propagated in problem soils and its effect on the salinity and acidity level of the soil. This study assessed the effect of some *Azolla* spp in the improvement of soil pH and electrical conductivity (EC) of acid and saline soils for production and determined the growth of *Azolla* spp in acidic and in saline soils.

Materials and Methods

The experiment was established in the screenhouse in 2017 and 2018 dry season (DS) then in 2019 dry season and wet season (WS) at the Philippine Rice Research Institute Central Experiment Station (CES) of the Department of Agriculture (DA-PhilRice) in Science City of Munoz, Nueva Ecija. Acid and saline soils were collected in mapped areas. The Maligaya clay soils were collected from the PhilRice CES as the check sample. Initial data of soil pH and electrical conductivity (EC) were gathered from pre-collected soil samples of identified acidic, saline, and Maligaya clay soils (Table 1).

Table 1. Initial soil pH and electrical conductivity (EC, mS cm^{-1}) of the collected samples of acidic, saline, and Maligaya clay soils after subjected to submerged condition prior to sowing of the different *Azolla* accessions under greenhouse condition. PhilRice Central Experimental Station (PhilRice CES) 2017-2019.

	2017 DS		2018 DS		2019 DS		2019 WS	
	pH	EC	pH	EC	pH	EC	pH	EC
Acidic soils	5.28	2.26	5.56	3.03	6.8	0.32	6.6	0.21
Maligaya soils	5.65	4.44	6.73	3.56	6.6	0.58	6.4	0.37
Saline soils	6.64	22.46	5.88	12.73	7	1.39	6.3	1

In 2017, six *Azolla* accessions from the germplasm of International Rice Research Institute (IRRI) were collected: *Azolla microphylla* (MA), *A. microphylla* 4018 (MI 4018), *A. caroliniana* 3005 (CA 3005), *A. mexicana* 2028 (ME 2028), *A. mexicana* 2024 (ME 2024), and *A. filiculoides* 1001 (FI 1001). Similar accessions were utilized in the 2018 set up. In 2019 DS, only *A. mexicana* 2024 and *A. microphylla* 4018 were re-used in the trials. The unavailable *Azolla* accession was substituted: *A. caroliana* 3016 to *A. caroliniana* 3005; and *A. filiculoides* 1001 to *A. filiculoides* 1011. Additional accessions were tested like the *A. microphylla* 4114 and 4113 and *A. pinnata* (PI 72). In the last trial during the 2019 wet season, only five *Azolla* species were available and acquired from the University of the Philippines-Los Baños (UPLB) as IRRI had already turned over all their algae and *Azolla* materials: *Azolla mexicana* 2024 (ME 2024), *Azolla pinnata* (PI 0072), *Azolla filiculoides* 1011 (FI 1011), *Azolla caroliniana* 3016 (CA 3016), *Azolla microphylla* 4114 (MI 4114), *Azolla microphylla* 4018 (MI 4018), and *Azolla microphylla* 4113 (MI 4113).

Samples were from the Maligaya soil series, which is clay representing the normal soils. The saline soils and acidic soils used for 2017 and 2018 trials were collected from NUMASS (Yost et al., 2000), in which most of the soil samples were taken from Barangay San Antonio, Ilagan Isabela - a hilly upland planted with rice and maize (Walker et al., 2009). For 2019 experiments, soils were collected from Pangasinan based on soil characterization by Collado (2015).

One gram of *Azolla* from each accession was applied in the 2 L capacity basins separately containing 500 g each of saline and acidic soils submerged in 2 - 3 cm water. The *Azolla* accessions were grown for 30 days, then harvested and weighed. Immediately after harvesting, the same *Azolla* accessions were regrown (2nd *Azolla* application) in the same basin with the same soil. The second set-up also lasted for 30 days, harvested and weighed. Same procedure was done for the 3rd *Azolla* application. Continuously sowing *Azolla* in the same basin was done three times per trial season or 90 days per trial per cropping season.

Some *Azolla* accessions, however, were not available for all the seasonal trials. *Azolla microphylla* 4018 (MI 4018) died due to pest infestation; hence, was not used in the 2019 wet season. *Azolla mexicana* 2024 (ME 2024) was supposedly to be included in the 2018 DS trial only but was used in the other three trials (2017 DS, 2019 DS, and 2019 WS).

The treatments were laid in Compete Randomized Design with three replications. Soil salinity was measured by the soil electrical conductivity (EC) readings while the acidity of the soils was measured through pH meter. Soil acidity and salinity were obtained before sowing the *Azolla* accessions, which served as the starting level of the soil status, and were

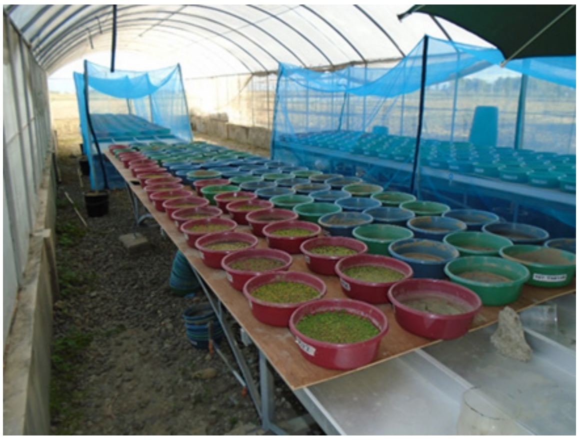


Figure 1. Experimental set-up.

measured again after each harvest. Fresh biomass of each *Azolla accession* was also recorded as indicative of their growth and sporulation every after harvesting.

Data on *Azolla* biomass, electrical conductivity (EC), and pH of the soils were taken every harvest per set that lasted for 30 days each set. Data per one season trial were collected from the three batches of set-ups per season, each batch lasting for 30 days after sowing.

Results and Discussion

Changes in Acidity

Generally, there was a significant increase of soil pH upon sowing the *Azolla* accessions in normal and acidic soils. The change was noticeable in 2017 and 2018 experiments. However, changes between the normal and acidic soils were not significantly observed in the 2019 trials (Figure 2). The initial acidity level (pH 5.4) increased to slightly acidic (pH 6) after irrigation had been introduced into the rearing basin.

No significant effect was observed among the *Azolla* accessions (Figure 3) in terms of increased soil pH. In the exact soil regrown with the same accessions, higher soil pH was observed after the 2nd and 3rd sowing or *Azolla* application. In the first trial, the *Azolla* spp had significantly changed the acidity of the soils but this change was significantly observed only in 2017 and 2018.

In the 2019 dry season, *Azolla* accession PI 0072 (7.7) gave the highest increase in soil pH by 10% from its initial reading of 6.8 in acid soil treatment. However, in the Maligaya soil check treatment, *Azolla* accession CA 3016 (7.7) gave the highest increase in soil pH. Lowest readings were observed in pots sown with MI 4114 for acid soil and MI 4018 in Maligaya soil. Me 20204, FI 1011, CA 3016, and MI 4018 gave similar reading of 7.5 while MI 4113 recorded 7.6 for acid soil treatment.

In the succeeding experiments, all had significantly increased the soil pH from its original reading of 5.5 to 6.6 (Figure 4) regardless of the *Azolla* accession applied. Although soils were acidic, the pH was increased merely by the interaction of the water (Ponnemperuma, 1998).

Changes in Salinity

In the 2017 trial, salinity was significantly reduced during the 3rd application regardless of *Azolla* accession applied. Decreasing trend was already

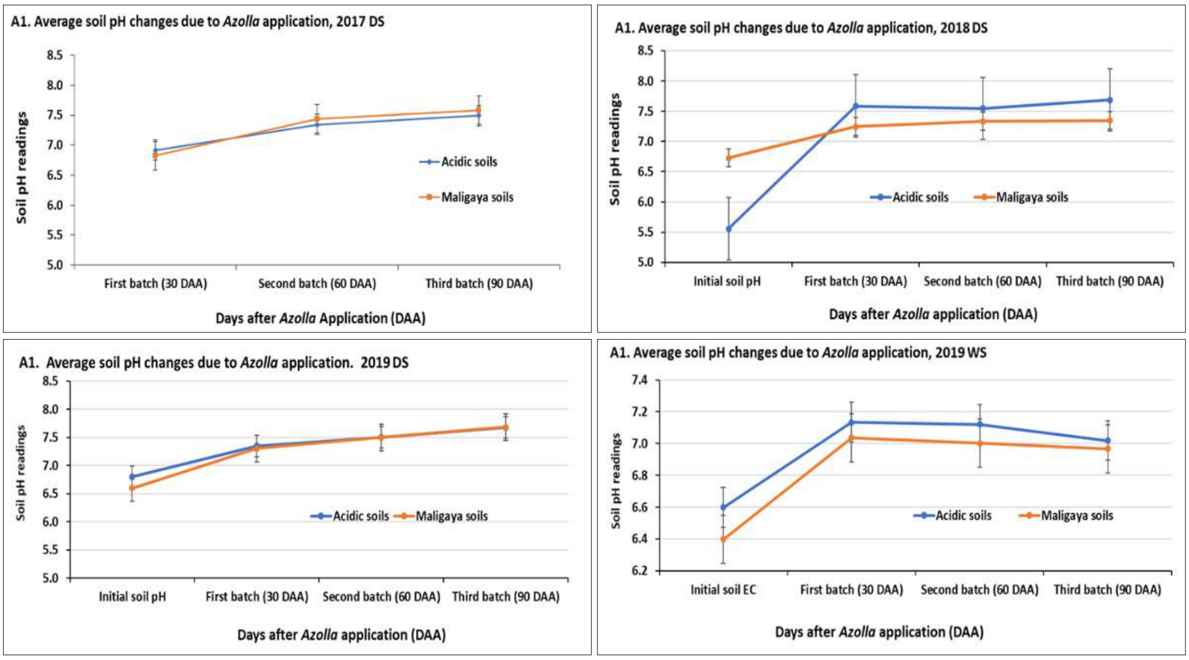


Figure 2. Average changes of soil pH in acidic and normal soils due to the application of *Azolla* spp regardless of the accessions, in 2017 DS, 2018 DS, 2019 DS , and 2019 WS under green house experimentation. PhilRice CES.

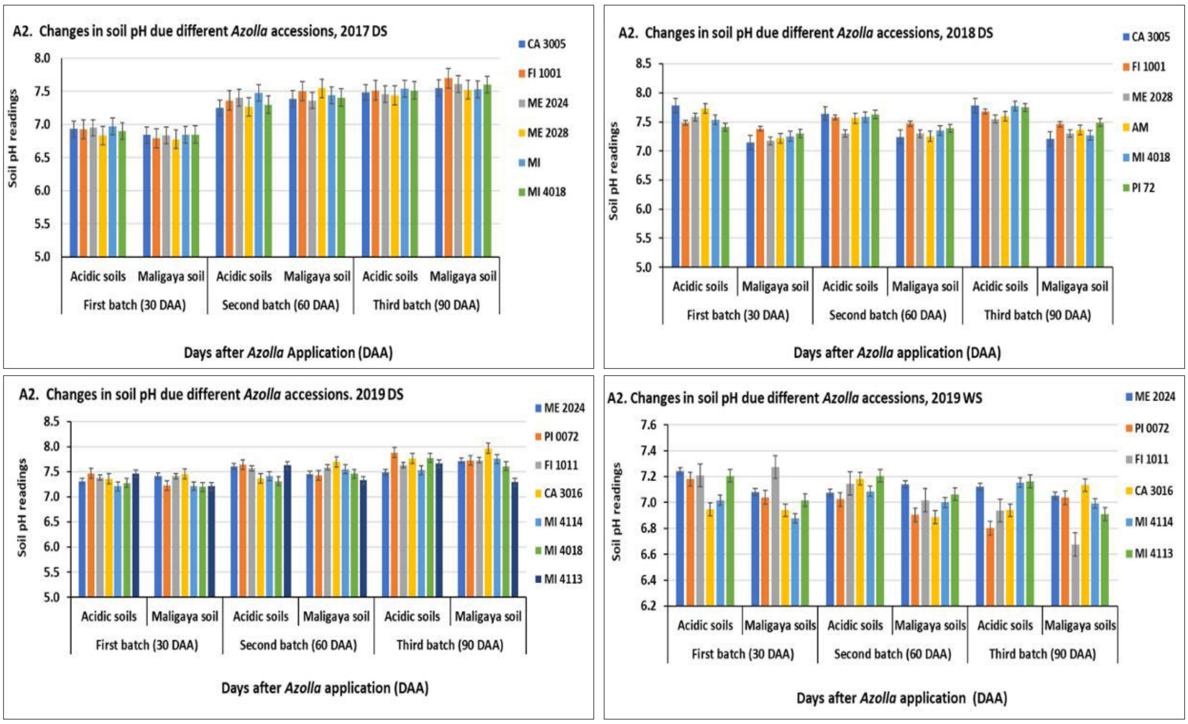


Figure 3. Changes of soil pH in acidic and normal soils due to the application of different *Azolla* accessions in 2017 DS, 2018 DS, 2019 DS, and 2019 WS under green house experimentation. PhilRice CES.

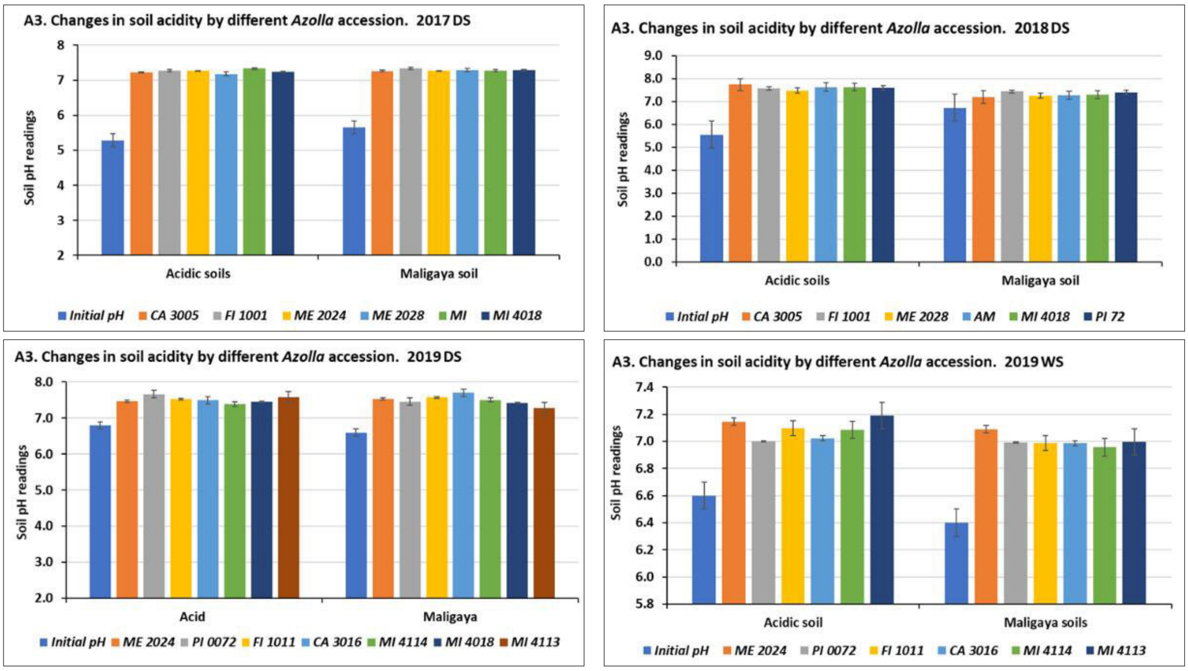


Figure 4. The average total effect of the *Azolla* accessions on the changes of soil acidity after 3 applications in 2017 DS, 2018 DS, 2019 DS, and 2019 WS under green house experimentation. PhilRice CES.

observed at the 2nd *Azolla* sowing. *Azolla caroliniana* 3005 was the most potential phytoremediating species as it reduced salinity faster in the 2nd sowing than the other accessions. On the other hand, *A. filiculoides* reduced salinity only in the 3rd application. *Azolla mexicana* 2028 also showed significant decline of soil EC in the 3rd application, which was comparable with *A. micropylla* (Figure 4).

In 2018 trial, the trend in salinity reduction showed similar findings from the previous year. Although there was a big decline in salinity level in the test soils, the soil EC reading was still higher than the critical limit of salinity at 4 dS m^{-3}. Significant reduction in salinity was observed after the 3rd sowing or application regardless of *Azolla* accessions. Again, the soil EC in the 3rd application did not reach the critical level for agricultural soils. As expected, soil EC dynamics were not observed in the Maligaya clay soils, which still showed similar soil EC readings from the 1st to the 3rd application of *Azolla* in 2017 and 2018 trials (Figure 5).

In both seasons of 2019, soils were drastically normalized and no longer within the range of a saline soils (Figures 5 and 6). However, the soil EC reading of the saline soils were still higher than the normal (Maligaya soils) (Figures 6 and 7). The effect of sowing *Azolla* in both soils showed no significant differences in changing the salinity of the soils (Figure 6). *Azolla microphylla* 4113 (MI 41133) was found to be the best species to ameliorate acid soil. In saline soil, the lowest average reading was recorded in *Azolla microphylla* 4114 (MI 4114).

Azolla Biomass

Azolla growth or sporulation was affected whenever it ameliorates the salinity and acidity of flooded soils.

Biomass as Affected by Saline Soils

In 2017, reduction in *Azolla* growth ranged from 32 - 55% due to salinity in the first application; however, growth was increased in the second and third sowing particularly that of *A. microphylla* and *A. filiculoides*. Continuous reduction in sporulation

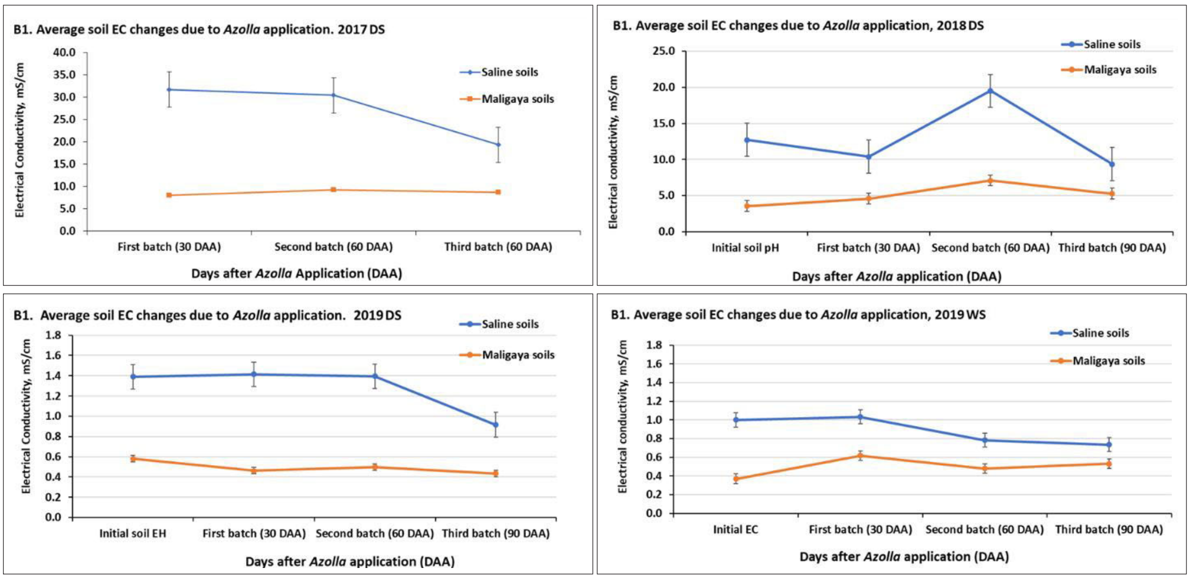


Figure 5. Average changes of soil salinity in saline and normal soils due to the application of *Azolla* spp regardless of the accessions, in 2017 DS, 2018 DS, 2019 DS, and 2019 WS under green house experimentation. PhilRice CES.

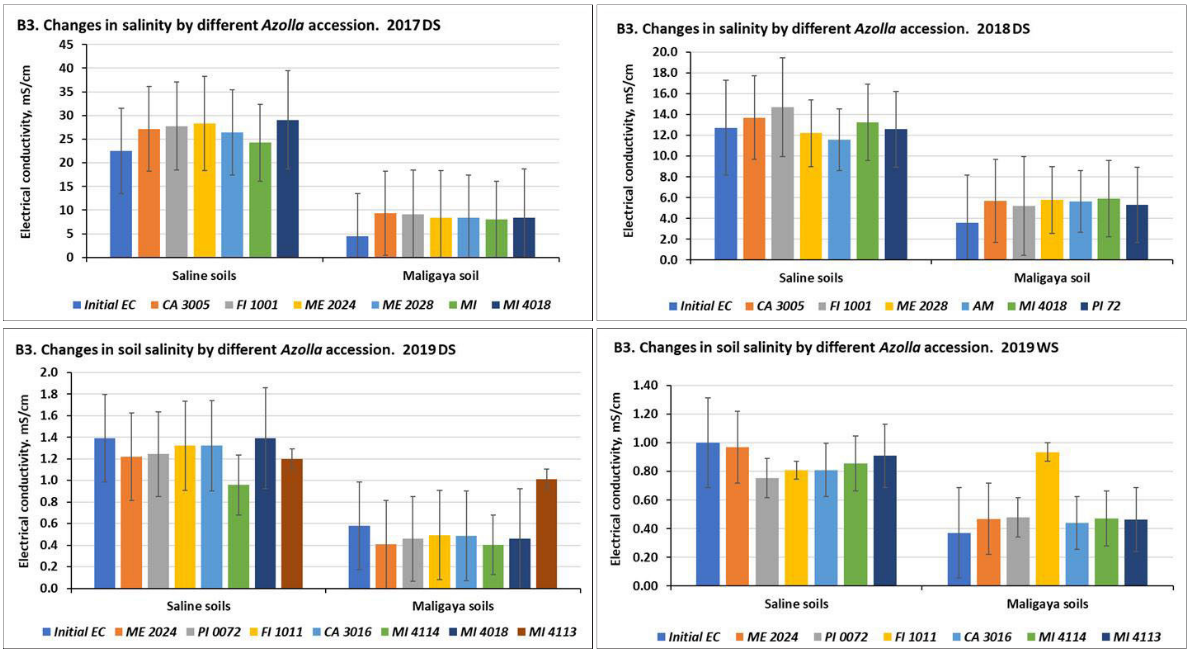


Figure 6. The average total effect of *Azolla* accessions on the changes of soil acidity after 3 applications in 2017 DS, 2018 DS, 2019 DS, and 2019 WS under green house experimentation. PhilRice CES.

due to salinity was more observed among the rest of the *Azolla* spp. Most significant reduction was observed in *A. microphylla* 4018 and *A. mexicana 2024*, the latter no longer sporulating (Figure 7). In 2018, *Azolla* sporulation was drastically reduced with salinity ranging from 50 to 100% mortality from first sowing to the third sowing. Only *A. pinnata* survived in the second application with 58% sporulation but its growth reduced in the 3rd application. In 2019, biomass of all the *Azolla* accessions was greatly reduced to 85% from the first application to the 3rd application. In the WS 2019, only ME 2024 recovered its growth in the 3rd application (Figure 7).

At the average, the *Azolla* accessions had lower biomass in the saline soils than in the normal soils in 2017 and 2018 trials (Figure 8). In 2019, soils had very low salinity level, in which the biomass of accessions sown in saline soils was higher than the *Azolla* spp sown in normal soils.

Biomass as Affected by Acidic Soils

The biomass of the *Azolla* accessions sown in acidic soils was not consistent throughout seasons and through the different batch of sowing per seasons.

In the 2017 dry season, biomass of *Azolla* accessions was comparably low when sown in acidic and in normal soils. Biomass had slightly increased in the 2nd sowing in acidic soil, but drastically reduced except for accession FI 1001 after the 3rd sowing. The *Azolla* accessions CA 3005 showed

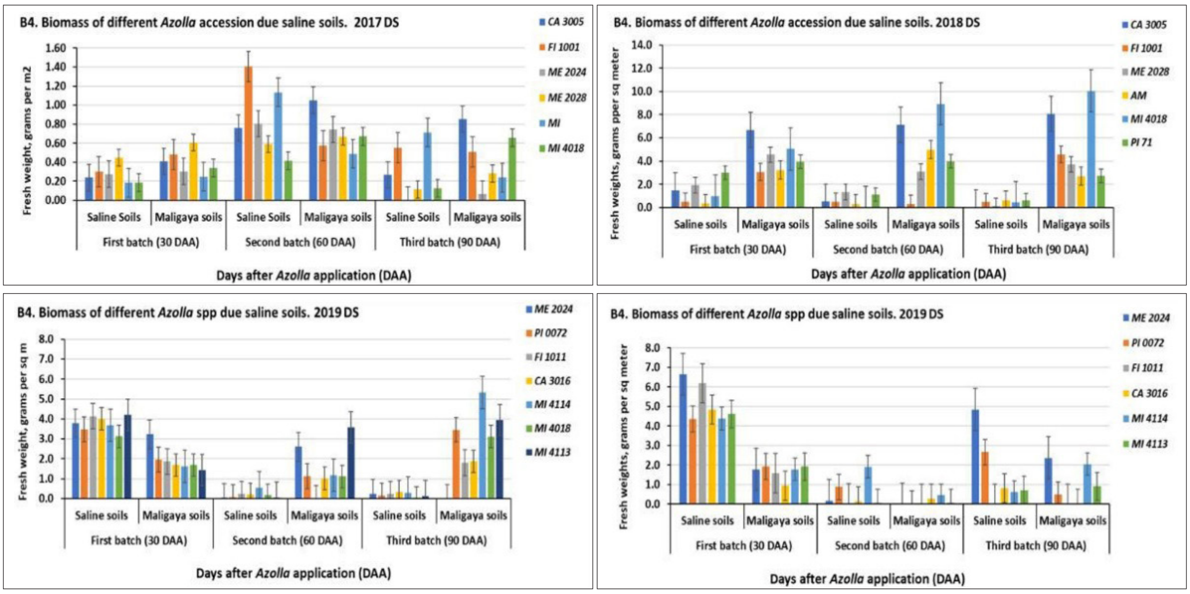


Figure 7. Biomass of the different *Azolla* accessions as exposed in saline and normal soils in 2017 DS, 2018 DS, 2019 DS, and 2019 WS under green house experimentation. PhilRice CES.

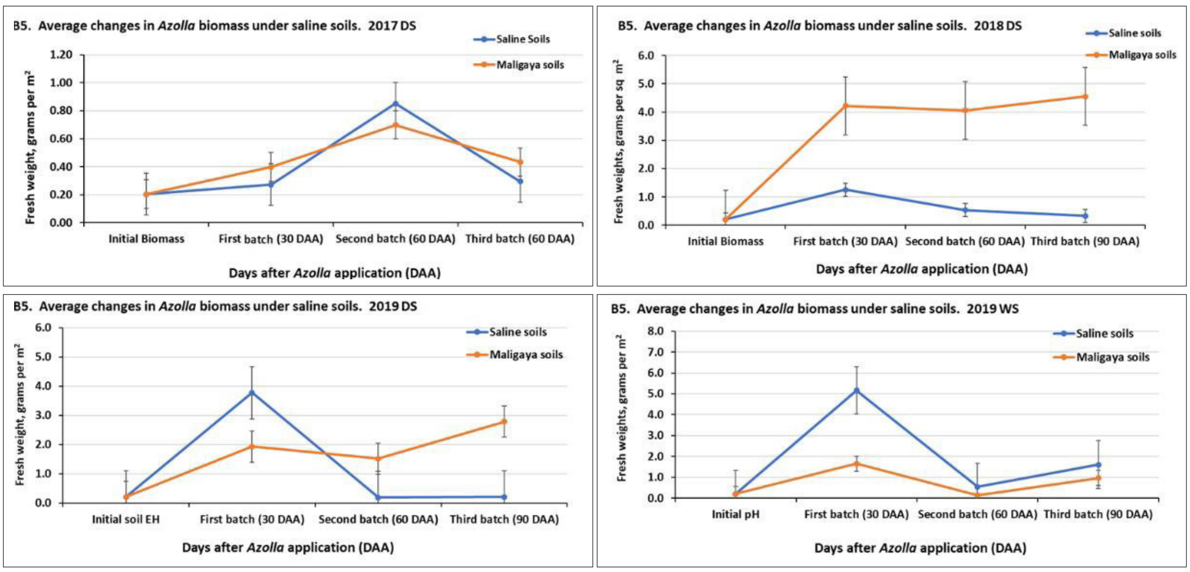


Figure 8. Average changes of the sporulation as indicated by biomass of the *Azolla* accessions sown in saline soils in 2017 DS, 2018 DS, 2019 DS, and 2019 WS under green house experimentation. PhilRice CES.

the highest biomass though the increase was not initially observed from its original sowing rate of 1 g basin^{-1}. Sporulation in 2018 DS was lower than in 2017 DS and in 2019 DS when *Azolla* spp was sown in acidic soil. The biomass of *Azolla* spp regardless of accession was significantly (88%) lower than those in the normal soil. In the 2019 WS, biomass of all accessions was similarly low in acidic and normal soils, while in the 2019 trials, accessions sown under the normal soils gave higher biomass than those sown under the acidic soils (Figure 9). However, the different *Azolla* accession deteriorated in sporulating as shown by the decrease in their biomass even under the normal soils.

Although the biomass had reduced the acidic soils, *Azolla* accessions: Me 20204, FI 1011, CA 3016, and MI 4018 gave similar reading of 7.5 while MI 4113 had a reading of 7.6 for acid soil treatment (Figure 10) showing their potential to ameliorate soil acidity. Resolving low sporulation needs further studies.

Summary and General Results

The results of the four trials showed no significant differences in the effect of *Azolla* accessions on the changes of soil pH and soil salinity. However, applying *Azolla* spp to saline soils showed significant reduction from the original EC of 22.4 mS m^{-2} to 1 mS m^{-2} (Figure 11). Changes in soil acidity were

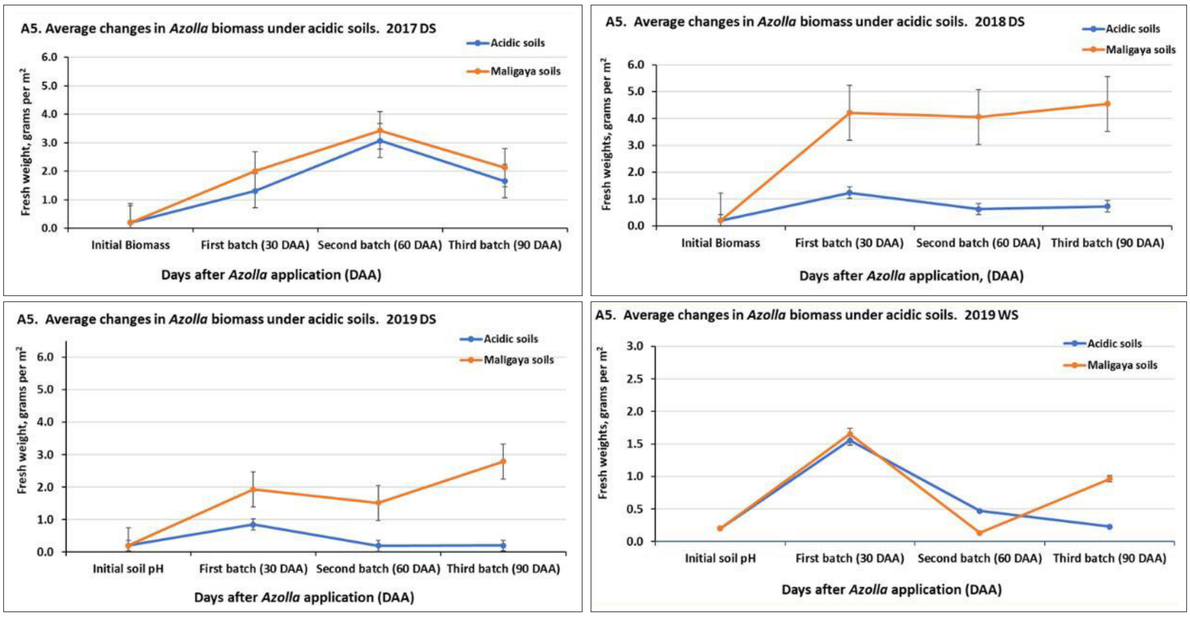


Figure 9. Average changes of the sporulation as indicated by the biomass of the *Azolla* accessions sown in acidic soils in 2017 DS, 2018 DS, 2019 DS, and 2019 WS under green house experimentation. PhilRice CES.

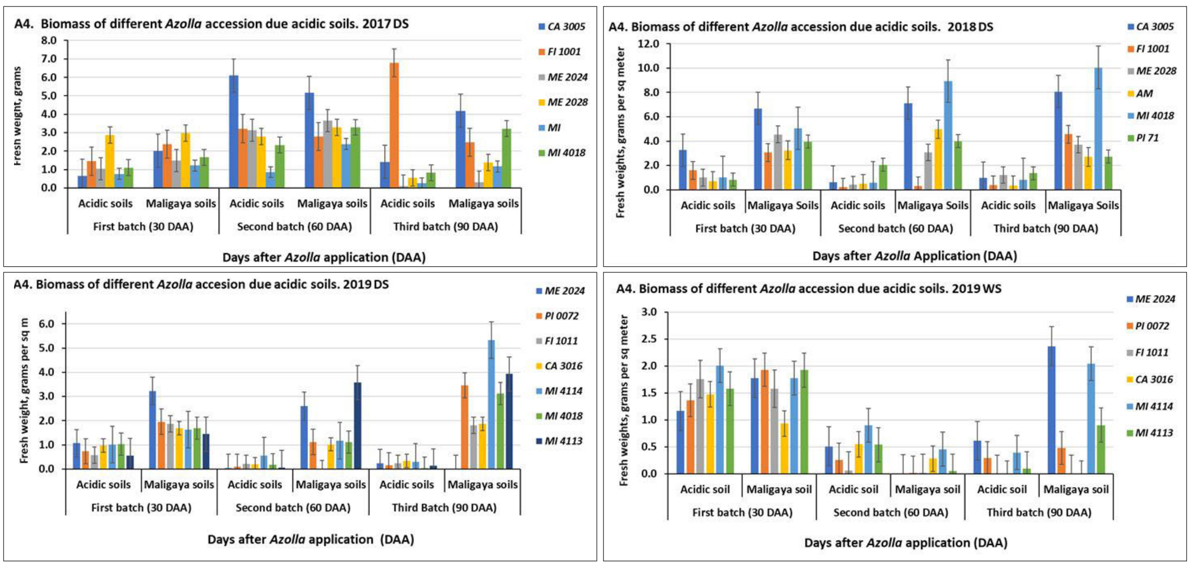


Figure 10. Biomass of the different *Azolla* accessions as exposed in acidic and normal soils in 2017 DS, 2018 DS, 2019 DS, and 2019 WS under green house experimentation. PhilRice CES.

also prominent after two years of *Azolla* sowing, and soil pH became more or less stable or comparable to the normal soils (Maligaya clay soil).

Generally, the biomass was affected within the growing period of the *Azolla* spp. (Figure 12). From similar amount of *Azolla* sown, growth was generally higher in the normal soils (Maligaya soils) though it decreased in 2019 WS. Growth of *Azolla* accessions sown in acidic and saline soils were consistently low. As amelioration was getting better, the biomass of those sown in saline soils had increased in the 2019 trials. Meanwhile, pH of originally classified acidic soils was normalized into normal, which was consistently observed in the four trials.

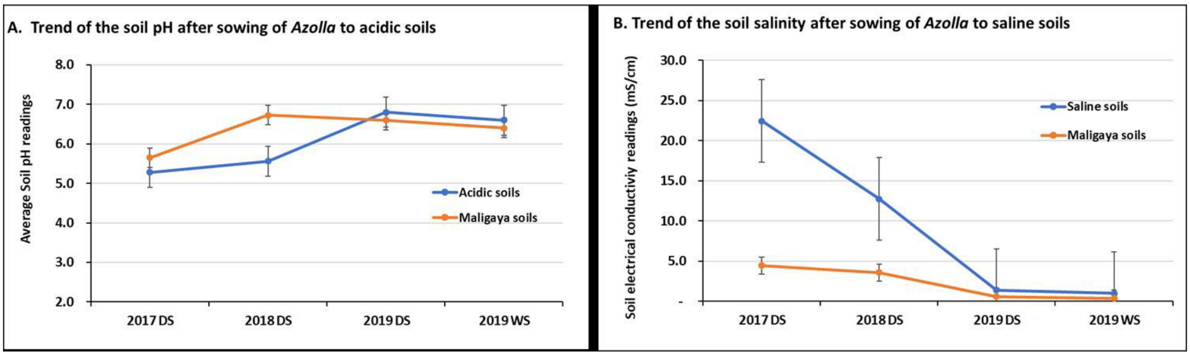


Figure 11. General trend of changes on the soil salinity (A) and soil acidity after *Azolla* was sown under greenhouse condition from 2017 to 2019. PhilRice CES.

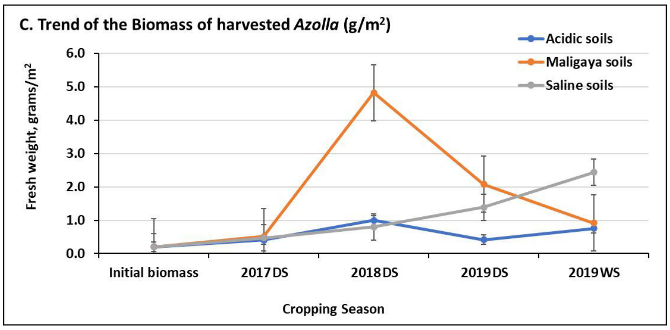


Figure 12. The average total effect of saline and acidic soils on the biomass of the different *Azolla* accession after 3 applications in 2017 DS, 2018 DS, 2019 DS, and 2019 WS under green house experimentation. PhilRice CES.

Conclusion

The experiments showed that the tested *Azolla* species can ameliorate acid and saline soils. In an organic rice production management and system, *Azolla microphylla* can be the best option as an alternate organic nitrogen source during the critical growth stages of the rice plants in normal and saline soil conditions.

The different soil treatments of *Azolla* species have shown similar trends of pH and EC readings, in which soil pH had increased while the soil EC readings had decreased. *Azolla microphylla* 4113 (MI 41133) and *Azolla microphylla* 4114 (MI 4114) were found to be the best ameliorating *Azolla* species for acidic and saline soil, respectively. Meanwhile, the acidity of the soils can be remedied by irrigating the paddy soils; conditioning the soils to normal or in pH conducive to rice plant growth.

Azolla spp showed its potential to ameliorate soil salinity, but there is a need to re-sow the species three times to have significant reduced soil EC. The degree of affected sporulation and subsequent reduction in biomass production of the different *Azolla* spp in the four trials is still high and may be considered as a research gap. Salinity was ameliorated in the third application of *Azolla*, but at the expense of their sporulation. There is a need to optimize the ameliorative potential of the *Azolla* without sacrificing sporulation. Although acidity was not much a problem in the study as it had changed from acidic (soil pH 5.4) level to slightly acidic and near neutral (soil pH 6.6), the sporulation or growth of the different *Azolla* was not consistent in the four trials; thus, a study is recommended to optimize its ameliorating potential.

The experiments, which used similar soils, showed the potential of ameliorating salinity with at least two years of using *Azolla* as phytoaccumulator. As its growth was also reduced and still lower than in the normal soils, another research study may still be conducted to further optimize the potentials of *Azolla* in ameliorating salinity and acidity of paddy soils.

Literature Cited

Banach AM, Banach K, Stępniewska Z (2012) Phytoremediation as a promising technology for water and soil purification: *Azolla caroliniana* (willd) as a case study. Acta Agrophysical **19**(2): 241-252

Breckle SW (2002) Salinity, halophytes and salt affected natural eco-systems. *In* Läuchli A, Lüttge U (Eds.). Salinity: Environment – Plants – Molecules (pp 53-77) Kluwer Academic Publishers: The Netherlands

Collado WB (2015) Simple soil series characterization. Philippines: Philippine Rice Research Institute

Devi MK, Singh WN, Singh WRC, Singh HB, Singh NM (2014) Determination of the ability of Azolla as an agent of bioremediation. Palegia Research Library. European Journal of Experimental Biology **4**(4): 52-56

Javier EF, Espiritu AE, Mapa, VIG, Ramos PS Jr (2019) The optimized quality of vermicast as affected by different substrates from a rice-based farming system. Discussion Paper Series No. 2019-08 (p 22). Philippines: Philippine Rice Research Institute

Javier EF, Tabien R (2003) Nitrogen dynamics in soils amended with different organic fertilizers. Phil Journal Crop Sci **28**(3): 49-60

Peters GA, Mayne BC (1974) The *Azolla-Anabaena azollae* relationship. Initial characterization of the association. Plant Physiol **53**: 813-819

Ponnamperuma FN (1985) Chemical Kinetics of wetland rice soils relative to soil fertility (pp.71-89) Proc. Wetland Soils: Characterization, Classification and Utilization Workshop. Philippines: International Rice Research Institute

Ponnamperuma FN (1972) The chemistry of submerged soils. Advances in Agronomy. **24**:29-96

Ponnamperuma FN (1965) Dynamic aspects of flooded soils and the nutrition of the rice plant. IRRI Symposium on Mineral Nutrition of the Rice Plant. IRRI. USA: Johns Hopkins Press, Baltimore, Maryland

Qadir M, Oster JD (2004) Crop and irrigation management strategies for saline sodic soils and waters aimed at environmentally sustainable agriculture. Phytoremediation of Saline Soils for Sustainable Agricultural Productivity. Sci Total Environ **323**: 1-19

Sto Domingo XXG, Espiritu AJ, Javier EF (2015) Evaluation and utilization of alternative and potential non-fossil fuel based (nFFB) nitrogen nutrition for rice farming. Farming without fossil energy Program. 2015 National Rice R&D Highlights. Philippine Rice Research Institute

Sufian, J, Golchin A, Avanes A, Moradi S (2013) Potentials of *Azolla* (*Azolla caroliniana*) for uptake of Arsenic from contaminated waters with different levels of salinity. International Journal of Agriculture and Crop Sciences **6**(12): 778-783

Walker T, Friday J, Casimero M, Dollentas R, Mataia A, Acda R, Yost R (2009) The early economic impact of a nutrient management decision support system (NuMaSS) on small farm households cultivating maize on acidic, upland soil sin the Philippines. Agricultural Systems, Elsevier **101**(3): 162-172

Yost R, Ares A, Bajita J, Wang X (2000) Diagnosing nutrient deficiencies. *In* Corton TM and Osmond D (Eds.). Workshop on diagnostic and predictive criteria in nutrient management. Philippines: Philippine Rice Research Institute

FULL PAPER

ROLE OF IMPROVED VARIETIES IN THE PHILIPPINE RICE PRODUCTION

Alvin D. Palanog[1], Mark Ian Calayugan[2], Gerald E. Bello[1], Marilyn Ferrer[3], Xavier Greg I. Caguiat[3], May Osano-Palanog[1], Cielo Luz I. Mondejar[1], Leo T. Sta. Ines[1], Thelma F. Padolina[3], Jose E. Hernandez[2], and Norvie L. Manigbas[3]

[1]Philippine Rice Research Institute, Negros Occidental, Philippines
[2]University of the Philippine, Laguna, Philippines
[3]Philippine Rice Research Institute, Nueva Ecija, Philippines
*Corresponding Author: adpalanog@up.edu.ph

Abstract

Rice is an important economic commodity in the Philippines and a major staple food of its population. The introduction of modern rice varieties with high-yielding potential brought positive impact to rice production, which resulted in dramatic increase in the production volume in the Philippines. However, local rice production is not enough to meet growing demand due to challenges brought about by climate change, growing population, declining land area, high cost of inputs, poor drainage, and irrigation facilities. Rice self-sufficiency remains an elusive goal for the country's rice sector. Breeding institutions such as International Rice Research Institute (IRRI), Philippine Rice Research Institute (PhilRice), University of the Philippines-Los Baños (UPLB), and private companies continue to develop varieties that can overcome constraints and challenges to rice production. The continuous introduction of modern varieties (MVs) resulted in increased farm yields. However, genetic gains in yield for the last decade have plateaued and extensive adoption of MVs remains to be exigent. Current innovations in breeding such as factory line approach in breeding, marker-aided selection (MAS), and genomic selection should be integrated to overcome the obstacles in maximizing genetic gains in yield and enhance competitiveness of the country's rice production.

Keywords: *Modern Varieties (MVs), Philippine Agriculture, Rice Breeding, Rice Production, Rice Technical Working Group, Rice Varietal Improvement Group (RVIG).*

Introduction

Philippines is one of the major rice-producing and consuming countries in Southeast Asia. The country produced 19.08 million metric tons (M mt) in 2018; however, it fell short to the national demand. Consequently, about 10% of the annual consumption is augmented from imports (PSA, 2018). The demand for rice continues to grow as population steadily increases at a rate of 1.7%, which is projected to reach 110 M in 2020. With the per capita consumption of 118.81 kg/person/year (PSA, 2020) and increasing population, rice self-sufficiency remains an elusive target for the country. To achieve rice self-sufficiency and security, one of the plausible options is to increase farm productivity.

The development and introduction of modern or improved rice varieties have contributed substantially to the increase of rice production in the country. The deployed first modern variety (IR8) developed by International Rice Research Institute (IRRI) is a new plant type characterized as shorter, earlier maturing, and photoperiod insensitive compared with traditional varieties. Its deployment paved way to the widespread adoption of modern varieties (MVs), which resulted in dramatic increase in rice production (Herdt and Capule, 1983; Launio et al., 2008). After the varieties' introduction in the 1960s, more than 50% of the total rice area especially in the irrigated ecosystem was planted with MVs. In 2002, it was estimated that around 95% of the total area harvested was planted with MVs and almost 100% in 2004 (Launio et al., 2008). Most of the rice varieties released were intended for irrigated, rainfed, and upland rice ecosystems, and later for cool-elevated, saline-prone, high temperature, drought, submergence for transplanted and direct-seeded. Philippine Rice Research Institute (PhilRice) – a government research institute leading the development of rice varieties, has released varieties for various ecosystems including NSIC Rc 300, Rc 216, Rc 218, and Rc 160 – all intended for irrigated lowland condition.

The rapid adoption of new rice varieties was influenced by Local Government Code in 1992 and Agriculture Modernization Act in 1998 (Launio et al., 2008). However, adoption of these varieties is constrained by various contexts. The use of high-quality modern varieties needs to be further promoted as majority of the farmers still use saved seeds. Furthermore, the changing contributions and adoption of newly-released varieties that influence yield increase and stability should be considered. Although MVs have changed the landscape of rice production in the country, the extent of its contribution is yet to be determined. Government policies that continually support and strengthen the current breeding research, development, and extension should also be prioritized.

This paper evaluated the contribution of improved rice varieties to rice production in the Philippines using pertinent data from the past decade, provided brief overview of the country's rice production profile, and discussed prospects for the improvement of rice production and the government efforts to boost rice production to achieve rice security.

National Agriculture Profile

Philippines is an archipelago composed of 7,107 islands in the Southeast Asian region with a land area of approximately 300,000 km^2. The country is divided into three major geographic areas: Luzon, Visayas, and Mindanao. It is located between 40 and 210 N latitude and 1270 E longitude; bounded by West Philippine Sea, Pacific Ocean in the east, Sulu and Celebes seas in the south, and Bashi Chanel in the north. The country's climate is tropical and maritime, which is further classified into four types based on Corona system: (1) two pronounced seasons – dry from November to April and wet throughout the rest of the year; (2) absence of dry period with maximum rains occurring from November to January; (3) dry from November to February and relatively wet for the rest of the year; and (4) more or less evenly distributed rainfall throughout the year (Figure 1)

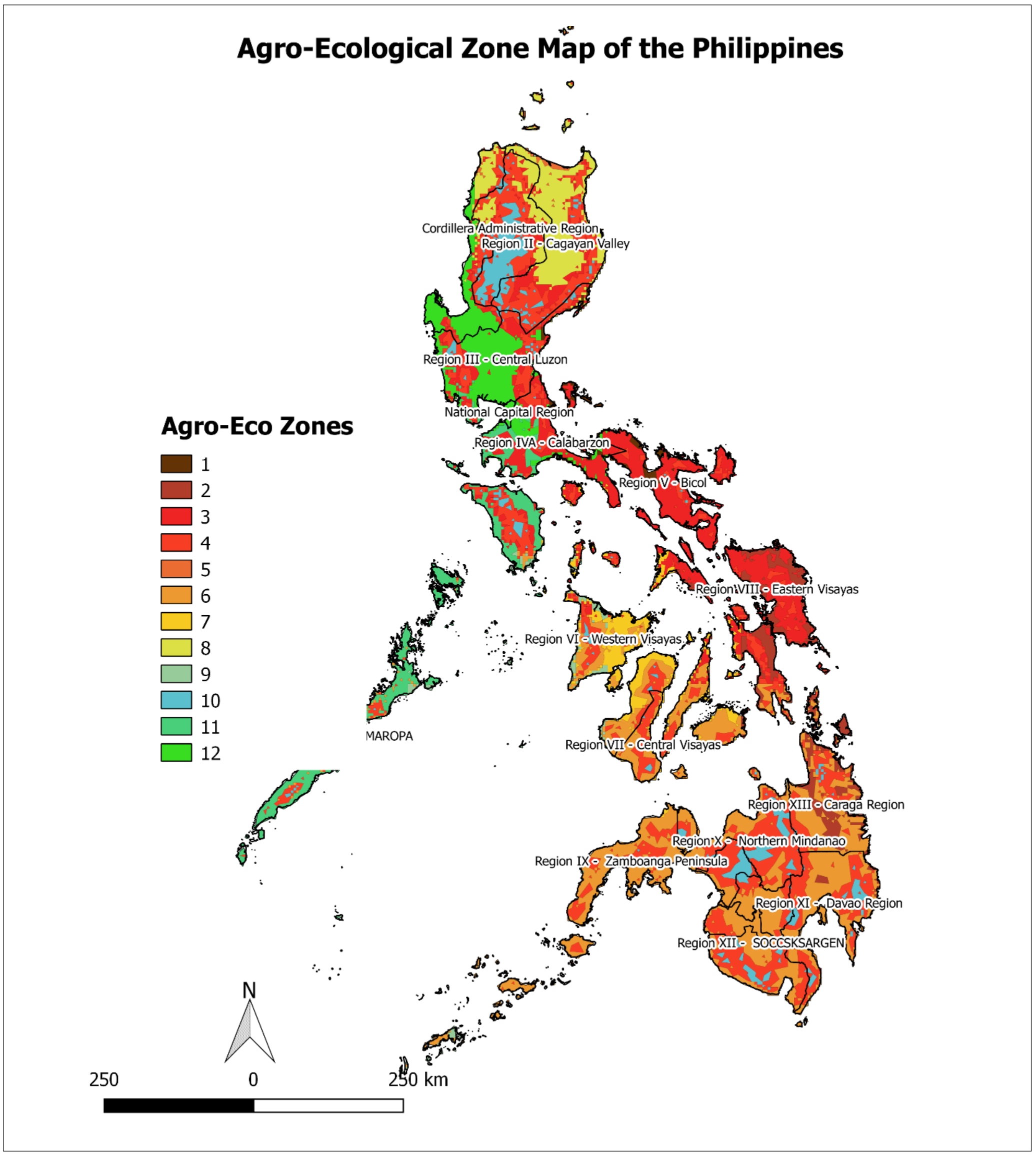


Figure 1. Twelve agro-ecological zones (AEZ) of the Philippines. Source: Bureau of Soils and Water Management, 2001.

(Lantican, 2001). Recently, areas in the country were further categorized into 12 distinct agro-ecological zones on which classification was based on elevation, slope, soils properties, and climatic factors such as rainfall, temperature, relative humidity (Figure 2) (BSWM, 2001). However, this classification is yet to be adopted by the government. Country's population is unevenly distributed throughout the archipelago due to geographical, social, and uneven development of each region (Altoveros and Borromeo, 2007). The United Nations estimates the population of the country at 108.12 M with annual growth rate of 1.72%.

Agriculture is an integral component of the Philippine economy; however, its relative contribution to gross domestic product (GDP) continuously declined in the past years (Brown et al., 2018). The sector accounted for 13 - 14% from 1998 to 2009 but decreased to 10% in 2017. The decline in the contribution of the agricultural sector does not necessarily mean that it is shrinking. It implies that faster growth is occurring in the structural transformations and services industry (Brown et al., 2018). Amidst the decline, agriculture employs 30% of the country's labor force (Brown et al., 2018).

The agricultural sector is comprised of crop, livestock, poultry, forestry, and fisheries subsectors. The crop subsector accounts for half of the agricultural output, 23% for the fisheries, and the rest are shared by remaining subsectors (Altoveros and Borromeo, 2007). Traditional crops such as rice, maize, and coconut account about 50% of the total area harvested of the crop subsector. Leading crops in terms of value include rice, maize, sugarcane, coconut, banana, mango, pineapple cassava, coffee, sweet potato, and eggplant; while the most extensively grown crops are rice, coconut, maize, sugarcane, cassava, coffee,

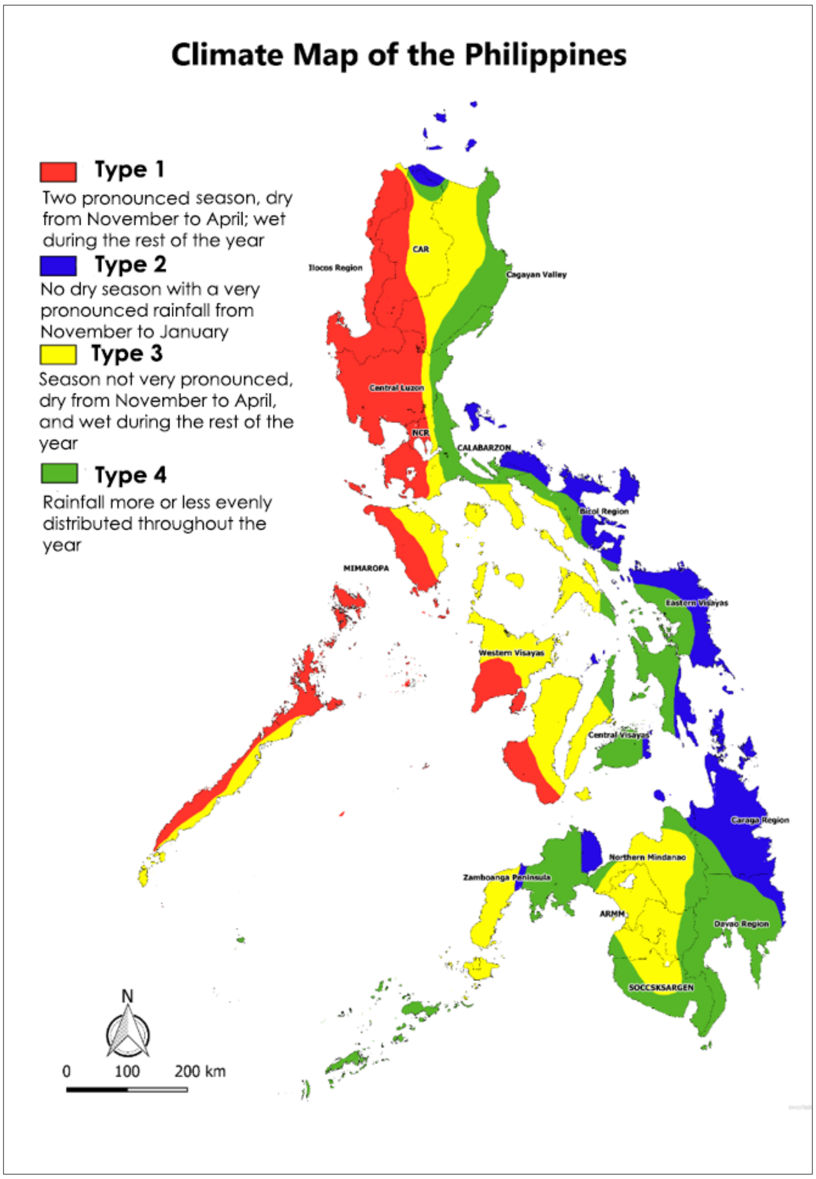


Figure 2. Four climatic classifications of the regions in the Philippines based on Corona System (Lantican, 2001).

mango, sweet potato, and Manila hemp (Altoveros and Borromeo, 2007). Several Philippine cropping systems are mainly based on major crops: rice, maize, coconut, and sugarcane. Major agricultural systems include lowland irrigated farming, rainfed farming, and upland farming. Rice-rice is the general cropping system in irrigated lowlands. Recently, additional commodities are introduced in rice after two cropping such as fish, duck, and legumes that include mungbean (*Vigna radiata*), peanut (*Arachis hypogea*), and soybean (*Glycine max*). In rainfed lowland areas, garlic (*Allium sativum*), onion (*Allium cepa*), and tomato are grown after rice in minimum or no tillage system. In coconut areas, common crops such as rice, maize, pineapple, coffee, lanzones, banana, and upland crops are planted depending on the age of coconut and distance planting. Cattles and small ruminants are also raised along with coconuts. Meanwhile, sugarcane is largely practiced in monoculture. Legumes are also planted in the early stage of the sugarcane that provides additional income.

Farming system practices in the country include agroforest/homestead gardens, multi-storey farming system, integrated farming system, diversified conservation farming in sloping lands (SALT), and multi-cropped home gardens (Altoveros and Borromeo, 2007). The Philippines exports coconut (copra, oil, and other coconut products), sugar, pineapple, and pineapple products, banana, coffee, and mango; and imports rice and corn. The agricultural exports earning reached 331.61 billion (B) in 2017, 32% higher than the previous year. Fresh banana remains to be the major earner generating PhP 56.88 B at 2.86 mt of fresh banana that shared 17.15% in the total agricultural export revenues. For centrifugal sugar export, the value increased to PhP 10.26 B with volume increased to 142.28% (440,773 mt) in 2017. The sugar export value contributed 3.09% to the total value agricultural export. Virginia tobacco, fresh mango, and pineapple registered PhP 1.21 B, PhP 1.17 B, and PhP 10.04 B, respectively. Interestingly, export values of rice and corn expanded at PhP 44.6 M and 84.11 M in 2017, respectively. From PhP 594.49 B in 2016, total expenditures for agricultural imports were slightly reduced to PhP 592.83 B in 2017. List of major exported crops and corresponding volume, value (PhP) and major producing-provinces is presented in Table 1. Rice led the total agricultural expenditures with import value of PhP 18.03 B at 0.89 M mt in 2017, which was 36.14% higher than the previous year. Meanwhile, the country imported 0.48 M mt of corn amounting to PhP 6.51 B in 2017, which was 35.41% lower than previous year. In general, the contribution of agricultural export revenue continued to increase at 9.58% but 12.24% decrease in total import expenditure was recorded in 2017.

Rice Production in the Country

Philippines is the 8th rice-producing country in the world (Maclean et. al., 2002). Rice production area was estimated at 3.8 M ha in 1995, which significantly expanded to 4.7 M ha in 2019. More than two-thirds (69%) of the area are irrigated, rainfed (30%), while the rest are upland and saline-prone areas. Majority of the country's irrigated rice is grown on the central plains of Luzon – the country's rice bowl. Meanwhile, rainfed rice is cultivated in the Cagayan Valley and Ilocos province in Northern Luzon and in Iloilo province and in the coastal plains of Visayas. Upland rice is grown in permanent and shifting cultivation systems scattered throughout the archipelago particularly on rolling to steep land areas. The major rice producing areas in the Philippines include Central Luzon (18.7%); Western Visayas (11.3%); Cagayan Valley (11%); Ilocos region (9.8%); SOCCSKSARGEN (7.5%) comprising provinces of North Cotabato, Sarangani, South Cotabato, and Sultan Kudarat; and Bicol region (6.8%). Table 2 shows the volume of rice production by region.

Table 1. Major exported crops of the country and the corresponding top producing provinces by volume. Source: PSA, 2020* and PSA, 2017**

Crop	Volume (mt)*	Value (PhP, '000)*	Provinces**
Banana	4,403,496.3	101,177,609.3	Davao del Norte, Bukidnon, Compostela Valley, North Cotabato, Davao del Sur
Pineapple	631,486.2	16,824,913.1	Bukidnon, South Cotabato, Camarines Norte, Cavite, Misamis Oriental
Rubber	124,272.0	4,180,687.8	North Cotabato, Zamboanga Sibugay, Basilan, Zamboanga del Sur, Zamboanga del Norte
Tobacco	40,425.6	7,997,817.1	Ilocos Sur, Isabela, La Union, Ilocos Norte, Pangasinan
Mango	14,211.8	1,017,482.3	Pangasinan, Zamboanga del Norte, Cebu, Davao del Sur, Batangas
Cacao	3,048.8	406,970.7	Davao del Sur, Davao City, Davao del Norte, Davao Oriental, Compostela Valley
Abaca	94.4	1,219,407.2	Catanduanes, Northern Samar, Davao Oriental, Surigao del Sur, Davao del Sur
Cassava	808.6	47,425.5	Lanao del Sur, Bukidnon, Basilan, Sulu, Misamis Oriental

Table 2. Regional volume of palay production in the Philippines from 2008 to 2019 (PSA, 2020).

Region	Yearly Rice Production Volume (*M mt, '000)											
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
CAR	445.16	265	400.4	429	453.5	460.2	452.6	401.1	382.9	445	391	418.3
Ilocos Region	1,691.30	831	1,558.40	1,602.80	1,737.70	1,750.10	1,796.20	1,776.90	1,805.13	1,872.10	1,719.80	1,851.30
Cagayan Valley	2,080.20	1,277	1,745.70	2,144.80	2,425.50	2,423.20	2,514.90	2,490.20	2,303.47	2,656.98	2,379.50	2,664.70
Central Luzon	3,014.30	1725	2,958.40	2,616.10	3,220.60	3,409.50	3,765.20	3,305.10	3,362.88	3,634.81	3,614.90	3,730.20
CALABARZON	428.10	235	390.2	399.2	389.3	411.8	405.6	392	407.12	410.88	419.50	380.80
MIMAROPA	863.20	572	857.5	981.7	1,030.60	1,033.90	1,081.90	1,081.70	1,080.41	1,159.83	1,231.70	1,195.20
Bicol Region	997.60	643	1,081.10	1,070.90	1,173.30	1,243.20	1,258.20	1,265.00	1,275.44	1,335.07	1,349.90	1,192.90
Western Visayas	2,118	1365	1,789.70	2,245.00	2,292.20	2,090.80	2,052.60	2,056.40	1,754.97	2,258.47	2,232.60	2,077.80
Central Visayas	311.80	170	270.5	322.8	327.1	347.7	338.8	335.8	176.24	297.57	308.90	223.10
Eastern Visayas	1,030	585	964.2	984	995	989.8	982.6	956.5	954.84	945.57	947.60	900.20
Zamboanga	551.30	348	552.7	622.2	618.8	639.1	656.8	662.5	581.08	700.59	728.32	677.40
Northern Mindanao	551	359	586.4	611	637.4	674.9	713.8	726	711.28	745.73	760.70	761.10
Davao Region	419.00	261	402.8	416.5	448.7	421.6	452.3	441	417.95	433.67	488.10	450.40
SOCCKSARGEN	1,234.80	756	1,185.20	1,244.20	1,270.90	1,347.70	1,364.90	1,292.30	1,200.64	1,325.51	1,342.30	1,343.10
Caraga	447.30	262	405.8	417	469.2	583.9	574.5	481	462.18	654.68	511.00	449.40
ARMM	631.70	356	623.3	576.8	542.8	612.1	557.2	488.2	543.49	477.98	638.70	674.80

Note: *M mt – Million metric tons

The per capita rice consumption (PCRC) of the Philippines, which averaged 109.5 kg person^{-1} in 2018, has increased significantly in the last decade. The PCRC has increased in each region with Central Visayas sharing the highest increase (41%) and CALABARZON having the lowest increase (4%). About 10% of the total rice consumption of the country is provided by imported rice. With constantly growing population, supplying enough rice exert significant pressure on the local rice sector.

As the single most important source of livelihood among small farmers and landless agricultural workers, rice sector has continuously played a major contributor for agricultural gross value-added accounting for 20% of the total value. It represents the bulk of the labor force in agriculture (40%) and largely influences the growth trend in agriculture (Balisacan and Ravago, 2003).

Agriculture and Rice Production Constraints

Compared with other countries, the Philippine agriculture is characterized by limited diversity and low productivity. The poor performance of crop sector can be attributed to typhoons and El Niño affecting rice and corn production, pest infestation in coconut, and limited adoption of high-yielding varieties. Hence, limited diversification and poor productivity poise as major challenges in the country's agricultural transformation (Brown et al., 2018). Brown et al. (2018) enumerated the factors influencing productivity in Philippine agriculture: access to credit and agricultural insurance, farm mechanization and post-harvest facilities, irrigation system, R&D support, extension services, agrarian reform implementation, ageing farmers and fisherfolks, and connectivity of production areas and markets. Climate change that brings adverse environmental conditions such as flooding, typhoons, drought, soil degradation, and pest emergence is also a threat on agricultural productivity.

The Department of Agriculture (DA) through PhilRice has initiated programs and projects that address challenges in rice production. These include distribution of seeds of recommended varieties, promotion of integrated crop management technologies or PalayCheck System®, and generation of rice production information through Philippine Rice Information System (PRiSM). For the country to overcome these challenges and achieve transformations, investment on R&D should be prioritized. The country's annual investment in R&D (0.3% of GDP) is considered below the standard investment set by World Bank (1%).

Specifically, on rice production, high cost of inputs, inadequate mechanization, poor drainage, and inadequate irrigation facilities were identified as major constraints. Some of these constraints are interrelated. Unabated conversion of some agricultural land to residential, commercial, and industrial land reduces the area devoted to rice production, also leads to a shortage in domestic supply (Ricepedia, 2013).

The Philippines bears the brunt of typhoons coming in from the Pacific Ocean. Successive heavy rains cause severe drainage problems in paddy fields, resulting in a significant reduction in rice yield and quality. There is also concern about the deterioration of irrigation systems at least partially because of lack in maintenance funds.

Rainfed lowland rice suffers from uncertain timing of the arrival of rains, with drought and submergence often occurring in the same fields over the course of a single season or in different fields within a farm over the same season. Meanwhile, upland rice farming is constrained by weeds, drought, diseases (blast), acidic soils, and soil erosion. The high cost of inputs particularly fertilizer also hinders farmers from applying optimal fertilizer amounts to input-responsive high-yielding varieties.

Technology Delivery

Research and development (R&D) that addresses concerns for agricultural subsectors is usually undertaken by corresponding government research institutes and agencies attached to the Department of Agriculture. R&D priorities are aligned with respective strategic plans and mandates, which act as blue prints. For instance, DA-PhilRice in consultation with its major partners and key stakeholders had mapped out the Strategic Plan 2017-2022, which is guided by its vision of "Rice-Secure Philippines" and execute strategies on creating significant impact on the lives of rice stakeholders (PhilRice, 2016). Developed technologies such as Minus-One Element Technique (MOET), Leaf Color Chart (LCC), and PalayCheck® are tested through collaborated efforts among technical institutes, local governments, farmers' and farmers' associations, and other stakeholders.

The mandate of training of technical persons and agricultural technologists is given to Agricultural Training Institutes (ATI) with the assistance of technical supervisions from the agency or institute that developed the technology. Extension workers of each local governments are assigned to lead in disseminating matured technologies to farmers and fisherfolks. With the enactment of Local Government Code of 1991 and participatory governance, agricultural extension workers plan and implement extension strategies and approaches that are best for the community along with the strategies advocated by DA (Lopos, 2007). However, the devolution of extension to Local Government Units (LGUs) resulted in fragmented extension activities especially on rice. The current implementation of Rice Competitiveness Enhancement Fund (RCEF) created by Rice Tariffication Law (RA 11203), which aims to improve rice farmers' competitiveness and income, requests the help of LGUs in implementing its four components: Seed, Rice Extension Services, Mechanization, and Credit programs.

Past and Current Performance of Rice Production

The introduction of modern technology and substantial investment in irrigation, rice R&D, and modern technologies such as fertilizers in 1960s led to dramatic increased in rice production (5.9%) in the 1970s or the Green Revolution era. Generally, yield increase contributed to the significant increase in rice production and a fair contribution from expansion of rice production areas. Eventually, rice production growth slowed down and population increased rapidly which led to rice importation; however, this is much lower compared to the previous decades (Baliscan and Ravago, 2003). Despite the decrease in domestic production in 1980s, the proportion of total imports to the total rice production was low, which can be attributed to the decrease in per capita demand due to decline in the consumers' average income (David and Balisacan, 1995). Rice production gained momentum in the 1990s with an increasing annual average growth of 2.8%. The rise of real domestic rice price and decrease in the input prices can be attributed to the increase in the growth rate during this decade. Amidst gains, a sluggard growth in yield and area were recorded. The onslaught of El Niño in 1998 significantly affected the rice production performance that plummeted by 24.2% but regained instantly in the succeeding year; recording a positive production output increase of 37.8%. Yield growth was observed across rice ecosystems with 2.3% and 3.6% in irrigated and rainfed rice, respectively, from 1997 to 2007. This led to production growth that was consistently observed across rice production regions in the country ranging from 1.3 to 5.6% per year. Increase in regional rice production was observed in 9 of 16 provinces in the country (Mataia et al., 2011). In 1997 - 2007, the country had a remarkable growth yield of 30% with the development and introduction of new technologies. The adoption of high-quality seeds particularly certified seeds and improvement in irrigation spurred yield growth (Mataia et al., 2011).

Rice production trend is generally increasing in the last 10 years (Figure 3). Yield fluctuated in some years due to La Niña and El Niño. Decrease in rice production was observed in 2009 and 2010, which posted the lowest production in the last decade, possibly due to moderate El Niño (Hilario et al. 2009). Subsequently, a strong La Niña battered rice production in 2011 causing a significant yield reduction compared to succeeding years. Rice production picked up pace from 2012 to 2014 posing an increasing performance in three consecutive years. A very strong El Niño onslaught in the later part of 2015 and the early part 2016 and weak La Niña in the later part of 2016 resulted in sudden drop of production. Meanwhile, a weak El Niño and La Niña in 2017 and 2018 possibly brought positive effects on rice production leading

Figure 3. National rice production volume in the Philippines in the last decade (2008-2018) showing positive growth (PSA, 2020).

to the highest production records of the decade. In this period, the use of high-quality seeds particularly certified seeds complemented with appropriate crop management coined as PalayCheck® – an integrated crop management recommendation for irrigated lowland contributed to the good performance of rice production (Bordey, 2011; Mataia et al., 2011). A general increase in production of about 3% and average yield of 3.83 t ha^{-1} across ecosystems was recorded during this period (PSA, 2018).

Trend analyses (Francisco et al., 2010) indicated that rice production increase is attributed to yield increase (Mataia et al., 2011). Analyses showed that there are two ways to improve rice production, which include technological change and efficient use of farm resources. Efficient use of farm resources such land, labor, capital, and other resources along with adoption of modern technologies can improve farm productivity and profitability. The use of yield-enhancing technologies such as hybrid rice varieties and certified seeds complemented with location- specific interventions significantly boosted yield. Records and data of rice production growth performance support that the use of quality seeds of modern or improved rice varieties can significantly increase yield and consequently rice production (Francisco et al., 2010; Mataia et al., 2011).

The Improved Rice Varieties

Variety Development

The development and adoption of improved rice varieties provide an opportunity for the rice farmers to increase productivity and profitability and improve food security in rice farming households (Mariano et al., 2012; Laborte et al., 2015). The establishment of PhilRice and IRRI has tremendously contributed to the extensive development of rice production technologies especially in breeding improved rice varieties. DA-PhilRice, IRRI, Bureau of Plant Industry (BPI), University of the Philippines-Los Baños (UPLB), and some private companies are major players in breeding of rice varieties in the Philippines (Launio et al., 2008). Promising lines developed by each institution are submitted and evaluated in the National Cooperative Testing (NCT) spearheaded by the Rice Technical Working Group (RTWG) and the Rice Varietal Improvement Group (RVIG) – a group of agencies and institutions (Figure 4) that tests, evaluates, and recommends promising lines to National Seed Industry Council (NSIC) for variety release. Promising lines are evaluated under various ecosystems, seasons, and locations. The lines' performance in the trials determines whether these will be released either regional, national,

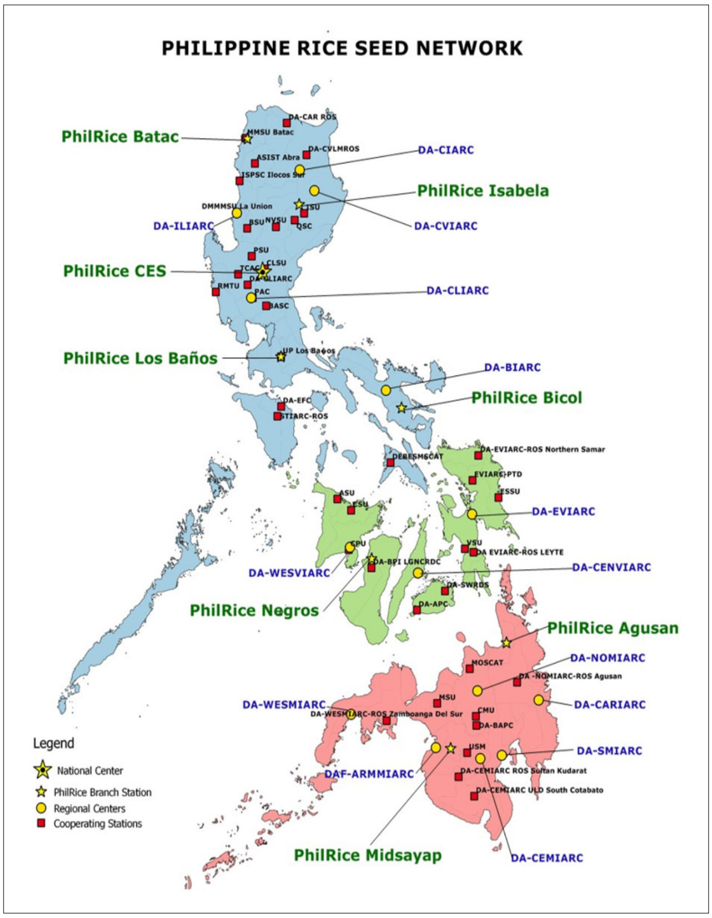


Figure 4. Network of rice research and development in the Philippines.

or seasonal. Upon approval of release, breeding institution submits breeder seeds to DA-PhilRice and its network (Figure 5) for seed multiplication and production into foundation seeds (FS). Foundation seeds are further multiplied into certified seeds (CS) that are eventually utilized by rice farmers (Figure 5). An average of four varieties are released every year. As of 2020, 411 rice varieties have been approved for release since 1955. The varieties were recommended for various ecosystems (irrigated, rainfed, upland, saline-prone, cool-elevated submergence, drought-prone, and high temperature), national or regional release, crop establishments (direct seeded and transplanted), and seasons (dry and wet). Majority of varieties were intended for irrigated lowland followed by rainfed ecosystem>upland>saline-prone>submergence>drought>cool-elevated >high temperature (Table 3). Before the release of semi-dwarf improved rice varieties, most farmers used traditional varieties commonly suited for upland and lowland ecosystems. These varieties have good eating quality but are low-yielding and late maturing. More than 70 traditional varieties were released from 1920s to 1960s.

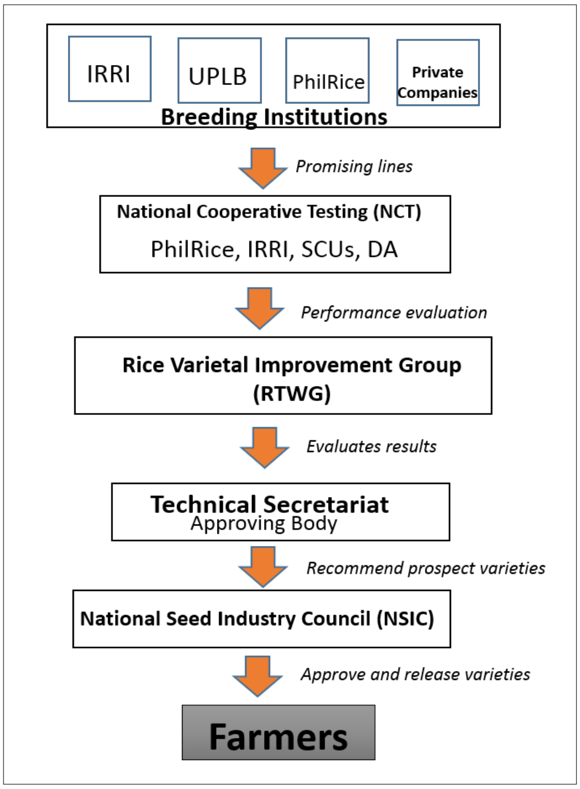


Figure 5. General flow of variety development and release in the Philippines.

The main goal of rice breeding in the country is to increase productivity in various rice ecosystems. Breeding programs are particularly geared towards achievement of priorities such as increased yield potential, tolerance to pests and abiotic stresses, good eating quality, appropriate growth duration, efficient nutrient uptake and utilization, and climate change resiliency. Breeding institutions pursue one or multiple breeding programs suitable for various ecosystems, which include: a) irrigated lowland (transplanted inbred rice and direct seeded inbred rice, hybrid rice and special purpose rice), b) rainfed rice, c) cool-elevated rice, d) saline-prone, e) upland rice, and f) heat-tolerant rice. Breeding institutions implement various breeding strategies to develop varieties and usually takes 8-12 years from hybridization to variety release. Some of the common strategies are conventional hybridization and selection, marker-aided breeding (MAB), anther-culture mediated, induced mutations, wide hybridization, and even genetic engineering.

Currently, DA-PhilRice and IRRI are developing rice varieties that can withstand major biotic and abiotic stresses through a collaborative project, “Accelerating the development and adoption of next-generation rice varieties for major ecosystems in the Philippines.” This project aims to introduce high-yielding inbred and hybrid rice varieties with biotic and abiotic resistance that will boost harvest and achieve rice security.

Before the official release of IR8 as semi-dwarf inbred rice variety for irrigated lowland, IRRI has initially released 50 t of seed to the agricultural

Table 3. Number of varieties per ecosystem released from 1968 to 2020. Source: (NSIC and DA-PhilRice, 2020)

Period	Irrigated Lowland	Rainfed Lowland	Upland	Drought	Cool elevated	Saline	Submergence	Heat	Total
1955-1967	15	4	13						32
1968-1988	43	4	7						54
1990-2010	90	10	5	1	6	18	1		132
2011-2012	20	9	1			4			37
2013-2014	37	10	3			11			65
2015-2016	25	14							39
2017-2018	23					5			28
2019-2020	7	10			4	8	1	2	32
Total	**260**	**61**	**29**	**1**	**10**	**46**	**2**	**2**	**411**

agencies in the Philippines in the wet season. Distribution of seeds was concentrated in Nueva Ecija (Huke and Duncan, 1969). Around 6 t of seeds were released to farmers (2,356) and government officials in various municipalities and cities as per request. Demonstration trials were also set-up in various areas that facilitated dissemination of seeds; however, distribution of seeds was not properly monitored (Herdt and Capule, 1983). Improved varieties were adopted more rapidly in the Philippine than any other countries in Asia. Data showed that 89% and 77% of improved rice varieties were planted in irrigated lowland and rainfed, respectively, in 1979-1980 (Herdt and Capule, 1983). Increase adoption of improved varieties was recorded in the early years of the release of high-yielding varieties; but eventually decreased in the succeeding years.

Classification of modern rice varieties were distinct in terms of characteristics in the decade of their release (Peng and Khush, 2003). The first generation of modern varieties (MVs), released from mid-1960s to mid-1970s, were dwarf varieties and highly responsive to fertilizers. These varieties include IR5 to IR34 developed by IRRI and C4 series developed by UPLB, which were significantly higher yielding than traditional varieties but were highly susceptible to pests. Released from mid-1970s to mid-1980s, the second wave of MVs including series of varieties released by IRRI (IR36 to IR62) have multiple disease resistance. The third generation of varieties released from mid-1980s to mid-1990s have better grain quality and stronger host plant resistance. The varieties included IR64 - IR72 and PSB Rc 1 - PSB Rc 74. IR64 became one of the most popular varieties not only in the Philippines but in other Asian countries and was considered a mega variety. The fourth generation of MVs were released after 1995 and were developed for adverse environments (Peng and Khush, 2003; Estudillo and Otsuka, 2006; Launio et al., 2008). In the succeeding decade (2000-2010), varieties were predominantly hybrid rice varieties and medium-maturing and high-yielding inbred rice varieties. Recently, released varieties were based on adaptability (seasonal, regional, and national) and were climate-change resilient. The significant increase in rice yield from the past decades can partly be attributed to the changes in rice farming practices and adoption of high-quality seeds of MVs and expansion of irrigated areas (Mataia et al., 2011).

Numerous improved varieties have been released but only few were widely adopted (Laborte et al., 2015) and preferred by the rice farmers. Most planted varieties include PSB Rc 10, Rc 18, and Rc 82. A study that consolidated a five-decade farm survey in major rice-producing province in the country (Central Luzon) showed that farmers adopt varieties that are high-yielding and early-maturing and have long and slender grains, high milling recovery, and intermediate amylose content (Laborte et al., 2015). The study also suggested that varieties with higher head rice recovery, less chalky grains, and resistance to pests are more likely to be adopted (Laborte et al., 2015). The choice of variety depends on several reasons and yield is usually the main consideration though not always the case (Laborte et al., 2015). The other important quality is marketability, which mainly dictated by the grain quality preferences of consumers, millers, traders, and other stakeholders in the value chain (Feder and Umali, 1993). Other determinants of MVs' adoption and diffusion include farm size, tenure status, education, and access to extension services and credit (Launio et al., 2008; Mataia et al., 2011). However, several of these factors are no longer important in the later stage of diffusion (Adesina and Zinnah, 1993).

Demonstrations and trials were conducted in farmers' field nationwide to accelerate the adoption and diffusion of newly-released rice varieties. Varieties' performance and availability are showcased in the demonstration farms. Participatory varietal selection (PVS) is also being conducted in major rice-production areas, which increased farmers' knowledge on the advantages of newly-released MVs. To further hasten adoption of MVs, local agriculture offices subsidized the cost of quality seeds.

Adoption of Improved Rice Varieties

Rice production has dramatically increased with the introduction of MVs in the 1960s. In 1970s, 50% of the total rice area was planted with MVs and steadily grew by 1980s. Around 90% and 80% of irrigated and rainfed areas, respectively, were planted with MVs during this period. In 2004, almost 100% of total rice production areas in irrigated lowland used MVs. Today, majority of the rice farmers use high-quality inbred seeds (45%) of MVs amounting to 8.3 M mt. Farmers' good seeds (FGS) of MVs is the second most utilized type of seeds (43%), followed by hybrid seeds (9%), while the rest are traditional varieties (3%). FGS are widely planted in 2.5 M ha, followed by inbred rice in roughly 2 M ha, and hybrid and traditional rice in <1 M ha (PSA, 2018).

The extensive adoption and diffusion of MVs have created significant impact in the improvement in rice production particularly in increasing rice yield of farmers. The pattern of increase in rice production volume was congruent to the increase in yield (Figure 6). Yield increase can be attributed to the improvement in the yield potential and characteristics of varieties across ecosystems (Figure 7). The genetic gain in yield during the introduction of MVs has increased tremendously (Figure 6) especially for irrigated lowland. Subsequently, the introduction of hybrid rice since late 90s resulted in higher yields in irrigated lowland (Launio et al., 2008; Mataia et al., 2011). However, it is interesting to note that yield increment has not significantly increased in the last two decades and plateau of the genetic gain in grain yield can be observed. Consequently, a mediocre growth rate or seemingly a plateau in the total rice production can also be observed (Figure 6).

Interestingly, farm-level rice yields in the Philippines grew in the last decade without a significant change in inputs (fertilizer, herbicides) and crop establishment methods. This progress in yield can be attributed to the use of good-quality seeds: hybrid and certified seeds, adoption of improved farming practices, and increase in irrigated areas (Mataia et al., 2011). With strong partnership with IRRI, the country recently released a rice variety for irrigated lowlands, the IRRI-bred Tubigan 18 (NSIC Rc 222/IRRI 154), which yields up to 10 t ha^{-1} and has an average of 6 t ha^{-1}, 12 - 13% higher than that of the popular and widely used rice variety PSB Rc82 – an IRRI-bred variety often used as check varieties in variety trials.

DA-PhilRice-bred NSIC Rc 216, Rc 160, and Rc 300 were included in the top five most preferred rice varieties in the irrigated lowland. These varieties have average yield of 6 - 7 t ha^{-1}. Rice-Based Farming Household Survey showed that utilization of PhilRice developed inbred rice varieties has increased from 5% in 1995 to 34% in 2017.

In 2020, NSIC released 10 new varieties composed of five varieties for saline that can yield up to

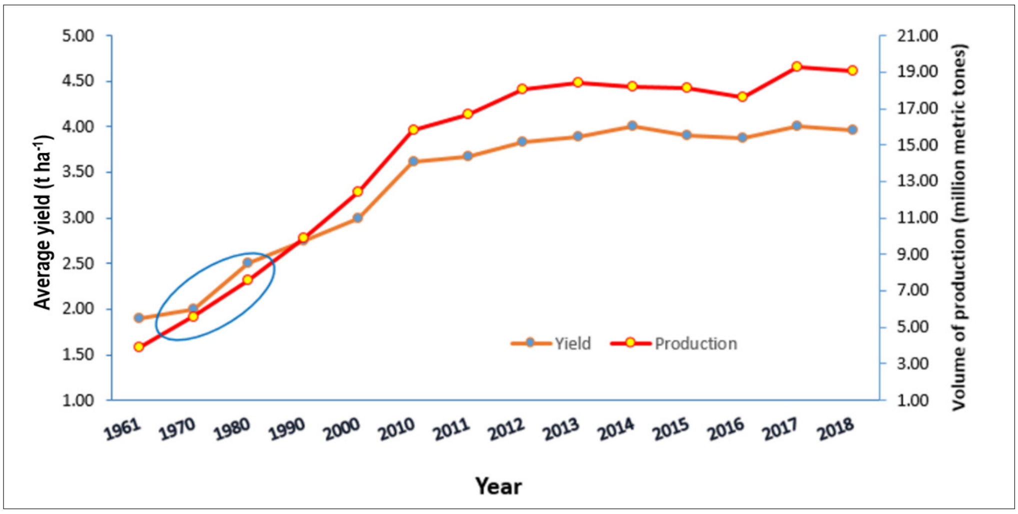


Figure 6. Rice production and yield performance in the past decades and recent years (1961 - 2018) in the Philippines highlighting dramatic increase in both yield and production with the introduction of modern or improved varieties (MVs). Source: NSIC, 2019

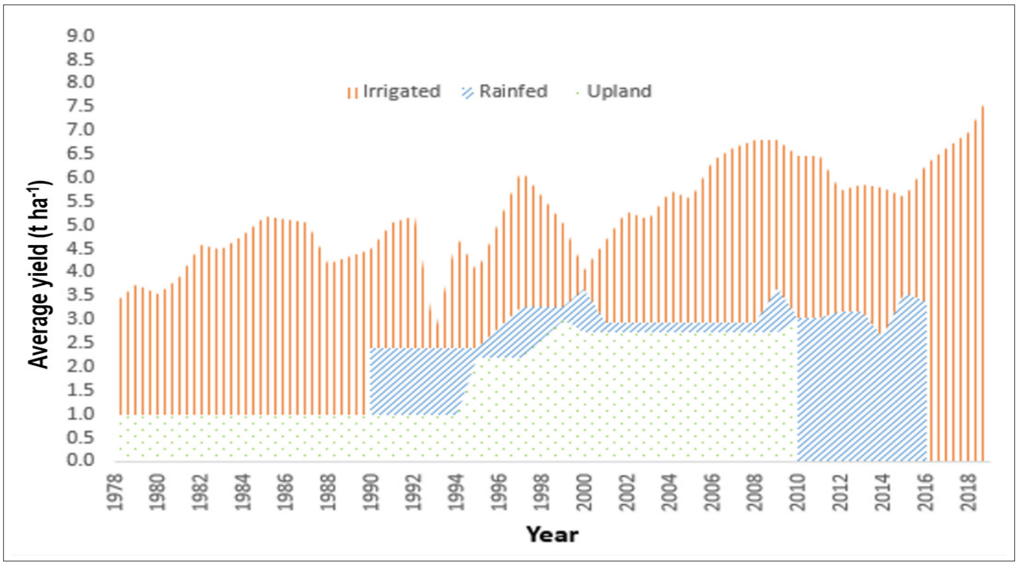


Figure 7. Yield trends of released varieties for various ecosystems from 1978 to 2018. Source: NSIC, 2019

3.2 t ha^{-1} and three hybrids with average yield of 6 t ha^{-1}. There are three new types of varieties developed by PhilRice and IRRI that possess unique traits: a) tolerance to both drought and salinity (GSRs), b) the first Zinc (Zn)-biofortified variety (NSIC Rc 460) with high Zn in the grain, and c) heat-tolerant varieties (NSIC Rc 600 and NSIC Rc 602).

Challenges in Rice Production

Rice is a highly political commodity. The Philippine rice sector has always been the nexus of the government's agricultural policies. The focal points of the policies revolve around achieving rice self-sufficiency and providing high income to farmers while making rice prices affordable to the consumers.

One of the most significant programs of the government for the rice sector is the "Philippine rice master plan 2009 – 2013: Enhancing provincial rice self-sufficiency." This rice master plan envisions a 100% self-sufficient rice economy by 2013 through improved rice productivity and increased income of rice farmers. This plan pursues location-specific interventions that can help farmers achieve higher yield. It focuses on how interventions can improve productivity toward sufficient yield. These include improvement of the effectiveness and efficiency of irrigation systems through rehabilitation, use of high-quality hybrid and inbred seeds and farmers' varieties, integrated and sustainable crop management technologies, provision of soft loans for the establishment of shallow tube wells and surface water pumps, and delivery of extension support services.

Rice seed subsidy schemes for farmers were implemented to acquire high-yielding varieties including hybrid rice varieties. The government also extends support for farm mechanization through its Rice Mechanization Program. It aims to procure and distribute postharvest (drying and milling) units and on-farm machinery through a financing scheme, in which the government shoulders significant amount. In 2013, the country's self-sufficiency level reached 96.8% with the target of 100% but was not achieved owing to frequent typhoons and floods (Ponce and Inocencio, 2017).

The major challenge for the rice sector recently is the implementation of Rice Tariffication Law or Rice Liberalization Act (Republic Act No. 11203) that liberalizes the importation, exportation, and trading of rice; lifting the purpose of quantitative import restriction in rice. An expected influx of cheap rice imports is deemed consequence of the passage of this law, which would compromise the price of local rice. To make the Philippine rice competitive in the market, the Rice Competitiveness Enhancement Fund (RCEF) amounting to PhP 10 B annually was guaranteed by the law to be used for the promotion of high-quality seeds, procurement of farm machinery and equipment, training of agricultural workers and farmers, and expansion of credit. Under the RCEF-Seed Program led by DA-PhilRice, certified inbred seeds are given to qualified farmers for two consecutive planting seasons. Recently, over 236,000 farmers across the country received 1.2 M bags of certified seeds from the program (Biwang, 2020).

Rice production in the country is constantly challenged by land conversions, growing population, and climate change. Increasing farm productivity through increasing farmers' yield [1 t ha^{-1} for irrigated lowland and 0.5 t ha^{-1} for rainfed lowland (PhilRice, 2016)] is a promising option to improve rice production through breeding. The challenge now for rice breeders is to break the yield plateau through increasing the genetic gains in grain yield and other important traits. This could be achieved by exploring novel technologies and concepts in rice breeding. Transformation of rice breeding was proposed by IRRI breeders/scientists (Collard et al., 2019) to increase rate of genetic gain for yield and to improve effectiveness and efficiency of breeding operations. The proposed changes will include rapid generation advance, earlier multi-location trials, increased selection pressure for yield, intensify use of molecular breeding, and use of variety product profile (Collard et al., 2019). Furthermore, it was suggested that breeding operations should be streamlined to make breeding like a "factory line" (Collard et al., 2019). Another proposed concept is the application of Genomic Selection (GS), which will enable the efficient handling and selection of large breeding materials that will eventually save time and labor (Meuwissen et al., 2001). GS is a novel alternative to traditional marker-aided selection (MAS) in quantitative traits such as grain yield (Hickey et al., 2017) by combining whole-genome molecular markers and phenotype in a training population to predict genetic values of future individuals in a test population for selection (Desta and Ortiz, 2014). DA-PhilRice, being the lead agency in rice research in the country, has initiated efforts in the conservation, development, improvement, and utilization of appropriate rice varieties for various rice ecosystems towards sustainable, profitable, and competitive farming. It combines different breeding strategies such as integrated management technologies, marker-assisted selection (MAS), classical hybridization and biotechnology, in-vitro culture and mutagenesis, and root plasticity development among other approaches to generate and develop improved breeding lines catered to target ecosystems (Palanog et al., 2020). Recently, DA-PhilRice released the first two heat-tolerant varieties in the country (NSIC, 2020) that could address problems in heat-prone rice areas.

Promising strategies are available to strengthen rice breeding in the country. However, the challenge is to make them suitable to the current breeding platform and to generate source of fund for the implementation.

Literature Cited

Adesina AA, Zinnah NM (1993) Technology characteristics, farmers' perception and adoption decisions: A tobit model application in sierra leone. Agric. Econ **9**: 297-311

Altoveros N, Borromeo TH (2007) The state of plant genetic resources for food and agriculture in the philippines (1997-2006): A country report. Department of Agriculture-Bureau of Plant Industry

Balisacan AM, Ravago MJV (2003) The rice problem in the Philippines: Trends, constraints, and policy imperatives. Presented at the 25th annual scientific meeting of the National Academy of Science and Technology, Manila, July 10, 2003

Biwang A Jr. (2020) Million bags of rcef seeds benefitted marginalized rice farmers. Retrieved from https://www.philrice.gov.ph/million-bags-of-rcef-seeds-benefitted-marginalized-rice-farmers/ (accessed January 4, 2021)

Bordey FH (2011) The impacts of research on Philippine rice production. Retrieved from https://www.researchgate.net/publication/43939636_The_impacts_of_research_on_Philippine_rice_production (accessed January 6, 2021)

Brown EO, Ebora RV, Decena FLC (2018) The current state, challenges, and plans for philippine agriculture. FFTC Agricultural Policy Platform. 59th Meeting of NPOs, Yogyarta, Indonesia

BSWM [Bureau of Soils and Water Management] (2001). Agro-ecological Zone Map of the Philippines. Philippines: BSWM

Collard BCY, Gregorio GB, Thompson MG, Islam Md, Vergara GV, Laborte AG, Nissila E, Kretzschmar T, and Cobb JN (2019) Transforming rice breeding: Redesigning the irrigated breeding pipeline at International Rice Research Institute (IRRI). Crop breeding, Genetics, and Genomics **1**: e190008

DA-ATI [Department of Agriculture - Agricultural Training Institute] (2020) Rice Competitiveness Enhancement Fund (RCEF). Retrieved from https://ati.da.gov.ph/ati-main/PROGRAMS/RCEF (accessed January 5, 2021)

David CC, Balisacan A (1995) Philippine rice supply demand: Prospects and policy implications. Makati City, Philippines: Philippine Institute for Development Studies

Desta ZA, Ortiz R (2014) Genomic prediction in CIMMYT maize and wheat breeding programs. Trends Plant Sci **19**: 592-601

Estudillo J, Otsuka K (2006) Lessons from three decades of green revolution in the Philippines. Dev Econ **44**: 123-48

Feder G, and Umali DL (1993) The adoption of agricultural innovations: A review. Technology Forecast Soc Change **43**: 215-39

Francisco SR, Mataia AB, Libetario EM, Oliveres, IV (2010) Sources of rice productivity growth in Region VI, Paper Presented to DA-RFU VI Regional Rice Planning Workshop, Iloilo Grand Hotel, Iloilo City, June 8-10, 2011

Herdt RW, Capule C (1983) Adoption, spread, and production impact of modern rice varieties in Asia. 1st Edition. Philippines: International Rice Research Institute

Hickey JM, Chiurugwi T, Mackay I, Powell W (2017) Implementing genomic selection in CBPWP. Genomic selection unifies animal and plant breeding programs to form platforms for biological discovery. Nature Genetics **49**: 1297-1303

Hilario F, De Guzman R, Ortega D, Hayman P, Alexander B (2009) El Niño southern oscillation in the Philippines: Impacts, forecasts, and risk management. Philippine Journal of Development **36**(1): 9-34

Huke RE, Duncan J (1969) Spatial aspects of HYV diffusion. Seminar on Economics of Rice Production in the Philippines. International Rice Research Institute

Laborte AG, Paguirigan NC, Moya PF, Nelson A, Sparks AH, Gregorio GB (2015) Farmers' preference for rice traits: Insights from farm surveys in Central Luzon, Philippines, 1966-2012. PLoS ONE **10**(8): e0136562

Lantican RM (2001) The science and practice of crop production. Philippines: SEAMEO, SEARCA, and UPLB

Launio CC, Redondo GO, Beltran JC, Morroka Y (2008) Adoption and spatial diversity of later generation of modern rice varieties in the Philippines. Agronomy Journal **100**(5): 1380-89

Lopos BE (2007) Agricultural extension service delivery in the Philippines: The case of Nueva Viscaya. CLRG-CIE-ACIAR. Philippines: University of the Philippines-Diliman

Mariano M, Villano R, Fleming E (2012) Factors influencing farmers' adoption of modern rice technologies and good management practices in the Philippines. Agricultural Systems (110): 41-53

Maclean JL, Dawe DC, Hardy B, Hettel GP (2002) Rice almanac: Source book for the most important economic activity on earth (3rd ed). UK: CABI Publishing

Mataia AM, Jamora N, Moya P, Francisco SR, Dawe D (2011) Sources of decade rice yield growth in the Philippines. Crop Protection Newsletter **36**: 20-29

Meuwissen THE, Hayes BJ, Goddard ME (2001) Prediction of total genetic value using genome-wide dense marker maps. Genetics **157**: 1819-29

NSIC [National Seed Industry Council] (2020). Quirino Avenue, Malate, Manila, Philippines. Registered Crop Varieties: Rice (*Oryza sativa*)

Palanog AD, Mondejar CLC, Bello GE, Calayugan MIC, Palanog MO, Caguiat XGI, Ferrer MC, Sta. Ines LT (2020) Rice breeding strategies in the Philippines. Journal of Scientific Agriculture **4**: 21-27

Peng S, Khush G (2003) Four Decades of Breeding for Varietal Improvement in Irrigated Lowland Rice in the International Rice Research Institute. Plant Production Science **6**(3): 157-64

PSA [Philippine Statistics Authority] (2016) Food and consumption nutrition. Agricultural indicator system. Philippines: Quezon City

PSA [Philippine Statistics Authority] (2018) Selected statistics in agriculture 2018. Philippines: Quezon City

PSA [Philippine Statistics Authority] (2020) Palay production in the Philippines. Philippines: Quezon City

PhilRice [Philippine Rice Research Institute] (2016) Roadmap for impact: The PhilRice strategic plan, 2017-2022. Philippines: PhilRice

Ponce ER, Inocencio AB (2017) Toward a more resilient and competitive Philippine rice industry: Lessons from the past three decades. 106. Retrieved from http://books.irri.org/2017-March-Rice-Report-Lessons-from-the-past-3-decades.pdf (accessed January 5, 2021)

Ricepedia (2013) Philippines. Retrieved from http://ricepedia.org/philippines (accessed January 6, 2021)

Tobias, M (2018) The Philippine rice tariffication law: Implications and issues. FFTC Agricultural policy platform (FFTC-AP). Retrieved from https://ap.fftc.org.tw/article/1372 (accessed January 06, 2021)

FULL PAPER

CUSTOMIZING AN OVERHEAD SPRINKLER IRRIGATION SYSTEM FOR AEROBIC RICE PRODUCTION

Alaissa T. Remocal, Kristine Samoy-Pascual*, and Ricardo F. Orge

Philippine Rice Research Institute, Science City of Muñoz, Nueva Ecija, Philippines
*Corresponding Author: kcsamoy@gmail.com

Abstract

The use of a sprinkler irrigation system (SIS) in aerobic rice is still new in the Philippines due to its high cost of acquisition. Hence, this study aimed to develop an affordable and custom-made system for aerobic rice application. The SIS prototype made use of a commercially available rotor sprinkler head and a fabricated collapsible frame, modified nozzle, and retro-fittings. The system was designed to cover an area of at least 0.25 ha (2500 m^2) in one setting to reduce operation cost. Laboratory performance test results showed that a 20-mm nozzle diameter had a maximum throw radius of 28.7 m, maximum wetted area of 2857 m^2, and maximum operating pressure of 267 kPa. Under field condition, the average uniformity coefficient (C_u) varied from 28 to 91% due to the effects of wind speed and operating pressure. In terms of grain yields, the flush flooding as farmer's practice (FP) did not significantly differ with sprinkler irrigation. The water use of the sprinkler was significantly lower by 59% than FP while water productivity was recorded at 0.90 kg m^{-3}. In general, this study underscored the potential use of an SIS in aerobic rice to improve water productivity. However, further study is needed to improve the system's water uniformity distribution to prevent possible localized drought stress during crop growth.

Keywords: *Drought, Flush Flooding, Grain Yield, Uniformity Coefficient, Water Productivity, Water Use.*

Introduction

Rice is the primary staple of more than half of the world's population with Asia representing the largest producing and consuming region (Redfern et al., 2012). Although rice is produced in vast areas of the world, the physical requirements for rice cultivation are limited to certain zones. In certain areas, rice requires high average temperatures during the growing season, abundant water applied in a timely manner, good drainage, and a subsoil stratum that inhibits the percolation of water (FAO, 2014). In most cases, water availability largely determines the yield potential of rice but complemented with nutrient, weed, and pest management. Rice grown conventionally under irrigated condition consumes water that is 2 - 4 times more than other cereal crops like corn and wheat (Shaobing et al., 2006). With the increasing demand for food and threat of water scarcity due to rapid increase of population and competing water demands for domestic, agriculture, and industrial use, there is a need to explore alternative methods of growing rice with less water. In the Philippines, water scarcity for irrigation is also worsened by the declining water supply associated with degradation of watersheds (Rola et al., 2015). Thus, shifting from the conventional practice of growing rice under continuously flooding condition to being partly or even completely aerobic field condition is necessary (Tuong and Bouman, 2003).

A system called 'aerobic rice' was developed, in which rice is grown in non-puddled and non-saturated soil like an upland crop (Bouman et al., 2007). The target environments for aerobic rice are irrigated lowlands with water shortage and favorable uplands with access to supplementary irrigation (Belder et al., 2005a). Aerobic rice production offers some advantages in terms of addressing issues on water scarcity. It uses less than 50% of the irrigation water required by conventional flooded rice (Bouman et al., 2007). Flush flooding or applying minimal water just to keep the soil wet is the most common irrigation method in aerobic rice production (Belder et al., 2005b). Another irrigation method is through use of sprinkler. In other countries like Brazil, sprinkler irrigation is already being practiced for aerobic rice production (Castañeda et al., 2004). However, in the Philippines, the potential use and application of modern irrigation systems like sprinkler irrigation has not been fully explored for aerobic rice cultivation due to high cost.

ATRemocal and KSPascual contributed equally in the writing of manuscript

Sprinkler irrigation simulates natural rainfall by spreading water in the form of rain uniformly over the land surface when needed at required quantity in a well-distributed pattern (Zakari et al., 2012). Irrigating field with sprinklers enables economical water usage through control over uniformity of application and its rate. In support to the advocacy of the Philippine-Department of Agriculture in advancing agricultural technology under the Fourth Industrial Revolution or Industry 4.0 (Dar, 2019), the use of micro and sprinkler irrigation to improve water use efficiency and water productivity of rice is explored. The Agriculture 4.0 focuses not only on the uniform application of water and fertilizers in an entire field but on the minimum required quantities of resources to be used in a very specific area (De Clercq et al., 2018).

In general, sprinkler irrigation systems are custom-designed to fit the requirement of the target crops or farms. Most of the systems' components like sprinkler heads and accessories needed to complete the whole system are already available in the market. In the Philippines, these systems are commonly used in high-value crops but are quite expensive as these are equipped with imported and sophisticated components. Therefore, this study was conducted to: 1) develop a prototype of a low-cost sprinkler irrigation system suited for aerobic rice that maximizes the use of components, which most farmers already have such as the engine-driven irrigation pumps and hoses, and can irrigate an area of at least 2500 m^2 in one setting; 2) evaluate the performance of the prototype sprinkler irrigation system in terms of water uniformity distribution; and 3) test the prototype and its effect on grain yield, water use, and water productivity of rice under field condition.

Materials and Methods

Description of the Sprinkler Irrigation System

The sprinkler irrigation system developed in this study is composed of three main assemblies, which include the water pump assembly, water delivery assembly, and sprinkler head assembly, which are designed to be portable and transportable using a hand tractor-pulled trailer. When in operation, all these assemblies are established on site and connected to each other. The water pump assembly can be stationed near the water source (wells, rivers, lakes) and pumps water to the sprinkler assembly, passing through the water delivery assembly.

The development of the system maximizes the use of existing irrigation pumps and accessories, which most farmers usually have, and standard parts that are commercially available. Unavailable parts in the market were designed and fabricated to complete the prototype sprinkler irrigation system. For the water pump and water delivery assembly, the prototype was built with existing engine-driven centrifugal pumps and PVC hose and fittings used by farmers in irrigating their crops (Figure 1).

For the sprinkler head assembly, a commercially available impact-type rain gun sprinkler head with a specified throw radius of 20 - 33 m, operating pressure of 206 - 482 kPa, and a trajectory angle of 23° was used. To provide support for the sprinkler head's installation in the field, an attachment using a 50 mm (2-in) diameter galvanized iron (GI) pipe and fittings was fabricated, which was supported by a collapsible tripod made of 25 mm (1 in.) GI pipe and flat bar (Figure 2). The height of the sprinkler head assembly

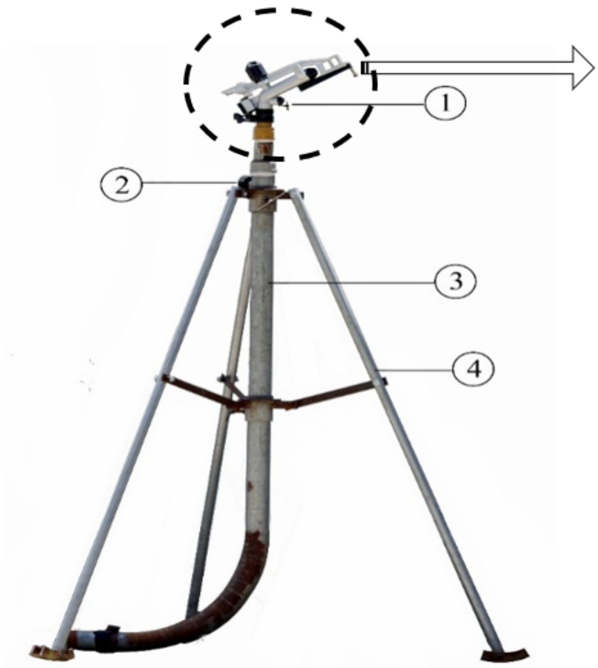
Figure 1. A typical irrigation pump (left) and low-density polyethylene pipe (right) commonly used by farmers in irrigating fields.

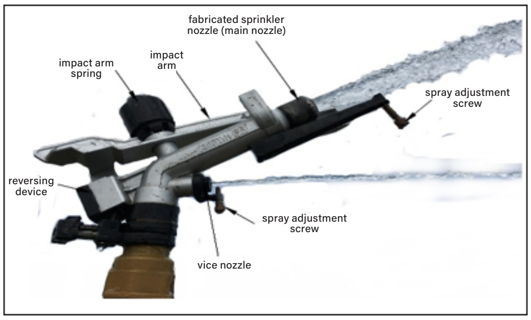
was fixed at 1.5 m, slightly higher than the height of most rice varieties ranging from 1 to 1.4 m at maturity (IRRI, 2015). The whole assembly weighs 17 kg, which can be established in the field by 1 - 2 persons.

The prototype sprinkler irrigation system was designed to irrigate at least 2,500 m^2 farm area in one setting. It was also generated in such a way that the sprinkler assembly can be moved from one location to another to reduce the cost of having many sprinklers with overlapping pattern of water distribution.

Laboratory Test

Laboratory tests were done prior to the field experiments to verify if all system components are functioning well. This test was conducted to verify the actual throw radius and operating pressure of the acquired sprinkler head using different nozzle sizes provided by the manufacturer. Tests also determined the appropriate size of nozzle that can cover an area of not less than 2,500 m^2 in one setting. A 50-m measuring tape was used to measure the distance of the throw radius and a built-in dial-type pressure gauge for the operating pressure. Initial test was conducted using the manufacturer-supplied 8-mm and 14-mm nozzles of the sprinkler head. However, the throw radius fell short of the design requirement; thus, additional nozzles (16 and 20 mm) were fabricated using GI couplings (Figure 3), following the same threaded connection as that of the manufacturer-supplied nozzles. For the water delivery assembly, a flat-hose made up of polyvinyl chloride (PVC) and a low-density polyethylene (LDPE) pipe were tested to determine the suitable material that can withstand the sprinkler's operating pressure using either a 3.7





No.	Parts
1	Sprinkler head (Impact rain gun)
2	Pressure gauge
3	Bent 50 mm (2-in) diameter GI pipe nipple with end fittings to accommodate sprinkler head and pressure gage at the top and hose at the bottom
4	Collapsible Frame

Figure 2. The impact rain gun sprinkler assembly.

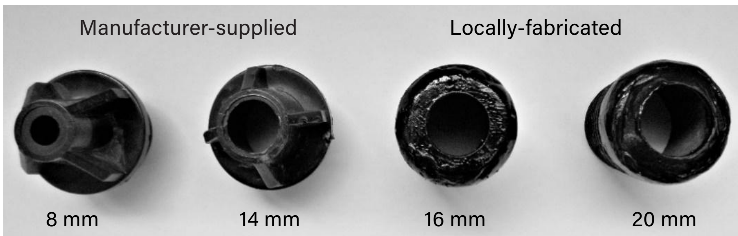


Figure 3. Different sprinkler nozzle sizes were tested.

kw (5 hp) or 4.8 kW (6.5 hp) engine. The testing was conducted in a vacant field without crops near a shallow tube well as irrigation source.

Field Experiment

A field experiment was conducted to evaluate the performance of the prototype SIS when used in aerobic rice production, particularly its effect on the agronomic performance of the rice crop, water use, and water productivity. The use of the prototype SIS and farmers' practice of flush flooding was also compared.

The experiment was conducted in an experimental farm at the Central Experiment Station of Philippine Rice Research Institute of the Department of Agriculture (DA-PhilRice) (15°40'07.7"N 120°53'28.4"E) in Science City of Muñoz, Nueva Ecija from December 2019 to April 2020. The climate in Muñoz is Type 1 based on Corona Classification (PIDS, 2005) with pronounced dry and wet season. Dry season starts from November to April while the rest of the year experiences wet season. Monthly average minimum temperature during the field experiment was at 22.1°C, maximum temperature at 31.8°C. The average solar radiation was 18.4 MJ m^{-2}, with relative humidity of 76.5% and wind speed of 2.3 m s^{-1}. The rainfall was almost negligible at 21.8 mm. The soil texture of the area was sandy clay loam with 27.2% sand, 20.3% silt, and 52.5% clay. For practical implementation of the experiment using the sprinkler, one experimental block covering 1600 m^2 area was used, while the farmers' practice of flush flooded was conducted in another block with three 6 m^2 x 5 m^2. In sprinkler irrigation, water runs at a pre-determined time at 6 hours when the reading of the tensiometer dropped to "wet" indicator (0-5 kPa) while in flush flooding, field is streamed with up to 3 cm water depth every irrigation (Dasberg et al., 1999).

Crop Management

The field was prepared dry using 4-wheel tractor with attached rotavator. Paddy seeds of NSIC Rc 222 were sown using a mechanized seeder (Bautista et al., 2019) at 1-2 seeds per hill and 20-cm row spacing on December 16, 2019. At three days after sowing (DAS), the field was irrigated up to 3 cm to promote seed germination. A total of 120 kg ha^{-1} of nitrogen (N) fertilizer was applied in three equal splits: first application at 10 DAS, second application during mid-tillering, and top dress during early panicle initiation. However, at sprinkler plot, additional 32 N kg ha^{-1} was applied based on leaf color chart or LCC (PhilRice, 2007) as the leaves turned pale green at 66 DAS. In both treatments, phosphorus and potassium were applied each at a rate of 40 kg ha^{-1} at 10 DAS. Pre-emergence herbicide was applied during 6 DAS and post emergence at 2 and 11 DAS in both treatments.

Data Gathering and Measurements

Uniformity Coefficient

To measure the water uniformity distribution of the sprinkler irrigation system, 15 circular plastic containers in 11 cm diameter were randomly placed around the sprinkler to collect water discharge. The volume of water collected from the catch container was determined using direct volumetric measurements (Ella et al., 2009). Due to the lightweight of the container, each was attached to a 65-cm high with 2.5-cm width bamboo stick installed on the soil. Nine trials for the measurements were conducted during the actual time of irrigation. The Christiansen's uniformity coefficient (C_u) was used as an index for water uniformity and was expressed as percentage using the formula in Equation 1 (Christiansen, 1942).

$$C_u = 100\, x \left[1 - \frac{\sum_{i=1}^{n} \left|V_i - \underline{V}\right|}{\sum_{i=1}^{n} V_i}\right] \quad (1)$$

Where,

V_i = individual catch can measurement, ml

= average application volume of overall catch can measurements, ml

For rotor and impact head sprinklers, 70% is the acceptable minimal performance to be categorized as "very good" (Mecham, 2004).

Crop and Water Parameters

Soil tensiometers were installed 15 cm below the soil surface for each replicate plot in farmers' practice and in four spots in sprinkler irrigated area. Treatment plots were irrigated whenever the soil water tension reading reached 30 kPa during vegetative period (Bouman et al., 2007), 20 kPa during panicle initiation, and 10 kPa during flowering to avoid possible spikelet sterility (Shaobing et al., 2006). Ten plants in a 1 m x 1 m sampling area were tagged for the plant height measurement at 10, 30, 45, and 60 DAS. At maturity, crop cut was gathered from 10 rows measuring 2.5 m (~5 m^2), each a replicate plot of farmer's practice, and three randomly selected spots in the sprinkler irrigated area. The samples were threshed, cleaned, dried, and weighed. The moisture content of the grains was measured using a digital moisture meter (GMK 303 RS, Korea) while the grain yield was computed based on 14% moisture content. In addition, two linear positions at 0.5 m each in the plot were also selected to determine yield components. Panicle number of each plant was counted to determine the panicle number m^{-2}. Plants were also separated into straw and panicles. Panicles were hand-threshed while filled spikelet were separated from the unfilled. Spikelet per panicle, percent filled grain, and 1,000-grain weight were determined. The irrigation water input was measured using a pre-calibrated flow meter for the sprinkler irrigation system (installed at the pump discharge outlet and coupled to the hose assembly), while a volumetric method was used in flush flooding. The total water input was computed as the sum of the irrigation and rainfall. Water productivity was determined as the ratio of the grain yield over the total water use. Rainfall and other climatic data were obtained from the agrometeorological station located at PhilRice.

Partial Cost Analysis

A partial costing was used to compare the irrigation cost between SIS and flush flooding, considering the targeted area of 2,500 m^2. Irrigation costs included material, labor, and fuel costs. The projected life span of the materials under sprinkler irrigation system is five years, while three years for the PE hose under flush flooding. The cost of the engine-pump set was not considered in the calculation assuming that the farmers already have the materials. Engine-pump was not also modified as the objective of this study was only to improve the traditional practice of flush flooding. The labor cost was estimated by multiplying the number of persons to install and irrigate the area by the prevailing cost of labor per season. The fuel cost was determined as the product of the total fuel consumption and the prevailing price of gasoline. The interest on investment and repair and maintenance were computed as 12 and 10% of the total material cost, respectively (FAO, 1992). The cost of irrigation per m^2 was determined as the ratio of the total irrigation cost and the area irrigated.

Statistical Analysis

The data were analyzed using an open source software Statistical Tool for Agricultural Research, which is implemented in R statistical package (IRRI, 2013). Independent t-test was used to analyze comparison of means of grain yields, water productivity, and other crop growth parameters between sprinkler and flush flooding treatments. Descriptive analysis was used to compare the water use between sprinkler and flush flooding. This was measured because the sprinkler was evaluated in a large area without replication. Laboratory test results were also analyzed descriptively because wind speed and operating pressure during testing cannot be duplicated and were uncontrollable.

Results and Discussion

Sprinkler Irrigation Performance

One of the major challenges addressed during the test trials was the occurrence of leaks at the hose connections, which significantly reduced the operating pressure of the system and resulted in low throw radius for the same nozzle size (Table 1). Initially, the system duplicated the farmers' practice on preventing these leaks; however, it did not work at high pressure. In this study, the recorded operating pressure varied from 55 to 267 kPa. Zoldoske (2007) reported that at low pressure, the rotational speed of the sprinkler is affected and high pressure may damage the sprinkler. Previous study reported that the use of a pressure regulator overcomes fluctuating pressure on the sprinkler pressure during irrigation (Darko et al., 2017). To address the observed leaks, a commercially available 50 mm (2-in) PE female threaded adapter was retrofitted, which made the connections easier compared with clamps and rubber ropes commonly used by farmers. This modification of the sprinkler irrigation system eliminated leakages. The installation and connections of the whole system due to retro-fitted adapter, collapsible frame, and lightweight PE hose were made easy while giving better mobility during irrigation.

Changing the nozzle size from 8 to 16 mm increased the throw radius by 144% but still fell short to the targeted wetted area of not less than 2500 m^2 (Table 1). PVC lay flat hose was used in all trials. The repetitive rolling and unrolling of the hose, even with hose reel, slowly developed several folds and was eventually damaged with continuous use. PVCs easily deteriorate from UV-radiation when exposed for long periods and turn brittle (Stuyt et. al., 2005). The lay flat hose was also punctured over time. To address the problem, the PVC was replaced by a LDPE hose. The LDPE material is lightweight and flexible similar to PVC hose but more durable and was reportedly used with sprinkler laterals (Stryker, 1997. LDPE pipes can be connected perfectly to the SIS assembly using PE adapter. This would prevent leaks and can be moved comfortably from place to place and can be easily connected by hand. Using a 20-mm nozzle, the maximum throw radius was 28.7 m covering a wetted area of 2,857 m^2, slightly higher than the design criteria of 2,500 m^2. Large nozzle maximizes the wetted diameter and minimizes wind distortion (Darko et al., 2017) while throw radius of a sprinkler irrigation increased with operating pressure (Osman et al., 2014).

Table 1. Nozzle size, throw radius, and wetted area of the sprinkler irrigation system tested in laboratory set-up.

Trial	Nozzle Size (mm)	Throw Radius (m)	Wetted Area (m^2)
1	8	7.0	153.94
2	8	15.0	706.86
3	14	2.7	22.90
4	14	7.0	153.94
5	14	12.1	459.96
6	16	17.1	918.64
7	20	20.5	1320.26
8	20	20.5	1320.26
9	20	20.2	1281.90
10	20	28.7	2587.71

During crop growth, the C_u of the sprinkler irrigation system varied from 28 to 91% across trials (Figure 4) with an average value of 57%, which was below the minimum acceptable C_u value of 70% for rotor and impact head sprinklers (Mecham, 2004). The large variation of the C_u could be attributed to the large variation of wind speed varying from 0.45 to 3.78 m s^{-1}. These values are within the category of low to moderate wind speed condition as described by Solomon (1990). Wind problem can be managed by choosing the right time of the day to operate the sprinkler, possibly at dawn when the environment is relatively calm. The authors also considered adjusting the spacing (relative to the previous location) to improve the performance of the sprinkler irrigation system as affected by wind condition. At low wind condition, the recommended spacing was 60 - 65% of the wetted diameter (Solomon, 1990). Water pressure also varied from 117 to 165 kPa while the throw radius ranged 13 - 16 m. Although Osman et al. (2015), reported that factors such as wind speed, size and type of nozzle, riser height, operating pressure, and sprinkler spacing influence the water uniformity distribution. The low C_u recorded in this study was also due to the absence of overlapping pattern of water distribution during the measurements. According to Mateos (1998), the overlapping patterns of single sprinklers working simultaneously along a lateral produce the water distribution over the whole field. However, it is noteworthy to mention that in this study, the original concept of the system design was a mobile unit to operate from one spot to another without using several sprinklers operating simultaneously in a large area to reduce cost. According to Solomon (1979), uniformity test results exhibit considerable variability and some factors are not controlled, or even measured. This study hypothesized that even with the low C_u, areas receiving less water can be corrected by transferring the sprinkler to another spot, eventually re-creating the overlapping pattern of water distribution in actual condition. Darko et al. (2016) also said that C_u itself is not a measure of how well a system distributes water within the root zone.

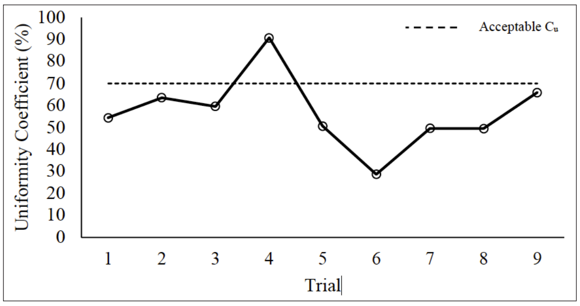


Figure 4. Uniformity coefficient of the sprinkler irrigation system in actual field condition.

Looking at different perspective, the amount of water applied in various areas relative to the location of the sprinkler head assembly did not vary significantly, except for sites within the 6 m radius, which is the nearest from the SIS (Figure 5). This can be solved through adjusting the secondary nozzle of the sprinkler, which discharges water in smaller radius.

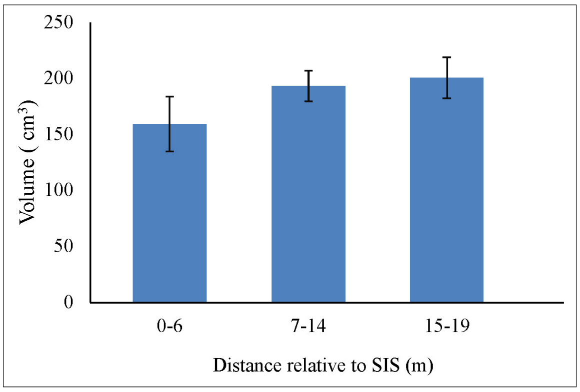


Figure 5. Average volume of water collected at different distance relative to the SIS assembly. The error bar is the standard error of the means.

Agronomic Performance and Water Productivity

Table 2 shows the effect of flush flooding and sprinkler irrigation method on plant height. There were no significant differences on the plant height at 10, 30, and 45 DAS. At 60 DAS, plant height was significantly ($P < 0.05$) higher under flush flooding than sprinkler irrigation. The result coincided with the study of Pinto et al. (2020) that plant height was reduced under sprinkler irrigation in aerobic rice and under increasing soil moisture tension from 10 to 40 kPa. In this study, the actual soil moisture tension reached a maximum of 35 kPa depending on the growth stages of the rice plant. During flowering stage, 10 kPa was maintained to prevent spikelet sterility (Figure 6). Hence, any possible drought stress during the field experiment was minimized especially in the flowering stage. Even with the plausibility of localized drying in the vegetative stage, Yoshida (1981) reported that stunted or delayed growth due to drought during the vegetative stage may not necessarily bring negative effects on grain yield if rice plants are re-watered and recovered before the flowering stage. Previous report also showed that soil water tension of 10 kPa is adequate for sprinkler irrigation in aerobic rice, especially during the reproductive period (Pinto et al., 2020). Thus, the reduced plant height observed under sprinkler at 60 DAS could be the effect of low N applied based on the LCC monitoring at 66 DAS, which was immediately corrected by applying N fertilizer. In terms of grain yield, there were no significant differences between plots irrigated with sprinkler and flush flooding; although, grain yields under flush flooding were higher by 18% than sprinkler irrigation (Table 3). The trend was similar to a previous report, which showed that flooding resulted in slightly higher yield than sprinkler irrigation (Pinto et al., 2020). In terms of yield components, there were no significant differences between treatments except for the percent filled spikelet, in which higher values were recorded from the sprinkler irrigation than flush flooding (Table 3). However, in the study of Shaobing et al. (2006), spikelet m^{-2} contributed more to the yield gap between aerobic and flooded rice than percent filled spikelet and 1000-grain weight. In this study, the yield gap between aerobic rice and flush flooding was within the range of reported values by Shaobing et al. (2006), which compared grain yields in aerobic and flooded rice for eight seasons.

Table 2. Plant height at different sampling days between sprinkler and flush flooding, 2020 DS.

Days After Seeding	Sprinkler Irrigation System	Flush Flooding	p-value
10	4.07^a	6.00^a	0.1066
30	17.73^a	18.80^a	0.4226
45	26.80^a	28.08^a	0.4148
60	46.67^b	56.87^a	0.0060

Means in the same row followed by the same letter are not significantly different according to t-test (P < 0.05)

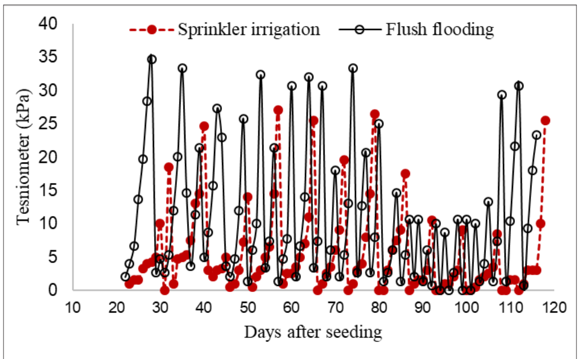


Figure 6. Average soil moisture tensions between sprinkler and flush flooding, 2020 DS. The broken line shows the 10 kPa reading from the tensiometer.

Table 3. Yield components of aerobic rice under sprinkler and flush flooding irrigation, 2020 DS.

Parameters	Sprinkler Irrigation	Flush Flooding	p-value
Grain yield (kg ha^{-1})	4760.55^a	5835.93^a	0.0927
Number of tillers m^{-2}	443^a	447^a	0.9503
Number of panicle m^{-2}	393^a	389^a	0.9523
Number of spikelet/panicle	73^a	60^a	0.2240
Percent filled spikelet (%)	77.42^a	70.82^b	0.0491
1000-grain weight, g	20.90^a	19.30^a	0.0864

Means in the same row followed by the same letter are not significantly different according to t-test (P < 0.05)

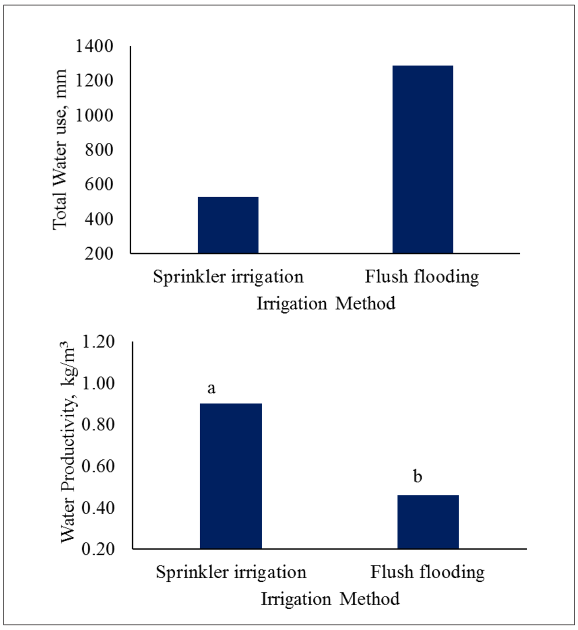


Figure 7. Total water uses and water productivity between sprinkler irrigation and flush flooding. Means followed by the same letter are not significantly different based on t-test (P < 0.05).

The total water use of the sprinkler irrigation was lower by 59% than flush flooding. As expected, water productivity of the sprinkler irrigation was significantly higher by 90% than flush flooding due to lower total water use (Figure 7).

Irrigation Cost

Evaluating the potential of the system while at the prototype stage can be done by comparing its irrigation cost with the farmers' practice. This will help in deciding to further pursue its development. The material cost of the sprinkler system accounted 60% of the total cost of irrigation (Table 4). However, with the projected useful life of five years for the sprinkler system with no salvage value, the annual total cost of irrigation was lowered by PhP 3,412.04 relative to flush flooding. Lower fuel cost for pumping water contributed to the reduced irrigation cost under sprinkler as less water was used in the targeted service area of 2,500 m^2. The average total cost of fuel under sprinkler was 57% lower than flush flooding. The projected irrigation cost per m^2 under sprinkler irrigation system was PhP 8.62 m^{-2} while PhP 9.98 m^{-2} under flush flooding.

Table 4. Irrigation cost for the sprinkler and flush flooding in aerobic rice, 2020 DS.

Cost	PhP	
	Sprinkler	Flush Flooding
Material cost (excluding water pump)	19,860.75	3,500
Average interest on investment	2,383.29	
Annual depreciation	3,972.15	1,166.67
Labor cost	5,250.00	5,250.00
Fuel cost	7,956.44	18,544.00
Repair and maintenance	1,986.75	
Total Cost for 0.25 ha	21,548.63	24,960.67
Total cost m^{-2}	**8.62**	**9.98**

Life span for sprinkler and accessories is five years; PE hose for flush flooding is three years.

Conclusion

Results indicated that the prototype SIS achieved the targeted service area of 2,500 m^2 when equipped with 20-mm diameter sprinkler nozzle. Factors such as wind speed and pressure affected system performance. The average uniformity coefficient of the sprinkler irrigation system varied largely and most of the values were below the published standard minimum C_u for impact rotor sprinkler. The difference in terms of grain yield was insignificant although flush flooding was higher by 18% than sprinkler irrigation. The water use under sprinkler was lower than flush flooding, which increased water productivity.

Recommendation

The first prototype of the sprinkler irrigation system is a potential alternative irrigation method to increase water productivity without significant yield loss in aerobic rice production. This alternative must be explored to address water shortage and to enable pump irrigation in favorable upland. However, the water uniformity distribution of the sprinkler must be improved to avoid possible localized drought stress during crop growth and to increase the water use efficiency of rice. Although irrigation cost per m^2 is projected to be lower using sprinkler than flush flooding, the economic advantage of aerobic rice production using sprinkler irrigation system must be validated. The SIS should also be equipped with a filtration system to prevent clogging the nozzle during irrigation. This has to be based on the used size of the sprinkler nozzle to minimize the pressure loss consequence. It is further recommended that more on-farm field-testing should be conducted to verify initial results and determine the application to other crops to maximize its use.

Acknowledgment

This study was funded by the Climate Resiliency for Enhanced Agricultural Trade and Efficiency for Rice (CRP-002) program of DA-PhilRice.

Literature Cited

Belder P, Spiertz JHJ, Bouman BAM, Lu G, Tuong TP (2005a). Nitrogen economy and water productivity of lowland rice under water-saving irrigation. Field Crops Res **93**:169-185

Belder P, Bouman BAM, Spiertz, JHJ, Peng S, Castaneda AR, Visperas RM (2005b) Crop performance, nitrogen, and water use in flooded and aerobic rice. Plant and soil **273**:167-182

Bautista EG, Gagelonia EC, Abon JE, Corales AM, Bueno CS, Banayo NP, Lugto RV, Suralta RR, Kato Y (2019) Development of hand tractor-mounted seed drill for rice-based cropping systems in the Philippines. Plant Prod. Sci **22**: 54-7

Bouman BAM, Humphreys E, Tuong TP, Barker R (2007) Rice and water. Adv. Agron. **92**: 187-237

Castañeda AR, Bouman BAM, Peng S, Visperas RM (2004) Testing of Aerobic rice in the Philippines: Results of field experimentation at IRRI. Philippine Agricultural Mechanization Bulletin **11**: 24-35

Christiansen JE (1942) Irrigation by sprinkling. California Agricultural Experiment Station Bulletin **670.** Retrieved from https://archive.org/details/irrigationbyspri670chri/page/n1/mode/2up (accessed December 18, 2020)

De Clercq M, Vats A, Biel A (2018). Agriculture 4.0: The future of farming technology. Retrieved from https://www.worldgovernmentsummit.org/api/publications/document?id=95df8ac4-e97c-6578-b2f8-ff0000a7ddb6 (accessed December 18, 2020)

Dar W (2019) Is PH agriculture ready for Industry 4.0? The Manila Times. Retrieved from https://www.manilatimes.net/2019/05/02/business/agribusiness/is-ph-agriculture-ready-for-industry-4-0-2/548248/ (accessed December 18, 2020)

Darko RO, Shouqi Y, Junping L, Haofang Y, Xingye Z (2017) Overview of advances in improving uniformity and water use efficiency of sprinkler irrigation. International Journal of Agricultural and Biological Engineering **10**: 1-5

Darko R O, Yuan S, Hong L, Lui J, Yan H (2016) Irrigation, a productive tool for food security - a review. Acta Agriculturae Scandinavica **66**: 191-206

Dasberg S, Or D (1999) Drip system design. *In* Drip Irrigation. Applied Agriculture (pp 70-99). Denmark: Springer-Verlag Berlin and Heidelberg Gmbh & Co. Kg

Ella VB, Reyes MR, Yoder R (2009). Effect of hydraulic head and slope on water distribution uniformity of a low-cost drip irrigation system. Applied Engineering in Agriculture **25**(3): 349-356.

FAO [Food and Agriculture Organization] (2014) FAO Statistical Yearbook 2014: Asia and the Pacific Food and Agriculture. Retrieved from http://www.fao.org/3/i3590e/i3590e.pdf (accessed December 18, 2020)

FAO [Food and Agriculture Organization] (1992) Cost control in forest harvesting and road construction. Paper 99. Retrieved from http://www.fao.org/3/T0579E/T0579E00.htm (accessed January 18, 2021)

IRRI [International Rice Research Institute] (2015) Rice Production Manual. Philippines: International Rice Research Institute, Los Baños, Laguna

IRRI [International Rice Research Institute] (2013) Statistical Tool for Agricultural Research. Plant Breeding Genetics and Biotechnology Biometrics and Breeding Informatics. Philippines: Los Baños, Laguna

Mateos L (1998) Assessing the whole field uniformity of stationary sprinkler irrigation system. Irrigation Science **18**: 73-81

Mecham B (2004) Using distribution uniformity to evaluate the quality of a sprinkler system. Northern Colorado Water Conservancy District, Berthoud, CO 80513. Retrieved from http://www.irrigationtoolbox.com/ReferenceDocuments/TechnicalPapers/IA/2004/IA04-1120.pdf (accessed November 15, 2020)

Osman M, Hassan SB, Yusof KB (2015) Effect of combination factors of operating pressure, nozzle diameter and riser height on sprinkler irrigation uniformity. Applied Mechanics and Materials **695**: 380-383

Osman M, Hassan SB, Yusof KW (2014) Effect of low pressure on irrigation uniformity of solid set sprinkler irrigation system. Applied Mechanics and Materials **567**: 26-31

PhilRice [Philippine Rice Research Institute] (2007) PalayCheck® system for irrigated lowland rice. Philippines: PhilRice

PIDS [Philippine Institute of Development Studies] (2005) Basics on Philippine climatology. Economic Issue of the Day **5**(2). Retrieved from https://dirp4.pids.gov.ph/ris/eid/pidseid0502.pdf (accessed December 18, 2020)

Pinto MA, Parfitt JM, Timm LC, Faria LC, Concenço G, Stumpf L, Nörenberg BG (2020) Sprinkler irrigation in lowland rice: Crop yield and its components as a function of water availability in different phenological phases. Field Crops Res **248**: 107714

Redfern S, Azzu N, Binamira JS, Meybeck A, Lankoski J, Gitz V (2012) Rice in Southeast Asia: Facing risks and vulnerabilities to respond to climate change. Retrieved from http://www.fao.org/3/i3084e/i3084e18.pdf (accessed December 18, 2020)

Rola AC, Pulhin JM, Tabios GQ, Lizada JC, Dayo, MH (2015) Challenges of water governance in the Philippines. Philippine J. Sci **144**(2): 197-208

Shaobing P, Bouman BAM, Visperas RM, Castaneda A, Lixiao N, Hong-Kyu P (2006) Comparison between aerobic and flooded rice: Agronomic performance in a long-term (8-season) experiment. Field Crops Res **96:** 252-259

Solomon K (1990). Sprinkler irrigation uniformity. Irrigation Notes. Retrieved from http://www.californiawater.org/californiawater/sprinkler-irrigation-uniformity-900803/ (accessed December 18, 2020)

Solomon K (1979) Variability of sprinkler coefficient of uniformity test results. Transactions of the ASAE **22**(5): 1078-1080

Stryker J (1997) Irrigation tutorials. General information about irrigation Systems. Retrieved from https://www.irrigationtutorials.com/sprinkler-system-lateral-pipes/ (accessed November 17, 2020)

Stuyt, LCPM, W. Dierickx, J. Martinez Beltrán (2005) Materials for subsurface land drainage. FAO Irrigation and Drainage Paper 60. Retrieved from http://www.fao.org/3/ah861e/ah861e.pdf (accessed December 18, 2020)

Tuong TP, Bouman BAM (2003) Rice production in water-scarce environments. Retrieved from https://publications.iwmi.org/pdf/H032635.pdf (accessed December 18, 2020)

Yoshida S (1981) Fundamentals of Rice Crop Science. Philippines: International Rice Research Institute, Los Baños

Zakari MD, Maina MM, Abubakar MS, Shanono NJ, Lawan I, Tadda MA, Nasidi NM (2012) Design, construction and installation of sprinkler irrigation system. Journal of Engineering and Technology **7**(2): 109-117

Zoldoske DF (2007) An overview of smart water application technologies™ (SWAT™) and achieving high water use efficiency. American Society of Agronomy: 111-119

FULL PAPER

UTILIZATION OF RICE STRAW AS FEEDSTOCK FOR THERMOCHEMICAL CONVERSION: EFFECTS OF AGE AND SIZE OF STRAW ON GASIFICATION PERFORMANCE

Paulino S. Ramos[1], Manuel Jose C. Regalado[1], and Arnold R. Elepaño[2]

[1]Philippine Rice Research Institute (PhilRice), Science City of Muñoz, Nueva Ecija,
[2]University of the Philippines Los Baños (UPLB), Laguna
*Corresponding Author: mjcregalado@philrice.gov.ph; psramos@philrice.gov.ph

Abstract

Rice straw is the main biomass resource available in rice fields. Its thermochemical conversion to energy is an attractive option because of its high energy content. This study determined the effects of age and size of rice straw on its gasification into producer gas fuel. Rice straw was produced at five-month interval per growing season and removed from field two months after crop harvest. Three straw ages at five months, two months, and new harvest were combined with 40 - 50, 30 - 40, and 20 - 30 mm straw lengths as independent factors in the gasification experiments. Results showed that rice straw age and size significantly affected straw heating value, gasification rate, and gasification efficiency. The most aged rice straw had higher heating value of 4.6 MJ kg^{-1} than the newly-harvested straw, which had 3.0 MJ kg^{-1}. The shortest straw size resulted in significantly higher heating value at 4.5 MJ kg^{-1} than the longest straw size at 3.0 MJ kg^{-1}. Moreover, as straw age increased and length became shorter, the production of CO and H_2 (combustible gases) increased. Therefore, rice straw is suitable as feedstock for gasification provided it is aged and reduced in size.

Keywords: *Biomass Utilization, Gasification, Heating Value, Producer Gas, Rice Straw.*

Introduction

In the Philippines, the major outcry in the industry and energy sectors is the ever-increasing cost and too much dependence on fossil fuel imports. Hence, the government is exploring alternative and renewable sources of energy such as solar, wind, hydro, and biomass. Biomass energy resources are derived from animals and plants, which can be converted into energy (Wise, 1983). Conversely, the call from the environmental side is the generation and utilization of huge amount of biomass from rice such as rice hull and rice straw. Rice straw is one of the main non-edible biomass resources in Asia including the Philippines (Ngo, 2011). The Philippine paddy rice production in 2018 was 19.07 M mt (PSA, 2019), which means that the rice straw production was 23.8 M mt based on the average rice grain: rice husk: rice straw ratio of 1.0:0.25:1.25 (Haefele et al., 2011).

Most of the time, rice straw is left on the fields and sometimes reincorporated in the soil, but a significant portion is considered a waste and occupies large areas of the fields, before its disposal through open-air burning or degradation. Mendoza (2015) stated that area-wise, crop residue burning still dominates the Philippine agriculture landscape and 76% of rice lands and 64% of sugarcane lands are still burned. Migo-Sumagang et al. (2020) noted that, in the Philippines, farmers turned to open-field burning to drive away pests and to avoid the labor-intensive, manual gathering of rice straw. Casiwan et al. (2015) conducted a survey of rice stubble and straw management practices covering the 2009-2010 crop year in four major rice-producing provinces, namely: (1) Nueva Ecija – top rice producer; (2) Leyte – representing the Visayas and a province with an existing provincial ordinance banning rice straw burning; (3) North Cotabato – largest rice producer in Mindanao; and (4) Ilocos Norte – representing a province where there is an existing rice straw market. They reported that 30% practiced open-field burning, 40% scattered and incorporated the straw into soil during land preparation, and the rest either left the straw in the threshing area to decompose or for feeding animals, or gathered and stacked it in one place for other purposes such as mulching for vegetable crops. They found that the most cost-effective option for farmers is to incorporate stubble and straw in the soil more than 30 days before crop establishment. They recommended looking for alternative uses of rice straw and finding ways to reduce the cost of collection and transportation of rice straw, coupled by the strict enforcement of laws banning rice straw burning. In Mekong Delta of Viet Nam, Nguyen et al. (2014) reported that 20 - 30% of the rice straw is left in the field after harvesting, 50 - 60% is burned in the field, 10% is used for mushroom cultivation, while the remaining straw is used for animal feed or other purposes. Rice straw left on the fields or burned in open fields creates pollution-related problems such as smoke and particle emissions due to incomplete combustion. It also produces emissions of greenhouse gases including methane and nitrous oxide due to anaerobic degradation (Ngo, 2011).

The purpose of using rice straw as fuel for energy production (direct heat or for electric production) is to reduce drastically the emissions of air pollutants from its open combustion as particulate matter (less than 10 micron and less than 2.5 micron), polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs), which are ~~as~~ dioxins and furans (Summers, 2001). These air pollutants have significant toxicological properties and are notably potential carcinogens. Air pollution not only affects human health and the environment, but also indirectly a country's economy (Gadde et al., 2009a).

There are other uses such as feed for animals, vegetables production, and organic fertilizers for very minimal percentage. However, conversion to energy is probably the most viable and attractive option because it has a high energy content like rice hull. One ton of rice straw is equivalent to around 360 L of diesel fuel or 408 L of gasoline (Braunbeck, 1994; Tiangco, 1990). Gadde et al. (2009b) estimated that the annual energy potential of rice straw produced in India, Thailand, and the Philippines, as a renewable fuel, is 312, 238, and 142 PJ, respectively, at 100% collection efficiency, assuming that all harvested straw was used for energy production. Nguyen et al. (2019) suggested that gathering rice straw for energy production is a possible solution that can bring financial benefit to farmers, reduce environmental footprint of rice farming, and prevent negative impacts of in-field burning.

For the recovery of energy from biomass, biochemical and thermochemical processes are used (Kirubakaran et al., 2009). Biochemical process involves bio-methanation or anaerobic fermentation of biomass, which produce biogas. Bio-methanation requires powdery and porous biomass with always greater than 60% moisture. In addition to biogas, the fermented biomass is very good manure for agricultural fields. Meanwhile, thermo-chemical processes include combustion, pyrolysis, and gasification. Combustion of biomass involves burning the biomass in air at a flow rate of 4 - 5 kg of air per kg of biomass. This process on small-scale is always used for thermal applications. A large-scale combustion plant with steam cycle is essential for power generation. Gasification is economical at all capacities from 5 kW electrical power onwards. As such, the production of energy from biomass through gasification prompts consistent interest among researchers (Kirubakaran et al., 2009).

Gasification is a thermal process that converts carbonaceous materials like biomass into useful gaseous fuels (Basu, 2010). It is the controlled combustion of biomass in a close compartment with limited amount of air brought on within the system. The resultant mixture of gases generated during the gasification process is called the producer gas. Producer gas is a mixture of combustible gases such as carbon monoxide, hydrogen, and methane, together with incombustible gases such as carbon dioxide and nitrogen (Balat et al., 2009). The gaseous products can be burned to generate heat or electricity, or they can potentially be used in the synthesis of liquid transportation fuels, hydrogen or chemicals. Depending on the carbon and hydrogen content of the biomass and the properties of the gasifier, the heating value of the producer gas ranges 4 - 20 $MJ{\cdot}m^{-3}$.

Studies on gasification of various biomass fuels were reported in the past. Payne et al. (1985) tested three sizes of wood chips in an updraft gasifier to measure the effect of wood chip size on operation and efficiency of the system while Coovattanachai (1987) conducted a developmental research. Hoki et al. (1992) reported a study on biomass gasifier to provide electricity for small scale industry. Singh et al. (1994) developed and tested a downdraft type paddy husk gasifier for on-farm electricity generation. Most rice biomass gasification studies were focused on rice husk gasification or gasifier design (Tiangco et al., 1996; Lin et al., 1998; Salam et al., 2010; Sivakumar and Mohan, 2010; Bautista et al., 2014; Belonio et al., 2018). Few researchers investigated rice straw gasification including Calvo et al. (2012) who assessed the behavior of the rice straw under fluidized-bed gasification and evaluated the effects of operation parameters to then evaluate the adequacy of the rice straw as a potential fuel in close-coupled boiler-gasifier reburn systems. In India, Kumar (2017) investigated the technical and economic aspects of off-grid and grid-connected small-scale electricity generation using rice straw gasification technology and found that a gasifier with an internal combustion engine designed to operate on 100% producer gas is the suitable option for installing a 250-kW grid connected power plant.

Hoer et al. (2016) enumerated problems that must be overcome in using rice straw as biomass fuel for gasification. One is that rice straw has high alkalinity, which creates problems with slagging in boilers; although the rice straw can be left in the fields for a longer period of time to allow for natural leaching of the alkaline compounds. Another problem with rice straw is its high silica content, resulting in high ash content that must be removed and disposed. The pretreatment of rice straw required for successful gasification is also often extensive. Generally, the rice straw must be dried to a moisture content less than 10 - 15%, chopped, and ground into fine particles or passed through a screen. Typically, the size requirements are between 20 and 80 mm (McKendry, 2002). The mode and time of collection, moisture content, and sizes are among the factors that affect the processing of rice straw. In consideration of these factors and despite its limitations as raw material, we postulated that rice straw, like rice hull, could still be used as a feedstock for thermochemical conversion through gasification into producer gas fuel, provided it is properly handled and processed. This study showed the technical feasibility of using rice straw as a biomass feedstock for thermochemical conversion into energy through gasification. Specifically, this study evaluated the effects of age and size of rice straw on gasification for the proper handling of this biomaterial as feedstock for a biomass gasifier.

Materials and Methods

Gasifier Assembly and Equipment

An updraft laboratory gasifier (batch type, single reactor, stationary) was used in this study (Figure 1). Air was supplied to the reactor or combustion chamber at controlled rate by a 6-V direct current computer fan. Combustible gases are generated from rice straw, which is burned inside the reactor and directly pass through the gas exhaust part.

Fuel Preparation

Three sets of rice straw fuel were used: newly-harvested rice straw in the 2014 wet season; 2-month old (2014 wet season), and 5-month old (2014 dry season). The 5-month-old rice straw was collected last season and stored in a shed. The rice straw samples were collected from the Central Experiment Station (CES) field of Philippine Rice Research Institute of the Department of Agriculture (DA-PhilRice). The test rice variety chosen for this experiment was NSIC Rc 222 as it is one of the most popular varieties for cultivation. The moisture contents of rice straw were measured using the biomass moisture meter and verified using oven method.

Size reduction of the rice straw was done using a biomass chopper (JHT Philippines) with the following specifications: capacity, 0.5 - 1.0 t h^{-1}; power requirement, 6.5 hp (4.8 kW) gasoline engine; fuel consumption, 0.8 - 1.5 L h^{-1}; machine weight, 75 kg; and labor requirement, 1 - 2 persons. Rice straw was fed into the chopper to reduce the size. One-pass chopping resulted in 40-50 mm length; two-pass, 30-40 mm; and three-pass, 20-30 mm. Length of the rice straw was measured using a digital caliper.

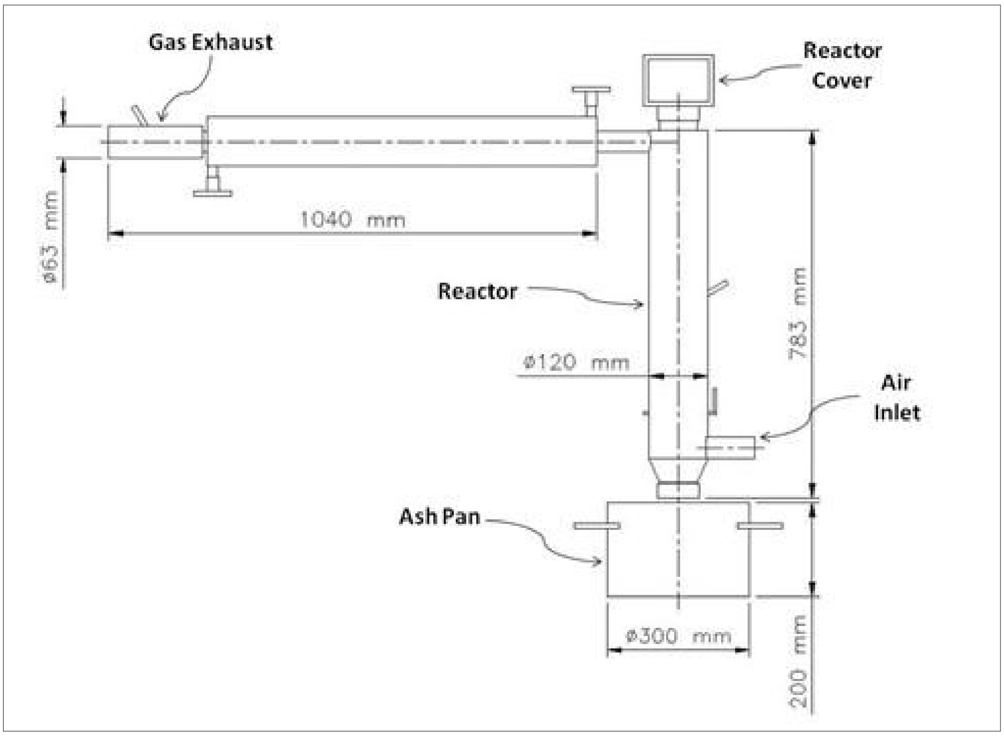


Figure 1. Schematic diagram of the laboratory updraft gasifier.

Parameters Measured During Experimentation

Appropriate measuring instruments were used during the experimentation. The following data were determined during the experiment:

Temperature

The system was fitted with K-type thermocouples for measuring the temperature of the reactor with a thermocouple placed at the middle of the reactor to monitor the temperature at the middle of gasification process. The temperature of the reactor was used as basis for the producer gas measurement. Another thermocouple was placed at the producer gas exhaust port to monitor the gas temperature (Extech. 4 channel Temperature Meter, Model SDL 200, Made in Taiwan).

Gas Flow Rate

A pitot tube manometer and anemometer (Extech, Model HD350, made in Taiwan) was used to take the measurement of the gas flow rate. It was measured at the exhaust and used for the calculation of gasification efficiency.

Producer Gas

Gas composition of the producer gas generated from the laboratory gasifier was determined using a portable gas analyzer (Gastec Pump, Model GV-100, made in Japan) with Gastec standard detector tube for the concentration of O_2, CO, CO_2, H_2, and HC. It was measured to calculate the heating value of the producer gas.

Test Parameters

Heating Value of the Producer Gas

Heating value of producer gas is a measure of the total energy content of the combustible gases present in the producer gas, which is represented by the following equation:

$$HV_{pg} = (H_{CO} * P_{CO}) + (H_h * P_h) \quad (1)$$

Where:

HV_{pg} = Heating value of the producer gas, MJ/kg

H_{co} = Heating value of CO, MJ kg^{-1}

P_{co} = Concentration of CO, %

H_h = Heating value of hydrogen, MJ kg^{-1}

P_h = Concentration of hydrogen, %

Capacity of the Gasifier

Gasification Rate (GR) was calculated using the weight of the rice straw gasified during a run, and the cross-sectional area of the reactor using the following relation:

$$\dot{GR} = \frac{Weight\ of\ the\ rice\ straw\ used (\frac{kg}{h})}{Cross\ sectional\ area\ of\ the\ reactor\ m^2} \quad (2)$$

Gasification Efficiency

Gasification efficiency or the percentage energy of rice straw converted into producer gas was calculated using equation (3) below.

$$\eta = \frac{Amount\ of\ gas\ produced\ X\ HV\ of\ gas}{Quantity\ of\ rice\ straw\ used\ X\ HV\ rice\ straw}[100] \quad (3)$$

Note: HV = heating value

Gas Produced

For the producer gas generated by the gasifier as a product of gasification, concentration of component gases was directly measured from the exhaust using the gas standard detector tube (Sampling Pump, Gastec GV-100, 50-100 mL, Made in Japan).

Experimental Design

The experiment was laid out in a split-plot randomized complete block design (RCBD) with age of rice straw as the main plot, and size as the sub-plot with three replications. Nine treatment combinations were used in the study.

Results

Moisture Content of Rice Straw at Different Ages

Table 1 shows the moisture content (percent dry basis) of rice straw at different ages from newly-harvested to five months. It is evident that as the rice straw ages its moisture content decreases.

Table 1. Moisture content (MC, % dry basis) of rice straw at different ages.

MC Determination Method	A1 (5 months)	A2 (2 months)	A3 (New Harvest)
Biomass moisture meter	10.25	13.33	16.85
Air-Oven	11.05	14.15	18.74

Effects of Age of Rice Straw on the Heating Value of the Producer Gas

Table 2 presents the heating value of producer gas of rice straw as affected by different ages of the rice straw. The heating value was highest at 4.63 MJ kg^{-1} for the 5-month-old feedstock, 3.40 MJ kg^{-1} for 2-month-old feedstock, and 2.97 MJ kg^{-1} for the newly-harvested rice straw.

The comparison among means showed that the heating value of the aged rice straw was significantly higher than the newly-harvested rice straw.

Effects of Size of Rice Straw on the Heating Value of the Producer Gas

Table 2 also presents the mean heating value of the producer gas as affected by the size of the rice straw when it was fed to the gasifier. The heating value of the rice straw with a size of 40 - 50 mm length (S1) was 2.96 MJ kg^{-1}, 3.56 MJ kg^{-1} for 30-40 mm length (S2), and 4.47 MJ kg^{-1} for 20 - 30 mm length (S3).

Comparison among means showed that S3 rice straw (20 - 30 mm long) produced significantly higher heating value than the S2 (30 - 40 mm) and S3 (40 - 50 mm) straw. The results showed that the gasification of rice straw was affected by the particle size and the heating value of the producer gas increases as the size of the straw decreases.

Effects of Age of Rice Straw on Gasification Rate

Table 3 shows that the gasification rate is affected by age of rice straw. A 5-month-old rice straw resulted in a gasification rate of 89.70 kg h^{-1} m^2, 2-month old resulted in 98.49 kg h^{-1} m^2, and the newly-harvested rice straw had a gasification rate of 107.06 kg h^{-1} m^2. However, the differences between the 2-month old and newly-harvested straw, and 2-month old and 5-month old were not significant. These results show that the fresher the straw, the higher is its gasification rate.

Effects of Size of Rice Straw on Gasification Rate

As shown in Table 3, gasification rate was also affected by size of rice straw. Size 1 (40 - 50 mm) resulted in a gasification rate of 92.20 kg h^{-1} m^2, S2 (30 - 40 mm), 100.42 kg h^{-1} m^2, and S3 (20 - 30 mm), 103.08 kg h^{-1} m^2. Results show that rice straw with shorter length had higher gasification rate than with longer straw length. However, the differences in mean gasification rate were not statistically significant.

Table 2. Mean heating value (MJ kg^{-1}) with different age and size of rice straw.

Age of Rice Straw	Size			
	S1	**S2**	**S3**	**Mean**
A1 (5 months old)	3.17	4.93	5.79	4.63a
A2 (2 months old)	3.08	2.62	4.49	3.40b
A3 (New harvest)	2.62	3.14	3.14	2.97b
Mean	2.96b	3.56b	4.47a	

Means with the same letter are not significantly different at 0.05 level of probability by Least Significant Difference (LSD).

Table 3. Mean gasification rate (kg h^{-1} m^2) with different age and size of rice straw.

Age of Rice Straw	Size			
	S1	**S2**	**S3**	**Mean**
A1 (5 months old)	83.11	93.36	92.62	89.70[b]
A2 (2 months old)	92.16	107.38	97.27	98.94[ab]
A3 (New harvest)	101.32	100.53	119.34	107.06[a]
Mean	92.2	100.42	103.08	

Means with the same letter are not significantly different at 0.05 level of probability by Least Significant Difference (LSD).

Table 4. Mean gasification efficiency (%) with different ages of rice straw.

Age of Rice Straw	Size			
	S1(40 - 50 mm)	**S2(30 - 40 mm)**	**S3(20 - 30 mm)**	**Mean**
A1 (5 months old)	41.77	45.18	42.91	43.92[a]
A2 (2 months old)	32.49	19.63	33.09	28.40[b]
A3 (New harvest)	22.4	25.72	16.18	21.43[b]
Mean	32.22	30.17	30.73	

Means with the same letter are not significantly different at 0.05 level of probability by Least Significant Difference (LSD).

Effects of Age of Rice Straw on Gasification Efficiency

Table 4 shows the mean gasification efficiency with different ages of rice straw. The 5-month-old rice straw had the highest gasification efficiency at 43.29%, while the 2-month-old and newly-harvested straw had 28.40 and 21.43% efficiency, respectively.

The gasification efficiency of the 5-month-old rice straw was relatively higher than the newly-harvested rice straw and the difference was statistically significant. The gasification efficiency was affected by the heating value of the producer gas produced during gasification.

Effects of Size of Rice Straw on Gasification Efficiency

Table 4 also presents the gasification efficiency as affected by different sizes of rice straw. The highest gasification efficiency was obtained at S1 (40 - 50 mm) equivalent to 32.22% while the lowest was at S3 (20 - 30 mm) equivalent to 30.73%. The analysis of variance showed that there were no differences in the gasification efficiency. Comparison among means showed that gasification was not significantly affected by the size of the rice straw.

Influence of Age of Rice Straw on CO, H_2 and CO_2 Production

Table 5 presents the carbon monoxide produced as affected by the age of rice straw fuel. The lowest emission was measured at A3 (newly harvested) feedstock equivalent to 3.22%, followed by A2 (2 months old) equivalent to 3.56%, and the highest CO emission measured was at A1 (5 months old) with 5.33%. Rice straw age treatment has a significant effect on the CO production.

Comparison among means further showed that CO production at A3 (new harvest) rice straw was significantly lower than the A1 (5 months old) fuel. The production of CO tended to increase with the increasing age of fuel. At A1 (5 months old) rice straw the gasifier produced 5.33% CO, which is one of the combustible gases.

Table 6 presents the percentage of hydrogen produced as affected by age of rice straw fuel. Results showed that the higher H_2 was produced and measured with A1 (5 months) rice straw at 3.44% and the lowest was with A3 (new harvest) rice straw at 2.22%.

The comparison among means (Table 6) also showed that production of H_2 was significantly affected by the age of rice straw. As the age of rice straw increases, the production of hydrogen also increases.

Table 6 shows that the CO_2 production was affected by the age of the rice straw. The mean CO_2 produced using A1 straw was 8.67%, A2, 6%, and A3 (new harvest) 6.33%. Highest amount of CO_2 was produced with the use of 5-month-old rice straw.

Analysis of variance and comparison of treatment means in Table 7 showed that the age of rice straw fuel affects the production of carbon dioxide. Carbon dioxide is one of the non-combustible gases present in the producer gas. The amount of carbon dioxide present in the producer gas varies from 5-15% according to Turare (2002).

Influence of Size of Rice Straw on CO, H_2 and CO_2 Production

Carbon monoxide emission is affected by different sizes of the rice straw (Table 5). The highest

Table 5. Mean carbon monoxide (%) with different ages of rice straw.

Age of Rice Straw	Size			
	S1(40 - 50 mm)	S2(30 - 40 mm)	S3(20 - 30 mm)	Mean
A1 (5 months old)	4	5.67	6.33	5.33^a
A2 (2 months old)	3	2.33	5.33	3.56^b
A3 (New harvest)	2.33	3.66	3.67	3.22^b
Mean	3.11^b	3.89^b	5.11^a	

Means with the same letter are not significantly different at 0.05 level of probability by Least Significant Difference (LSD).

Table 6. Mean hydrogen (%) with different ages of rice straw.

Age of Rice Straw	Size			
	S1(40 - 50 mm)	S2(30 - 40 mm)	S3(20 - 30 mm)	Mean
A1 (5 months old)	2.33	3.67	4.33	3.44^a
A2 (2 months old)	2.33	2	3.33	2.56^b
A3 (New harvest)	2	2.33	2.33	2.22^b
Mean	2.22^b	2.67^b	3.33^a	

Means with the same letter are not significantly different at 0.05 level of probability by Least Significant Difference (LSD).

Table 7. Mean carbon dioxide (%) with different age and size of rice straw.

Age of Rice Straw	Size of Rice Straw			
	S1(40-50 mm)	S2(30-40 mm)	S3(20-30 mm)	Mean
A1 (5 months old)	7.33	9.33	9.33	8.67[a]
A2 (2 months old)	6.33	6	5.67	6.00[b]
A3 (New harvest)	5.67	5.67	7.67	6.33[b]
Mean	6.44	7	7.56	

Means with the same letter are not significantly different at 0.05 level of probability by Least Significant Difference (LSD).

CO produced was measured at S3 (20 - 30 mm) equivalent to 5.11%, measured CO was 3.89% at S2 (30 - 40 mm), and the lowest, 3.11%, was at S1 (40 - 50 mm). Size of the rice straw significantly affected the production of carbon monoxide.

Comparison among means in Table 5 showed that the gasifier loaded with different sizes of fuel significantly affected CO production. The smaller the size of the fuel, the more CO is produced, which is consistent with the results obtained by Feng et al. (2011).

Table 6 also shows that hydrogen production is influenced by the size of rice straw fuel fed into the gasifier reactor. The highest amount of hydrogen produced was with S3 (20 - 30 mm), measured at H_2 value of 3.33%, and the lowest H_2 was measured with S1 (40 - 50 mm). Results showed that the smaller the straw size, the higher the amount of hydrogen produced.

The analysis of variance in Table 6 also showed that the differences in the amount of the H_2 produced as affected by the size of fuel were statistically significant. Hydrogen production in gasification was also influenced by the size of the straw fuel, as similarly found by Feng et al. (2011).

Table 7 presents the carbon dioxide (CO_2) produced during gasification with different sizes of rice straw. Results showed that the lowest volume of carbon dioxide released was with S1, which is equivalent to 6.44%, with S2, mean CO_2 released was 7%, and the highest CO_2 produced was with S3 (20 - 30 mm) at 7.56%. However, comparison among means of the three different sizes was not significant.

The analysis of variance for CO_2 production was not statistically significant but results showed that as the size of the fuel decreases the amount of CO_2 increases.

Equivalent Ratio

Equivalent ratio (ER) can be defined as the ratio of the actual air fuel ratio to the air fuel for complete combustion. The actual air fuel ratio in this experiment was 1.89 kg of air per kg of rice straw. Calculated ER was 0.39 for an open core throttle gasifier reactor, which is close to the optimum equivalent ratio of 0.40 for rice hull gasification (Jain, 2006).

Discussion

Effect of Age and Size of Biomass on the Quality of Producer Gas

The quality of the main product of biomass gasification, which is the combustible producer gas is measured by its heating value. The higher the heating value of the producer gas, the better is its quality as fuel. Results proved that age affects the heating value of biomass. According to Santana et al. (2011) carbon content was not affected with the increasing age of biomass while hydrogen content slightly decreases as the age increases. Geological age of the biomass influences the atomic ratio of the biomass. Atomic ratio is based on oxygen, hydrogen, and carbon content of the fuel. When the hydrogen-to-carbon (H/C) increases, the effective heating value of the fuel decreases. High oxygen and hydrogen content of the biomass results in high volatile and liquid yields. High oxygen consumes a part of the hydrogen in the biomass, producing less beneficial water; thus, the high H/C ratio does not result in high gas yield. Results (Table 2) showing that the 5-month-old rice straw had significantly higher heating value than the 2-month-old and newly-harvested rice straw are consistent with Basu (2010) who found that as the geological age increases, the energy content of the fuel also increases. As the 5-month-old rice straw also had the lowest moisture content (10%, dry basis), it can be inferred that the lower the moisture content of the biomass material, the better is its quality for gasification in terms of higher heating value of the producer gas produced.

When the particle size of the biomass fuel decreased from 50 to 20 mm, carbon monoxide and hydrogen increased remarkably. Combustible gases are important for the heating value of the producer gas. Feng et al. (2011) observed that when the particle size decreases, the reactions are mainly controlled by pyrolysis and gasification process; and when the particle size is increased, the reactions are mainly controlled by gas diffusion process, the speed of which is also influenced by particle size. Results showed that smaller particle size can produce high-quality gas better than the bigger particle size, as also found by Feng et al. (2011).

Effect of Age and Size of Biomass on Gasification Rate

As the rice straw age increases, gasification rate decreases owing to the longer time it takes to gasify older rice straw. As the gasification time for newly-harvested straw was shorter, its rate of gasification was significantly higher than that of the 5-month-old straw. The results are in accord with the findings of Reed and Das (1988), which showed that gasification is primarily affected by the introduction of adequate air that would react with the biomass. Chopped freshly-harvested straw has lower bulk density and more pore spaces; hence, it is less dense and so air would circulate better through the straw mass.

Results showed that shorter rice straw had higher gasification rate than the longer rice straw. However, in this study, the differences in mean gasification rate were not statistically significant because the differences in length of the rice straw (20 - 30 mm; 30 - 40 mm; and 40 - 50 mm) used in the study were not enough to significantly affect the gasification rate. According to the study of Kargbo et al. (2009), rice straw should be 5 - 20 mm to improve the combustion characteristics of.

Effect of Age and Size of Biomass on Gasification Efficiency

The gasification efficiency is calculated as the ratio of output energy to the input energy. The output energy is the energy produced during gasification and the input is the energy of the fuel before gasification. The gasification efficiency was significantly higher in the 5-month-old rice straw owing to the high heating value of the producer gas produced compared with that of using newly-harvested rice straw. The gasification efficiency of the 2-month-old and the newly-harvested rice straws was not significantly different, and likewise with the heating value produced. Gasification efficiency results confirm the findings of Kargbo et al. (2009), which showed that fine straws will improve the combustion behavior but the large sizes of biomass do not adversely affect the combustion performance.

Influence of Age of Rice Straw on CO, H_2, and CO_2 Production

Figure 2 shows that the age of rice straw influenced the production of gases during gasification. It was noted that as the age of the rice straw increased, the amounts of CO, H_2, and CO_2 also increased. As the age of the rice straw increased, the hydrogen-carbon (H/C) and oxygen-carbon (O/C) ratios decreased. The reduction in oxygen content resulted in higher gas yield, similar to the findings of Basu (2010).

Influence of Size of Rice Straw on CO, H_2 and CO_2 Production

Figure 3 shows the main composition of the gases produced during rice straw gasification. When the size of the rice straw increases, the relative volume of carbon monoxide, hydrogen, and carbon dioxide decreases. Hence, the size of the rice straw affects the production of gases during gasification. The volume of carbon monoxide, hydrogen, and carbon monoxide increased as the particle size of the rice straw decreased. This means that when the particle size is decreased, the combustion processes inside the reactor are mainly pyrolysis and gasification. As reported by Xiao and Meng (2011), these results also show that smaller size of solid biomass fuel is more advantageous in the production of combustible gases.

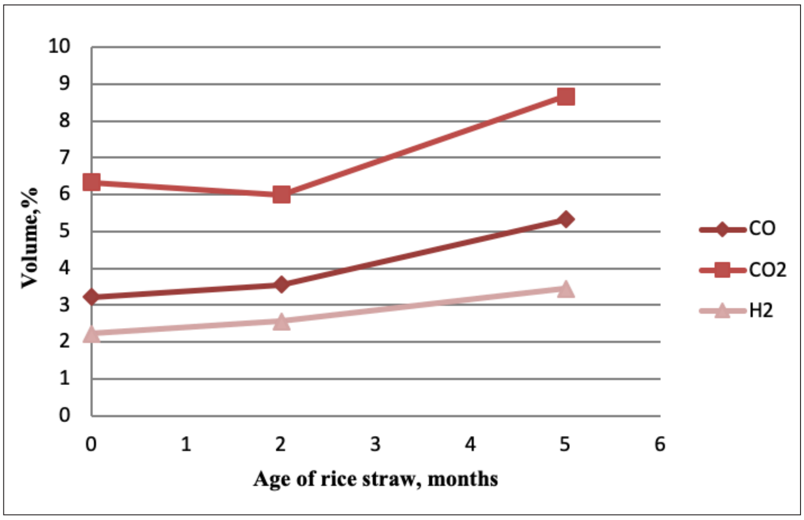


Figure 2. Influence of age of rice straw on gas composition.

Conclusion

The study determined the effects of age and size of rice straw on gasification performance as fuel for updraft, fixed bed, single reactor gasifier. The study was also conducted to establish the heating value of the producer gas produced by the rice straw biomass. An updraft, laboratory-scale, fixed bed, stationary gasifier was used in the experiment. The JHT chopper/crusher was used to reduce the size of the rice straw.

Results show that rice straw with different ages and sizes can influence the heating value, gasification rate, efficiency, and the production of gases.

In terms of heating value, using 5-month-old rice straw, which also had the lowest MC at 10%, dry basis, resulted in a higher heating value of 4.63 MJ kg^{-1} of the producer gas produced, compared with the newly-harvested rice straw with producer gas heating value of 2.97 MJ kg^{-1}. There was no treatment interaction observed but the smaller size of rice straw of S3 (20 - 30 mm) gave a higher heating value of 4.47 MJ kg^{-1} than the larger size of S1 (40 - 50 mm), which had a 2.96 MJ kg^{-1} heating value. Heating value of the producer gas for rice hull using the PhilRice gasifier was 2.60 MJ m^{-2} as reported by Ramos (2014).

In terms of gasification rate, the different ages of the rice straw resulted in significant differences in the gasification rate. The A1 (5-month old) rice straw resulted in GR of 89.70 kg h^{-1} m^2 while A3 (new harvest) rice straw had 107.06 kg h^{-1} m^2. The sizes of the rice straw used in this study did not significantly affect the gasification rate. Only the age of the rice straw had significant effect in terms of gasification efficiency. The use of 5-month-old straw made gasification 43.5% efficient while with the newly-harvested straw, only 21.4% gasification efficiency was obtained.

The production of gases such as carbon monoxide, carbon dioxide, and hydrogen were affected by the age and size of the rice straw. Combustible gases such as carbon monoxide and hydrogen were significantly affected by the age and size of rice straw. The 5-month-old rice straw yielded higher carbon monoxide and hydrogen volumes. Smaller size of the straw also resulted in higher carbon monoxide and hydrogen production. In terms of carbon dioxide production, only the age of rice straw had significant effect.

The following conclusions are drawn based on the results from this study: 1) To have high heating value of the producer gas generated by the gasification of rice straw, the age of the straw must be older (at least five months), its moisture content should be 10% (dry basis) or lower, and the size of the rice straw fuel should be 20 mm or shorter; 2) Gasification efficiency for this study was affected only by the age of the rice straw and the process is significantly more efficient with the use of older straw; 3) Production of combustible gases such as carbon monoxide and hydrogen was higher with older straw fuel, while smaller straw size produced more carbon monoxide and hydrogen; and 4) Rice straw is suitable a fuel for gasification provided it is aged, with low moisture content, and reduced in size.

Literature Cited

Balat M, Balat M, Kırtay E, Balat H (2009) Main routes for the thermo-conversion of biomass into fuels and chemicals: Part 2: Gasification systems. Energy Conversion and Management **50**: 3158-3168

Basu P (2010) Biomass Gasification and Pyrolysis: Practical Design and Theory. Oxford, UK: Academic Press, Elsevier Inc

Bautista EG, Saito M, Regalado MJC (2014) Performance of an updraft rice husk gasifier system for powering village rice mills in the Philippines. Journal of Food, Agriculture, and Environment **12**(2): 831-835

Belonio AT, Regalado MJC, Castillo PR (2018) Development of an appropriate rice-based biomass gasifier as source of power for farm use. Open Access Library Journal 5: e5054

Braunbeck CM (1994) Rice Husk Combustion. Stuttgart, Germany: Hohenheim University

Calvo LF, Gil MV, Otero M, Morán A, García AI (2012) Gasification of rice straw in a fluidized-bed gasifier for syngas application in close-coupled boiler-gasifier systems. Bioresource Technology **109**: 206-214

Casiwan CL, Asis Jr. CA, Manalili RG, Javier EF (2015) Economic analysis of rice straw management alternatives and understanding farmers' choices. *In* James D, Francisco H (Eds.). Cost-Benefit Studies of Natural Resource Management in Southeast Asia (pp 93-111). Singapore: Springer

Coovattanachai N (1987) Biomass Gasification Research and Field Developments. Hadyai, Thailand: Prince of Songkla University

Feng Y, Xiao B, Görner K, Cheng G, Wang J (2011) Influence of particle size and temperature on gasification performance in externally heated gasifier. Advanced Materials Research: 281

Gadde B, Bonnet S, Menke C, Garivait S (2009a) Air pollutant emissions from rice straw open field burning in India, Thailand and Philippines. Environ. Pollut. **157**(5): 1554-1558

Gadde B, Menke C, Wassmann R (2009b) Rice straw as a renewable energy source in India, Thailand, and the Philippines: Overall potential and limitations for energy contribution and greenhouse gas mitigation. Biomass and Bioenergy **33**: 1532-1546

Haefele SM, Konboon Y, Wongboon W, Amarante S, Maarifat AA (2011) Effects and fate of biochar from rice residues in rice-based systems. Field Crops Res **121**: 430-440

Hoer D, Phillips B, Wang A, Woodside R (2016) Feasibility of rice straw utilization for small scale power production. Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Thailand. Retrieved from https://ie.unc.edu/wp-content/uploads/sites/277/2016/03/rice_straw_to_energy.pdf (accessed January 12, 2021)

Hoki M, Sato K, Umezawa Y (1992) Sawdust Gasification for small power plant. Paper presented at the ASAE International Summer Meeting, American Society of Agricultural Engineers **92**:6001-6040

Jain A (2006) Design parameters for a rice husk throatless gasifier. Agricultural Engineering International **8**. Retrieved from https://cigrjournal.org/index.php/Ejounral/article/view/648 (accessed July 21, 2017)

Kargbo FR, Xing J, Zhang Y (2009) Pretreatment for energy use of rice straw: A review. African Journal of Agricultural Research **4**(12)

Kirubakaran V, Sivaramakrishnan V, Nalini R, Sekar T, Premalatha M, Subramanian P (2009) A review on gasification of biomass. Renewable and Sustainable Energy Reviews **13**: 179-186

Kumar G (2017) The Technical, Economic and Environmental Feasibility of Rice Straw Residue for Biomass Energy Production in India (Unpublished Dissertation). Humboldt State University, California, USA

Lin KS, Wang HP, Lin CJ, Juch CI (1998) A process development for gasification of rice husk. Fuel Processing Technology **55**: 185-192

McKendry P (2002) Energy production from biomass (Part 3): Gasification technologies. Bioresource Technology **83**: 55-63

Mendoza TC (2015) Enhancing crop residues recycling in the Philippine landscape. *In* Muthu SS (Ed.). Environmental Implications of Recycling and Recycled Products, Environmental Footprints and Eco-design of Products and Processes (pp 79- 100). Singapore: Springer Science + Business Media

Migo-Sumagang MVP, Maguyon-Detras MC, Gummert M, Alfafara CG, Borines MG, Capunitan JA, Hung NV (2020) Rice-straw-based heat generation system compared to open-field burning and soil incorporation of rice straw: An assessment of energy, GHG emissions, and economic impacts. Sustainability **12**(5327): 1-18

Ngo TTT (2011) Comparative Assessment of Using Rice Straw for Rapid Composting and Straw Mushroom Production in Mitigating Greenhouse Gas Emissions in Mekong Delta, Vietnam and Central Luzon, Philippines (Unpublished Dissertation). University of the Philippines Los Baños, Philippines

Nguyen VH, Jamieson C, Gummert M (2014) Rice straw for energy in South and Southeast Asia - A case study in Vietnam. Retrieved from https://docs.google.com/viewer?a=v&pid=sites&srcid=aXJyaS5vcmd8cG9zdGhhdmVzdC11bm10fGd4OjUxNjYyZjgxNzY2OWI2YWY (accessed January 13, 2021)

Nguyen VH, Sander BO, Quilty J, Balingbing C, Grace Castalone AG, Romasanta R, Alberto MCR, Sandro JM, Jamieson C, Gummert M (2019) An assessment of irrigated rice production energy efficiency and environmental footprint with in-field and off-field rice straw management practices. Sci Rep **9**: 16887

Payne FA, Dunlap JL, Caussanel P (1985) Effect of wood chip size on gasifier combustor operation. Trans. ASAE **28**(3): 903-906

[PSA] Philippine Statistics Authority (2019) Rice and Corn Situation and Outlook, January 2019 Round. Retrieved from https://psa.gov.ph/sites/default/files/Rice%20and%20Corn%20Situation%20and%20Outlook%2C%20January%202019_0.pdf (accessed February 26, 2020)

Ramos JA (2014) Performance of Four-Stroke Spark-Ignition Engine Using Scrubbed Producer Gas (Unpublished Master's Thesis). Central Luzon State University, Philippines

Reed TB, Das A (1988) Handbook of biomass downdraft gasifier engine systems. A product of the solar technical information program. Solar Energy Research Institute. Retrieved from https://www.nrel.gov/docs/legosti/old/3022.pdf (accessed July 21, 2017)

Salam PA, Kumar S, Siriwardhana M (2010) The Status of Biomass Gasification in Thailand and Cambodia. Thailand: Asian Institute of Technology

Santana WM, Calegario N, Arantes MDC, Trugilho PF (2011) Effect of age and diameter class on the properties of wood from clonal Eucalyptus. Cerne Lavras **18**(1): 1-8

Singh J, Jaswinder S, Jain AK, Bhatnagar AP (1994) 10-kW paddy husk gasifier for on-farm electricity generation. Proceedings of the International Agricultural Engineering Conference, Bangkok, Thailand

Sivakumar K, Mohan NK (2010) Performance analysis of downdraft gasifier for agriwaste biomas materials. Indian J Sci Technol **3**(1): 58-60

Summers MD (2001) Using Rice Straw for Energy Production: Economics, Energetics and Emission. USA: University of California

Tiangco VM (1990) Optimization of Specific Fuel Conversion Rates for Rice Hull Gasifier coupled to an Internal Combustion Engine (Unpublished Dissertation). University of California Davis, USA

Tiangco VM, Jenkins BM, Goss JR (1996) Optimum specific gasification rate for static bed rice hull gasifiers. Biomass and Bioenergy **11**(1): 51-62

Turare C (2002) Biomass Gasification: Technology and Utilization. Retrieved from http://127.0.0.1:1027/cgi-bin/gw?e=t1c...dl-1-O.30.B.137.1-11-100-20-00&q=&g=11 (accessed October 3, 2014)

Wise DL (1983) Liquid Fuel Developments. USA: CRC Press

Xiao X, Meng X (2011) Two-stage steam gasification of waste biomass in fluidized bed at low temperature: Parametric investigations and performance optimization. Bioresource Technology **102**(2): 1975-1981

DIVERSITY ASSESSMENT OF THE TRADITIONAL RICE VARIETIES COLLECTED IN NORTHWEST LUZON

Christopher C. Cabusora[1*], Gelyn D. Valida[1], Juliet P. Rillon[2], Betzaida M. Catudan[3], Anielyn Y. Alibuyog[3], and Nenita V. Desamero[1]

[1]Philippine Rice Research Institute, Science City of Muñoz, Nueva Ecija, [2]PhilRice Station, Batac, Ilocos Norte
*Corresponding Author: cccabusora@philrice.gov.ph, nvdesamero@philrice.gov.ph

Abstract

The agro-morphological traits of 53 traditional varieties (TRVs) collected from Northwest Luzon were evaluated in 2014 and 2015 dry season at the Philippine Rice Research Institute Central Experiment Station of the Department of Agriculture (DA-PhilRice). The TRVs were characterized for 11 agro-morphological traits at reproductive and maturity stages. Studied traits included days to heading, plant height at maturity, culm length, panicle length, productive tiller, panicle secondary branching, awn color, hull color, apiculus and endosperm color, and yield. The diversity in the phenotypes of TRVs was analyzed and measured using descriptive statistics, frequency distribution, histogram, and diversity index. The phenotypic diversity measured in terms of population coefficient of variation (CV) indicates comparative degree of variation in five quantitative traits, *viz*., days to heading, plant height at maturity, culm length, panicle length, productive tiller. Variable values of kurtosis were obtained indicating relative differences in the distribution of classes and frequency in each class in the histogram for the degree of variability assessment. For qualitative traits, the Shanon-Weaver diversity index (SWI) was determined. Variation in seedling drought response and resistance to rice blast were evaluated.

Keywords: *Agronomic Traits, Coefficient of Variation, Morphological Traits, Skewness, Kurtosis.*

Introduction

Traditional rice varieties (TRVs) exhibit high variability in terms of genotypic and phenotypic traits that are important in rice breeding programs. The main benefits of traditional rice to rice breeding are the availability of genes, which controls traits for more efficient nutrient uptake, utilization, and adaptation to environmental stresses such as submergence, salinity, and high temperatures (Azeez et al., 2018). Several reports have shown the usefulness of TRVs in developing new rice varieties. Some novel genes quantitative trait locus (QTL) from traditional varieties include the Saltol QTL from Pokkali (Singh et al., 2008) and the *Sub1* gene from the traditional rice variety FR13A (Mackill et al., 2010), which were successfully introgressed in the modern cultivar, IR64, and was released in 2013 as NSIC Rc 194 (Submarino 1). To date, the Genebank in DA-PhilRice in Nueva Ecija holds an approximate of 17,000 germplasm collections (Niones, 2020) with most of them phenotypically and genetically characterized (Rabara et al., 2014; Caguiat et al., 2017; Niones, 2020).

Newly released saline-tolerant or Salinas varieties NSIC Rc 292 (Salinas 7) and NSIC Rc 332 (Salinas 14) have traditional variety Wagwag. These improved Wagwag varieties have good agronomic traits and were no longer photoperiod sensitive (Desamero, 2000). With the importance of TRVs in modern rice breeding, this paper presents the variability of TRVs collected in Northwest Luzon that are useful and important in developing new rice varieties.

Materials and Methods

The collection of 53 traditional varieties was done from the 19 municipalities of the five provinces of Northwest Luzon (Table 1) from 2010 to 2013. The evaluation for agronomic and morphological traits was done in 2014 dry season at DA-PhilRice in Nueva Ecija.

Phenotypic Diversity Assessment

Each variety was established in unreplicated experimental design in a 4 m^2 plot with 5 rows x 20 hills at 20 cm x 20 cm spacing, and grown under irrigated condition. The TRVs were characterized for 11 traits at reproductive and maturity stages. These traits were days to heading, plant height, culm length, panicle length, productive tiller at maturity, panicle secondary branching, awn color, hull color, apiculus and endosperm color, and yield. Grain size and shape were also evaluated. The diversity in the phenotype of the TRVs was analyzed and measured using descriptive statistics, frequency distribution, and histogram using SPSS version 19 (IBM, New York,

Table 1. Traditional rice varieties collected in Northwest Luzon from 2010 to 2013.

Province	Municipality	No.	Local Name
Abra	Lagangilang	1	Langpadan
	Tayum	1	Payakan
Ilocos Norte	Banna	2	Balsamo (a), Zambales
	Currimao	3	Banglo, Balsamo b, Palawan a,
	Marcos	7	Buga, Burgis, Gannal, Maliketa, Minama, Purtok, Azucena (variant)
	Nueva Era	3	Rafinan, Mindoro, Azucena
	Batac	1	Gannal
	Piddig	2	Isic Pugot, Isic Diket
	Dumalneg	3	Parina, Fancy Rice, Pamplona
Ilocos Sur	Burgos	5	Bukutan, Lukdit ni abalayan, Malapay, Pinal-ug, Tagaling
	Nagbukel	2	Aringay, Awan Sapulemon (b),
	Quirino	2	Azucena, Dinorado
Apayao	Conner	2	Gobyerno (b), Nylon
	Kabugao	3	Kilong, Bulilising, Mindanao
	Luna	3	Saba, Sabadilla, Ballatinaw
	Calanasan	4	Balud, Arimuram, Dagmuy, Unig
	Pudtol	3	Baddang, Madalia, Sinelat,
Mt. Province	Bauko	4	Getbaw, Langka (Malagkit), Oskil, Ballatinaw
	Tadian	2	Ballatinaw dati, Pinyas,
Total		**53**	

USA) and Shanon Weaver Diversity Index (SWI) (Hutchenson, 1970).

Diversity in Drought Tolerance and Blast Resistance at Seedling Stage

The evaluation for drought tolerance response at seedling stage was conducted in 2015 dry season (DS). Fifty pre-germinated seeds of each entry were sown in 70 cm-row for wooden trays and 90-cm row for GIS trays, spaced 10 cm apart. A thin film of water of about 2 - 3 cm was maintained until withheld at 14 days after sowing. Soil moisture content (SMC) was monitored at regular interval from water withdrawal until before re-watering by gravimetric method. Leaf rolling (LeR) and leaf drying (LeD) were observed as manifestation of drought development. Scoring was based on the 2013 Standard Evaluation System for Rice of the International Rice Research Institute (IRRI). Re-watering was done as LeD score of IR64 reached 7. Plant recovery was observed 10 days after re-watering (10 DARw), then leaf vigor and biomass were gathered. Response of the TRVs to blast resistance were conducted in 2015 DS following the published protocol of PhilRice (NCT, 1997).

Results and Discussion

Evaluation for Agronomic and Morphological Traits

A sample size of five randomly selected plants were evaluated for agronomic traits and yield, while single plant was used for morphological characterization. Days to 50% heading of the traditional varieties ranged from 71 to 108 days after sowing (DAS), plant height ranged from 83 to 176 cm, culm length from 62 to 149 cm, panicle length and productive tillers from 18 to 36 cm, and 9 - 16 tillers. Negative values for skewness of the frequency distribution cum histogram of four traits including heading (-0.02), plant height (-1.59), culm length (-1.68), and productive tiller (0.28) were obtained. The grain yield of the 48 genotypes with skewness value of 0.57 categorized 46% of the TRVs yielding less, while 54% had yield higher than the population mean (2.5 t ha^{-1}). No grain yield was obtained from five genotypes: Azucena (Quirino), Gannal (Marcos), Isic Diket, Isic Pugot, and Palawan because 90% of the plants lodged.

Variable values of kurtosis were obtained ranging from -1.4 for heading to 3.1 for culm length, indicating relative differences in the distribution of classes and frequency in each class in the histogram of the traits evaluated (Figure 1).

Relative to the population mean of 92 DAS, majority (53%) of the varieties flowered early while 43% flowered longer. Majority of the TRVs are taller (62%) with longer culm (62%) and more productive tillers (55%) than the population mean. Equal proportion (43%) of the TRVs had panicle length shorter or longer than the population mean of 26 cm, with skewness value of 0.28 (Table 2). The phenotypic diversity measured in terms of population coefficient of variation (CV) indicates comparative degree of variation, with 12 - 15% CV, in the five quantitative traits. The largest variation was obtained in grain yield with 50% CV.

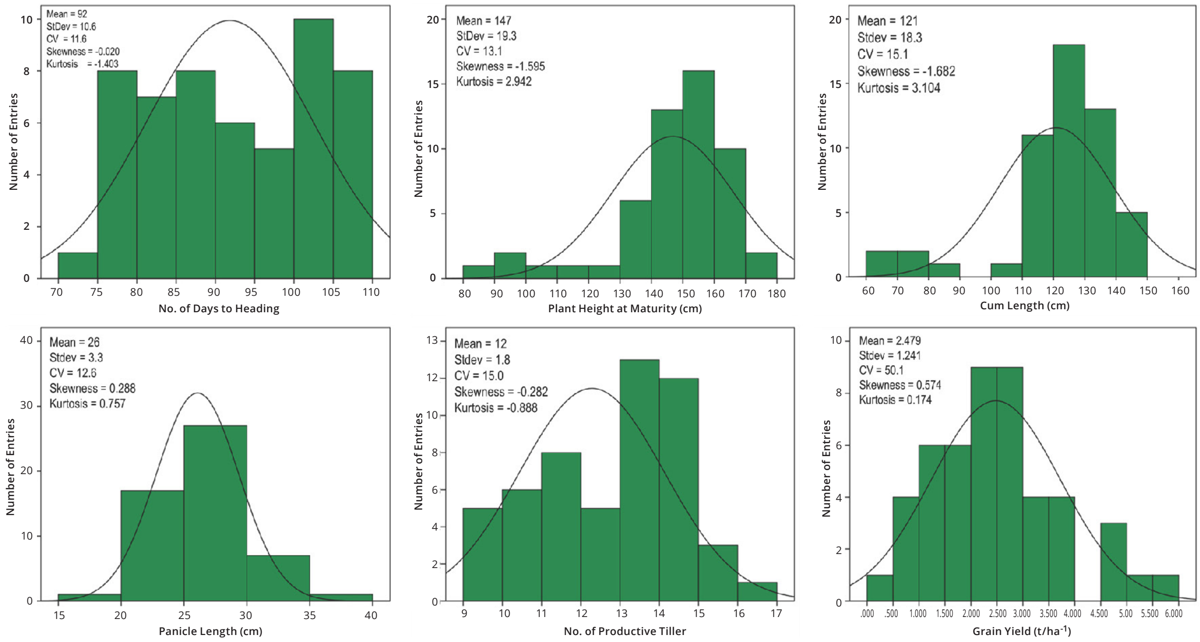


Figure 1. Frequency distribution of the TRVs for the six agronomic traits, 2014 DS.

Evaluation for Morphological Traits at Reproductive and Harvest Stage

The TRVs were evaluated for five morphological traits: panicle secondary branching, awn color, hull pigmentation, and apiculus coloration. Secondary branching of the panicles (Figure 2a and b) varied from absent, light, heavy, and clustered. Nineteen (33.3%) of the TRVs had clustered secondary branching; 5 (8.8%), heavy branching; and 14 (24.6%), light panicle branching (Figure 2). No branching was observed from the remaining 15 (26.3%) TRVs.

Variations in awn color (Figure 3) was also observed among the traditional varieties. Ten (17.5%) had red awn; 7 (12.3%), black; 5 (8.8%), purple; and 4 (7%) were straw-colored. Absence of awn was observed in the grains of the 27 (47.4%) TRVs. Variable hull color (Figure 4) was also observed among the TRVs collected, majority of which (30%) were straw-colored. Equal proportion (14%) of TRVs with golden brown and brown hull with furrows were obtained. Brown, purple, and black hull was observed from 2 (3.5%), 3 (5.3%), and 1 (1.8%) TRVs, respectively.

Endosperm color (Figure 5) of 29 (50.9%) TRVs was red; 21 (36.8%), white; 2 (3.5%), black; and 1 (1.8%) was in red and white mixture. Purple apiculus color was observed in 21 (36.8%) TRVs, black in 14 (24.6%), red in 4 (7%), and straw in 14 (24.6%) (Figure 6). Shanon-Weaver diversity index (SWI) for qualitative traits showed 1.6 for endosperm color and 1.7 for panicle secondary branching, color of the awn, hull, and apiculus (Table 3).

Evaluation for Grain Size and Shape

Variation in brown rice grain size and shape (Figure 7) was also observed among the 48 collected TRVs. Grain length (GL) varied from short grains measuring 4.8 - 5.3 mm; medium grains, 5.6 - 6.6 mm; and long grains 6.7 - 10.7 mm. Five TRVs had short grains; 35 (72.9%), medium; and 8 (16.7%), long grains. Grain width (GW) ranged from 2 to 3.1 mm and grain shape (GS) from 1.8 to 4.2 mm. Highest variation was obtained from grain shape with 20.51% CV (Table 4). Grain shape of 5 (10.4%) TRVs was slender, 11 (22.9%), intermediate; and 32 (66.7%), bold.

Positive values for skewness of the frequency distribution (Figure 8) of grain length (2.927) and shape (1.324) indicate that most of the population had shorter grain length than the population mean (6.2 mm) and lower grain shape value than the population mean (2.4 mm). Negative skewness and kurtosis value were obtained for grain width (-0.28). Five (10.4%) TRVs had long and slender grain size and shape, which is acceptable to the Filipino consumers.

Cluster Analysis Using Phenogram

Association among the 53 collected TRVs by UPGMA cluster analysis using agronomic and morphological traits (phenogram) revealed two major clusters. The larger cluster (Cluster 1) consisted of 47 TRVs (88.7%) while the smaller cluster (Cluster 2) was composed of 6 (11.3%) TRVs, namely Ballatinaw (Luna), Bulilising, Lukdit ni Abalayan, Minama, Sabadilla, and Sinelat. Lemma and palea (hull) color

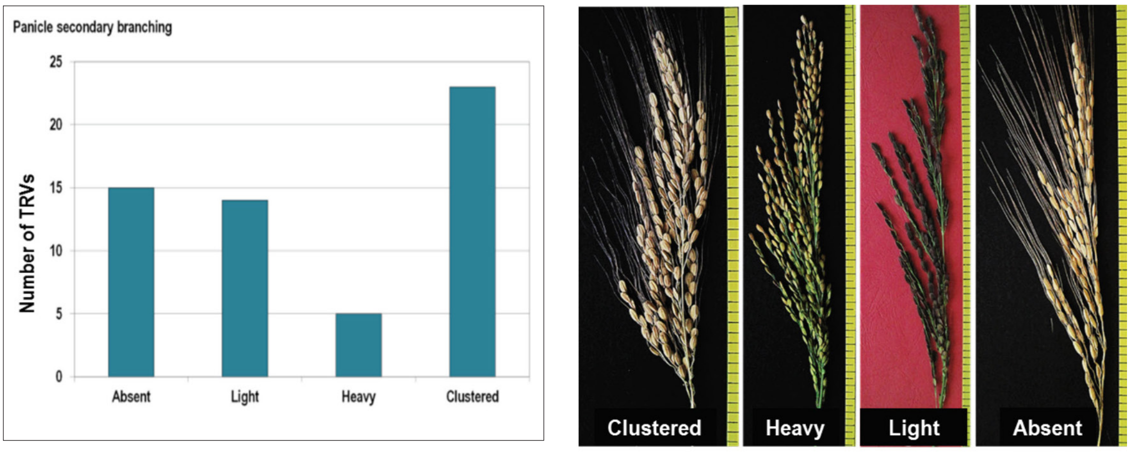


Figure 2. Frequency distribution and variation in panicle secondary branching.

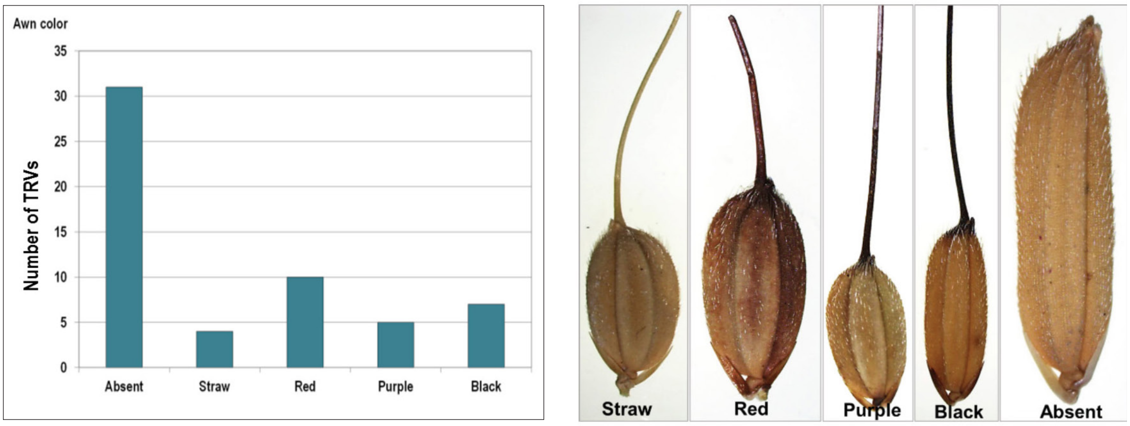


Figure 3. Frequency distribution and variation in awn color.

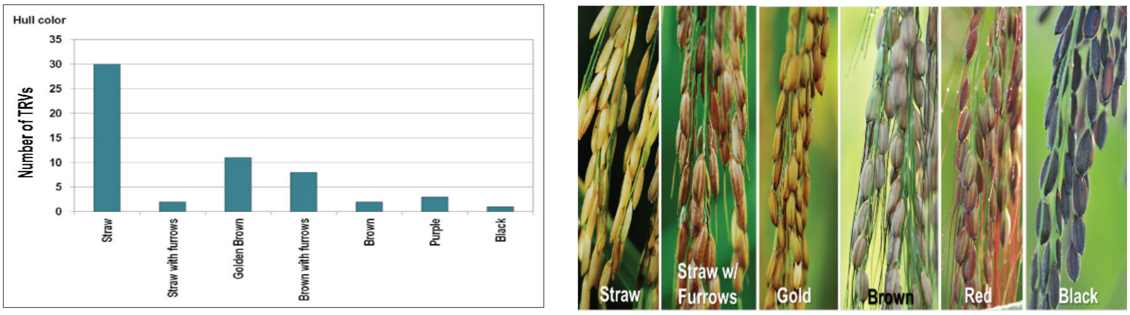


Figure 4. Frequency distribution and variation in hull color.

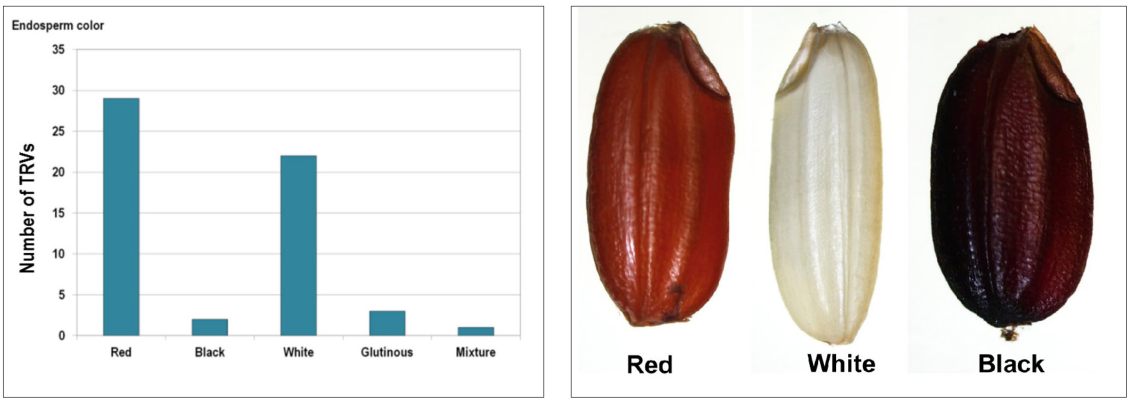


Figure 5. Frequency distribution and variation in endosperm color.

Table 2. Variation of the traditional rice varieties in six major agronomic traits, PhilRice CES, 2014 DS.

Agronomic Traits	Mean	Standard Deviation	Greater than the Population Mean		Less than the Population Mean		CV
			no.	%	no.	%	
Days to heading	92	10.6	23	43.4	28	52.8	11.6
Plant height (cm)	147	19.3	33	62.3	18	34.0	13.1
Culm length (cm)	121	18.3	33	62.3	17	32.1	15.1
Panicle length (cm)	26	3.3	23	43.4	23	43.4	12.6
No. of productive tiller	12	1.8	29	54.7	18	35.8	15.0
Grain yield (t ha^{-1})	2.5	1.2	22	45.8	26	54.2	48.4

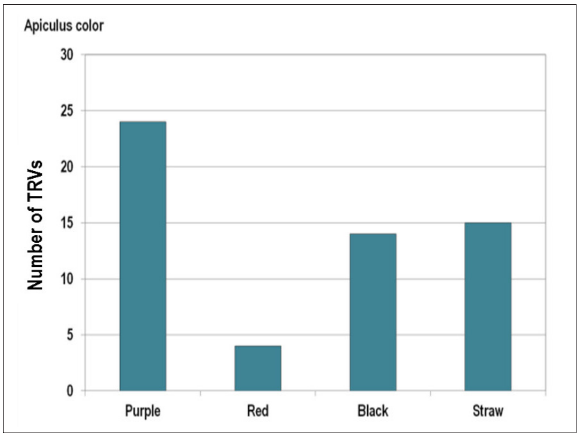


Figure 6. Variation in apiculus color of the collected traditional rice varieties

Table 3. SWI of the TRVs for panicle and grain morphological traits, PhilRice CES, 2014 DS.

No.	Morphological Trait	SWI
1	Panicle Secondary Branching	1.7
2	Awn Color	1.7
3	Hull Color	1.7
4	Apiculus Color	1.7
5	Endosperm Color	1.6

Table 4. Descriptive statistics of the traditional rice varieties for grain traits, 2014 DS.

Grain Trait	Min	Max	Range	Mean	Stdev	CV	Skewness	Kurtosis
GL (mm)	4.8	10.7	5.9	6.2	0.86	13.8	2.92	14.59
GW (mm)	2.0	3.1	1.1	2.6	0.29	11.2	-0.28	-.88
GS (mm)	1.8	4.2	2.4	2.4	0.49	20.5	1.32	2.26

Min - minimum, Max - maximum, Stdev - standard deviation, CV - coefficient of variation.

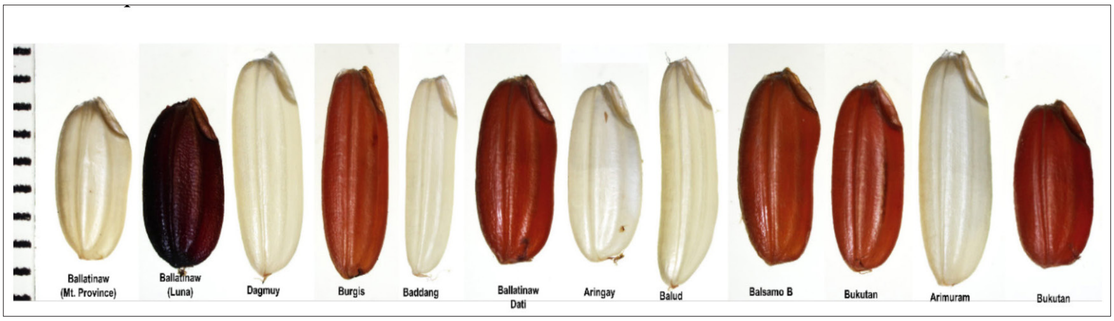


Figure 7. Variation in grain size and shape of the collected traditional rice varieties from Northwest Luzon.

Table 5. Pearson's correlation coefficient of 14 agro-morphological characteristics

Trait	Heading Days	Plant Height	Culm Length	Panicle Length	Productive Tiller	Grain Yield	Grain Length	Grain Width	Grain Shape	Panicle Branching	Husk Color	Awn Color	Apiculus Color	Endosperm Color
Days to heading	1													
Plant height	0.156	1												
Culm length	0.18	0.99*	1											
Panicle length	-0.12	0.39*	0.24	1										
Productive tiller	-0.24	-0.27	-0.30	0.06	1									
Grain yield	-0.19	-0.46*	-0.44*	-0.25	0.10	1								
Grain length	-0.17	-0.06	-0.10	0.18	0.08	0.10	1							
Grain width	0.04	0.42*	0.44*	-0.001	0.001	-0.38*	-0.37*	1						
Grain shape	-0.09	-0.28*	-0.33*	0.13	0.07	0.29*	0.84*	-0.80*	1					
Panicle Branching	0.06	0.18	0.23	-0.216	-0.03	-0.13	-0.21	0.35	-0.32	1				
Husk color	0.03	0.14	0.14	0.10	-0.004	-0.36	-0.15	0.30	-0.28	0.07	1			
Awn color	0.08	0.27	0.27	0.06	-0.31	-0.29	-0.06	0.43	-0.26	0.19	0.12	1		
Apiculus color	0.08	0.52*	0.50*	0.30	0.10	-0.46*	-0.09	0.11*	-0.11	0.29	0.04	0.13	1	
Seed coat color	0.10	0.36	0.36	0.13	-0.27	-0.24	-0.24	0.32	-0.36	-0.04	0.42*	0.35	-0.07	1

** Correlation is significant at 0.05 level (2-tailed) were distinct in the formation of two clusters. TRVs with straw-colored, straw with furrows, golden brown, and brown-colored hulls belonged to Cluster 1, while those with black hulls belonged to Cluster 2. Sub-groups from each major cluster showed the traditional varieties that are almost similar with each other (Figure 9).

Response to Seedling Drought Stress Tolerance and Blast Resistance

Out of the 56 TRVs, 4 (8%), 22 (42%) and 27 (48%) entries scored 5, 7 and 9, respectively, in terms of leaf rolling, when the LeR score of IR64 reached 9 and 7 for the tolerant check, PSB Rc14. In terms of leaf drying, 2 (4%), 36 (64%), and 18 (32%) entries scored 5, 7 and 9, respectively, when the LeD score of IR64 reached 7 and 5 for PSB Rc14. Survival and biomass of the TRVs were highly variable with coefficient of variation values of 72.1% and 102.6% (Table 6), respectively. Survival ranged from 0 to 66%, and biomass from which TRV *Aringay* and *Payakan* were identified to have comparable tolerance to the tolerant check, PSB Rc14 (Figure 10).

Blast screening of the collected TRVs showed variations in response, in which 40% of the collections were susceptible; 22%, resistant; while 38% had intermediate resistance (Figure 11).

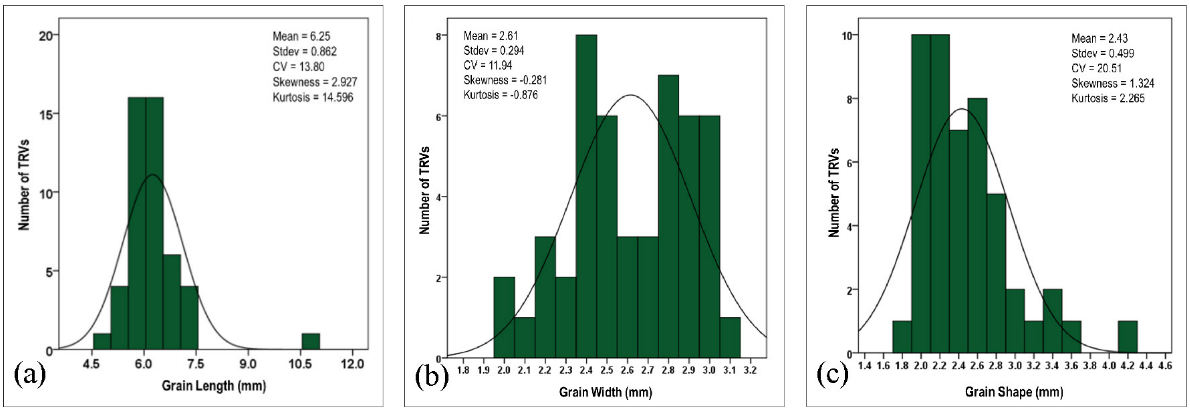


Figure 8. Frequency distribution of the Traditional Rice Varieties for grain length (a), grain width (b), and grain shape (c); variation in grain size and shape of the collected TRVs (d), PhilRice CES, 2014 DS.

Table 6. Variance statistics of the Traditional Rice Varieties for seedling drought tolerance, PhilRice CES, 2015 DS.

Drought Response	Minimum	Maximum	Range	Mean	Standard Deviation	Coefficient of Variation
Survival (%)	0.0	66.4	66.4	18.8	13.5	72.1
Biomass (g)	0.0	9.6	9.6	1.6	1.7	102.6
Survival + Biomass	0.0	76.0	76.0	20.4	14.9	73.3

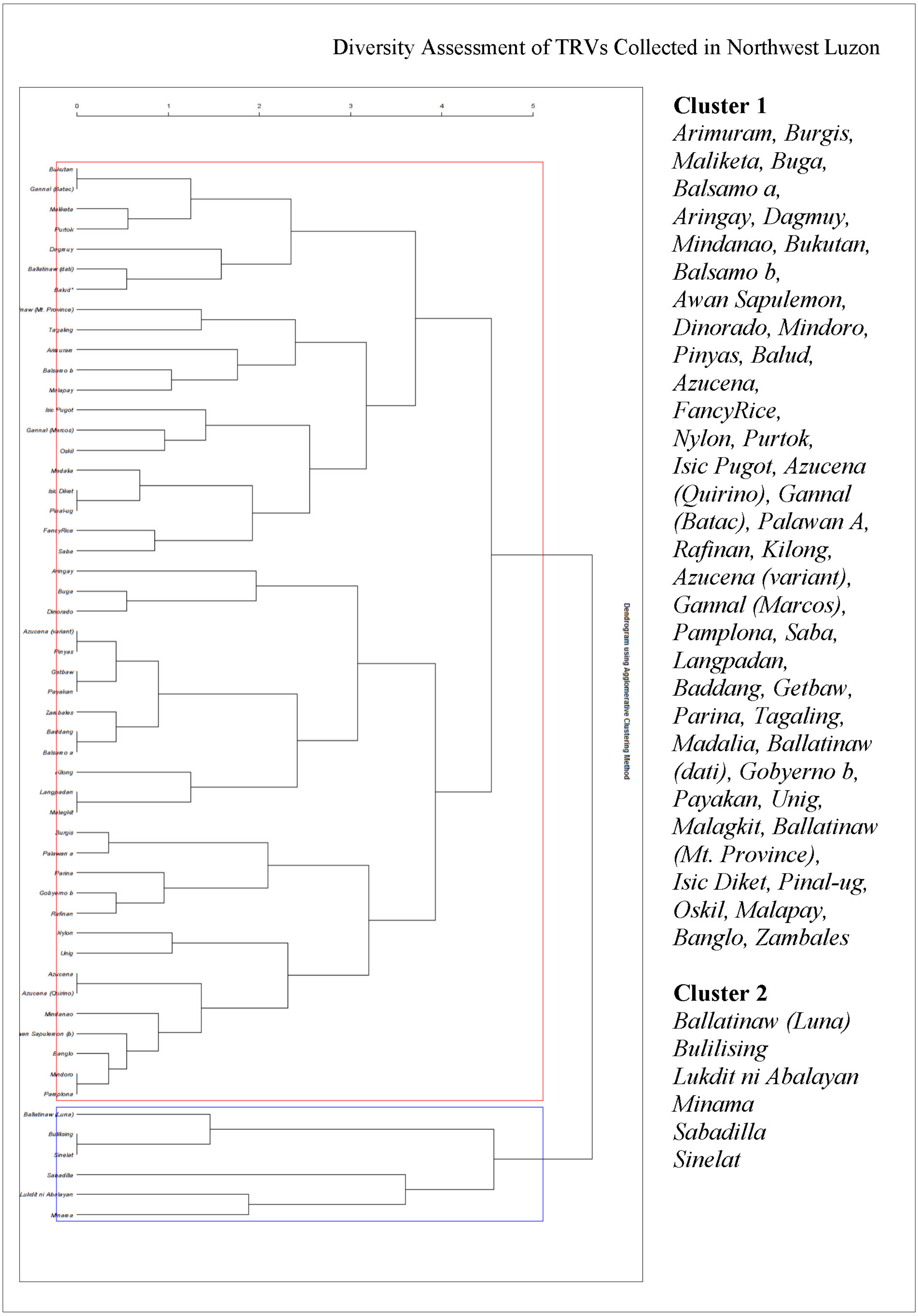


Figure 9. Cluster analysis using UPGMA of 53 traditional varieties collected in Northwest Luzon based on Euclidean Distances Estimated from five morphological traits.

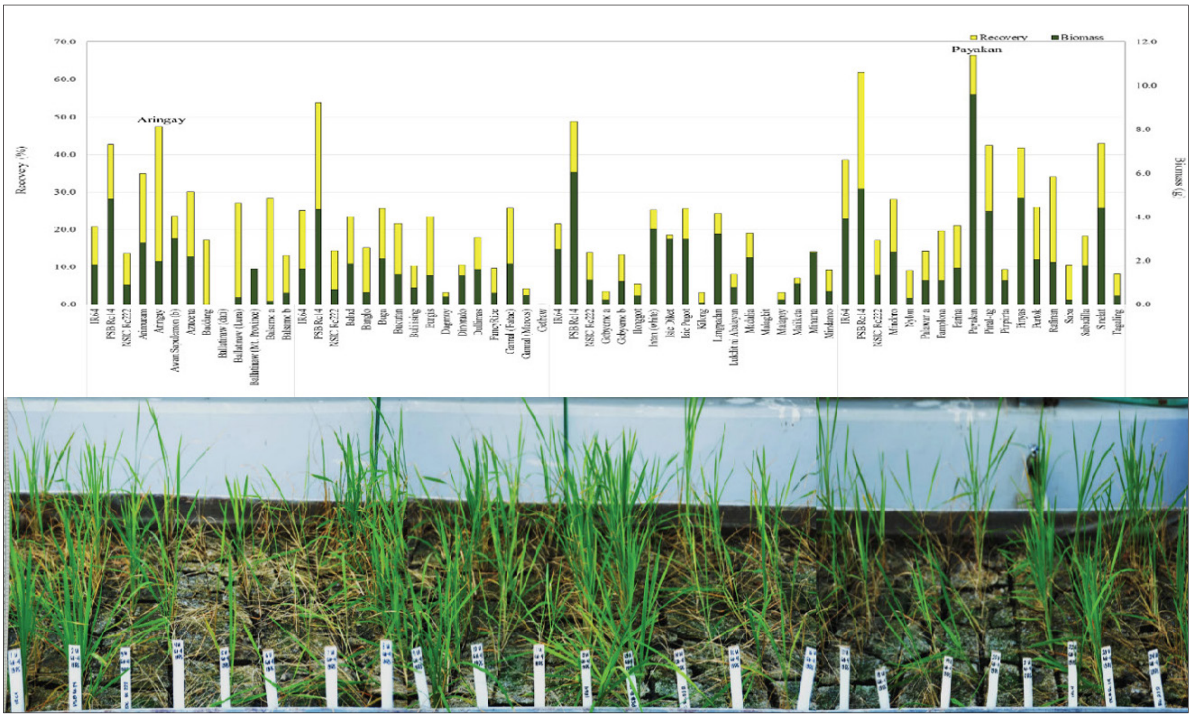


Figure 10. Variability in drought recovery and biomass (top) of the traditional rice varieties collections; TRVs at 10 days after rewatering (bottom), PhilRice CES, 2015 DS.

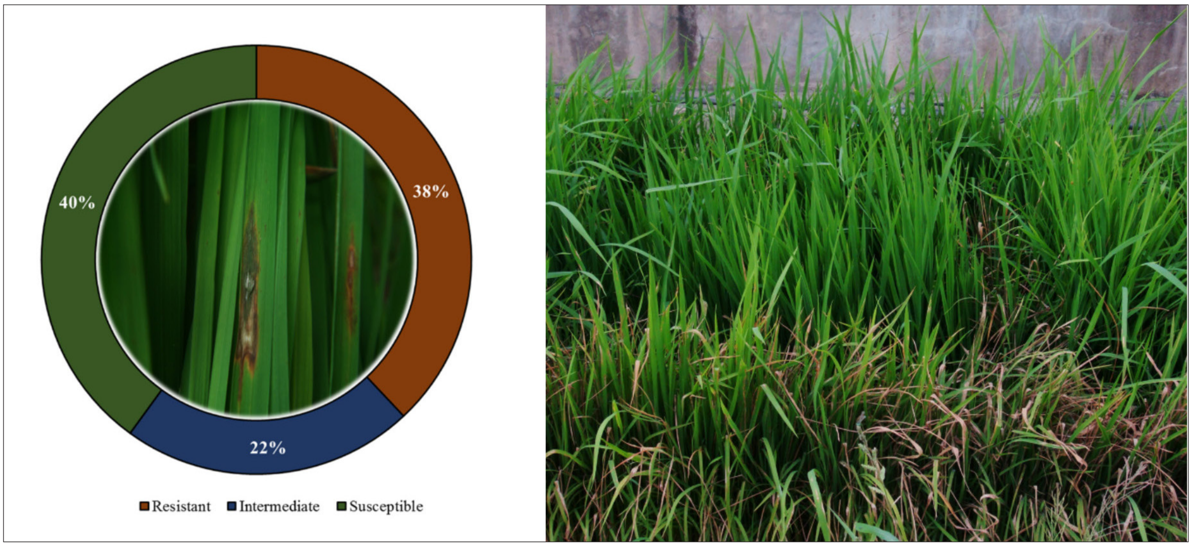


Figure 11. Blast screening response of the traditional rice varieties collections, PhilRice CES, 2015 DS.

Conclusion

Collected TRVs varied in agro-morphological and grain traits. Highest variation for quantitative traits, as reflected in the CVs, was obtained in grain yield and grain shape. Morphologically, the TRVs varied in panicle and grain traits. Variable grain size and shape were also observed. Cluster analysis using phenogram generated showed lemma and palea (hull) color as distinct morphological traits in two major clusters. Variable response in terms of recovery and biomass accumulation, as well as in blast resistance, were also observed. The characterization of the TRV collections from Northwest Luzon, provides information on their genetic pool as source of important traits to rice breeding.

Literature Cited

Azeez MA, Adubi AO, and Durodola FA (2018) Rediscovery of Landraces as a Resource for the Future. *In* Grillo O (Ed.). Landraces and Crop Genetic Improvement.

Caguiat XGI, Mamucod HF, Bulatao RM, Ferrer MC (2017) Molecular analysis of Philippine traditional pigmented rice germplasm stored at PhilRice Genebank. Philippine Journal of Crop Science **42**: 110-111

Desamero NV, Chico MV, Dimaano YA, Macabale SS, Diaz CL, Romero MV, Tabien RE, Guzman ED, Cardenas CC, Orbon CA, Cavite OV (2002) Traditional rice variety Wagwag Re-Invented. Paper presented (oral and poster) in 14th National Research Symposium, Department of Agriculture-Bureau of Agricultural Research (DA-BAR), November 27-29, 2002, Bureau of Soils and Water Management (BSWM), Visayas Avenue, Diliman, Quezon City

Hutcheson K (1970) A test for comparing diversities based on the Shannon Formula. Journal on Theoretical Biology **29**: 151-154

International Rice Research Institute (IRRI) (2013). Standard Evaluation System for Rice (SES). Philippines: Manila

Mackill D, Serres JB, Fukao T, Ronald P, Ismail A, Heuer S (2010) Submergence tolerant rice: SUB1's Journey from landrace to modern cultivar. Springer-Rice **3**: 138-147

National Cooperative Testing (NCT) (2002) Manual. Philippines: Philippine Rice Research Institute

Niones JM, Marcelo VAC, Lipio PLG, Labaros SJE, Mananghaya TE (2020) Assessment of genetic diversity and population structure of rice donor germplasm accessions in the Philippines. Philippine Journal of Science **149**(3-a): 685-696

Rabara RC, Ferrer MC, Diaz CL, Newingham MCV, Romero GO (2014) Phenotypic diversity of farmers' traditional rice varieties in the Philippines. Agronomy **4**: 217-241

Singh RK, Mohammadi-Nejad G, Arzanai A, Reza AM, Gregorio GB (2008) Assessment of rice genotypes for salt tolerance using microsatellite markers associated with saltol QTL. African Journal of Biotechnology **7**(6): 730-736

REACTIONS OF WEEDY RICE VARIANTS TO TUNGRO DISEASE AND BACTERIAL LEAF BLIGHT

Femia R. Sandoval, Edwin C. Martin*, Ma. Salome V. Duca, and Emmanuel R. Tiongco

Philippine Rice Research Institute, Science City of Muñoz, Nueva Ecija, Philippines
*Corresponding Author: ecmartin@philrice.gov.ph

Abstract

In the Philippines, where weedy rice (WR) is becoming a major threat in rice production, research studies are focused on determining its occurrence and extent of its distribution. WR's benefits such as being a possible source of resistance to major rice diseases, however, is not given research attention. Different WR variants collected from Central Luzon and Western Visayas were screened for rice tungro disease (RTD) and bacterial leaf blight (BLB) incidence in 2014 - 2015. Two variants (WR-B10 and B13) from Pampanga and Pangasinan provinces were found to have the lowest incidence of RTD after three consecutive trials. These variants averaged 23-26% infection after inoculation at 30 and 45 days after sowing (DAS), as compared with the susceptible check TN1, which showed 94.17% infection. Another variant (WR-B 3) from Aurora averaged 3% infection when inoculated at 45 DAS; also rated as intermediate incidence with 36% infection when inoculated at 30 DAS. Meanwhile, 12 WR variants had an intermediate incidence of BLB when inoculated at 45 DAS. One variant (WR-B4) from Tarlac had the least infection of 12%. All variants were susceptible to BLB when inoculated at 30 DAS._A confirmation trial was conducted in 2016 dry season. The variant WR-B3 from Aurora had 0% infection of RTD at 30 and 45 DAS while variant WR-B4 from Tarlac had 8.2% BLB incidence at 30 DAS. These variants may be recommended for further study and could be used as parent materials for breeding RTD and BLB-resistant rice varieties. Based on findings, it can be deduced that weedy rice has an evolved genetic mechanism that prevents rice diseases, which can be used for the improvement of cultivated rice.

Keywords: *Bacterial Leaf Blight, Resistance, Rice Tungro Disease, Weedy Rice.*

Introduction

Weedy rice (WR) is becoming a significant threat in major irrigated rice production systems in the world, particularly in Southeast Asia. It brandishes a wide range of undesirable agronomic traits resulting in uneven growth of rice plants, added production cost in weed management, and reduced grain quality of cultivated rice. WR also competes with cultivated rice for space, water, and nutrients; thus, reducing yield.

The term "weedy rice" does not refer to one specific weed. It is a variety of weeds with the same "assemblage of weedy traits" having different morphological and phenological characteristics (Delouche et al., 2007). As Ferrero (2003) puts it, it is composed of all the species of the genus *Oryza*, "which behave as rice and crop in rotation with rice weeds." Meanwhile, Rathore et al. (2016) called it "biosimilar rice with biological characteristics that identify it as a weed."

WR in the Philippine rice fields was first observed in Batasan, Mindoro Island (Second, 1991) when Second verified the report of Tateoka and Pancho (1963) on the presence of two populations of *Oryza officinalis* in the area. Second described the new form of rice that apparently evolved as having dark brown, pilous glumes, and medium-sized smooth awns, which shattered at milky stage.

A number of hypotheses were generated about the origin of WR. Foremost is that it may have developed from the natural hybridization between cultivars (Arashi, 1974) or between perennial wild and domestic types as postulated by Morishima et al. (1984). It is widely accepted that gene flow occurs from domestic to perennial wild type with the latter having less pollen grains and high outcrossing rate. The recurrent gene flow following this direction may have produced a weedy type with an indica-type nuclear genome and japonica cytoplasmic genome (Sato, 2000). In the case of weedy red rice, Jia and Gealy (2018) noted that it has increased genetic diversity and adaptive ability, and that the absence of human selection favored its development and helped its survival in the natural setting.

Weedy rice is prevalent in direct-seeded rice systems where it emerges alongside cultivated rice, making it difficult for farmers to differentiate and control. It is also herbicide-resistant, although it can be controlled by a number of cultural management practices such as planting quality seeds, following the stale seedbed technique (Chauhan, 2013), using seeders or planting rice in rows (Rathore et al., 2016), and practicing crop rotation (Watanabe et al., 2000).

Researches on WR were generally focused on surveys determining the occurrence and extent of its distribution, and on its control (Azmi et al., 2000; Baltazar and Janiya, 2000; Luat, 2000; Moody, 1994; Pyon et al., 2000). However, this study is yet the only undertaking conducted on the beneficial roles of WR in rice production as a possible source of resistance to major rice diseases.

The rice tungro disease (RTD) is one of the most notorious viral diseases of Philippine rice, which has caused huge losses to farmers during outbreaks. The need to develop tungro virus and vector-resistant varieties was already recognized in mid 1960s (Azzam and Chancellor, 2002). At the International Rice Research Institute (IRRI), screening for RTD began in 1963 while breeding initiatives started in 1966 (Khush, 1977 as cited by Angeles et al., 2008). As of 2015, nine RTD-resistant varieties (PhilRice, 2016) have been developed in the Philippines including the Matatag varieties [IR 69726-29-1-2-2-2 (Matatag 2), IR 73885-1-4-3-2-1-6 (Matatag 9), and NSIC Rc 120 (Matatag 6)], which were initially deployed to RTD hotspots in Mindanao (Ravelo et al., 2008). Matatag 9 was developed by crossing IR 64 and the RTD-resistant accession of *O. rufipogon* (105908) (Khush et al., 2004).

The bacterial leaf blight (BLB), which is endemic in Asia, Africa, and Australia, is another serious threat to Philippine rice production. A breakdown of resistance to BLB infection has been reported in varieties carrying major BLB resistance genes, which necessitates the identification of new genes from new sources. The wild rices *O. rufipogon* and *O. nivara* were identified, characterized, and genetically mapped to confer recessive and dominant BLB-resistant genes, respectively (Natarajkumar et al., 2010).

This study explored the potentials of weedy rice as possible sources of resistance for RTD and BLB. This is a compelling initiative as WR was hypothesized as the result of the natural hybridization between perennial wild and domestic types (Morishima et al., 1984). This view may have been corroborated by field observations and anecdotal accounts by rice farmers indicating that WR varieties are not generally infected by RTD and BLB, unlike cultivated rice (Donayre, personal communication). Such information should not be discounted because the wild rices *Oryza nivara* and *O. rufipogon* have been used as sources of resistance against the rice grassy stunt and tungro virus diseases, respectively (Khush and Ling, 1974; Shibata et al., 2007). Hence, this study determined whether weedy rice could serve as a source of resistance to RTD and BLB, which are among the major rice diseases in the Philippines.

Materials and Methods

Weedy Rice Seed Collection and Characterization

Weedy rice was collected in 2014 from infested rice fields in Pangasinan, Bulacan, Aurora, Tarlac, Pampanga, and Negros Occidental, where it has been known to occur at high density. Seeds of the samples were characterized at the Weed Science Laboratory of Philippine Rice Research Institute of the Department of Agriculture (DA-PhilRice) in Science City of Muñoz, Nueva Ecija. Ten seeds were randomly selected from each variant and characterized according to grain, pericarp, and awn color using the Royal Horticultural Society Color Chart (RHS, 1986) in the Descriptors for Wild and Cultivated Rice (*Oryza* spp.) (Biodiversity International, 2007). Grain and awn lengths were measured using a digital caliper. Seeds with similar characteristics were grouped together and considered as one variant. Twenty different variants were identified from the collection sites.

Weedy Rice Testing for RTD and BLB Resistance

Twenty variants were tested for resistance against RTD and BLB. Seeds of WR and check variety Taichung Native 1 (TN1) were pre-germinated in the laboratory, and were sown in 15 cm-diameter clay pots. Plant thinning was done 5-6 days after sowing (DAS), leaving 5 plants per pot with 2 pots per entry. The plants were inoculated 30 and 45 DAS.

Three consecutive trials were conducted for RTD incidence from January to April 2015 and for BLB incidence from May to July 2015. A confirmation trial from February to March 2016 was conducted to re-evaluate WR variants that showed lowest disease incidence of RTD and BLB.

Inoculum Preparation

Green leaf hoppers (GLH) were reared in the greenhouse for RTD inoculation. Newly developed adults were allowed to feed on tungro-infected plants for 4 days. After virus acquisition, the tungro-viruliferous GLHs were ready for inoculation.

A four-day-old test tube slant pure culture of *Xanthomonas oryzae* pv. *oryzae* (race 3) was used as source of inoculum. Ten mL sterilized distilled water was poured into a single slant culture and bacterial growth was scraped with sterilized wireloop. The scraped growth was poured into another clean and sterilized empty test tube, and mixed thoroughly using vortex mixer to obtain a homogenous mixture of bacterial suspension. Once homogenized, 0.5 mL of the suspension was transferred using a pipettor into solidified Wakimoto agar and spread evenly throughout the medium to allow uniform bacterial growth. The plated bacterial culture was incubated at room temperature for 3 - 4 days. After incubation, a BLB suspension was prepared by adding 1 L of sterilized distilled water into the 4 plated culture of *X. oryzae*. The suspension (10^8 bacterial cells per mL) was shaken before inoculation.

Inoculation of Test Weedy Rice Variants

RTD inoculation was done by releasing tungro-viruliferous GLH (5 adults per seedling) in a potted test WR plant covered with mylar cage. Inoculation feeding was allowed for 24 h, then the vectors were retrieved and transferred to the test plant in a water pan. The BLB suspension was inoculated using an inoculation clipper. The leaves were clipped 6 cm from the tip.

Evaluation

The reaction of weedy rice to RTD was evaluated 15 days after inoculation (DAI). Percent incidence of RTD was taken by dividing the number of infected plants by the number of inoculated plants, then multiplied by 100 (Azzam et al. 2000). Using the average percent incidence, the reaction of WR to RTD was evaluated as follows: 0 - 30% = resistant; 31 - 60% = intermediate; and 61 - 100% = susceptible.

BLB evaluation was done 14 DAI. The plants were scored for their percent incidence based on symptoms. The total number of leaves from the inoculated plants was evaluated by measuring the lesion and leaf lengths. Percent incidence was taken by dividing the lesion length by the leaf length, then multiplying the result by 100. The level of resistance was rated following the National Cooperative Testing (NCT) manual for rice. The scale was as follows: 0 - 12% =resistant; 13 - 25% =intermediate; 26 - 100% =susceptible.

Confirmation Trial for RTD- and BLB-Resistant Weedy Rice

Four pre-selected WR variants from Aurora, Pampanga, and Pangasinan were re-evaluated for tungro resistance under induced method in greenhouse conditions in 2016 dry season. TN1 was used as the check variety. Test plants were inoculated at 30 and 45 DAS, and evaluated 15 days after inoculation (DAI). Twelve pre-selected WR variants from Pangasinan, Tarlac, Bulacan, Pampanga, Negros Occidental were also re-evaluated for BLB resistance under greenhouse conditions in 2016 dry season.

Data analysis

The experiment was arranged in completely randomized design (CRD) with two replications (5 plants per replication). The data on percent incidence were transformed using arcsine square root transformation before the analysis. The data gathered were variance-analyzed (ANOVA) while the means were separated by standard deviation or Fisher's LSD at 5% level of significance using the Statistical Tool for Agricultural Research (STAR) 2.0.0 by IRRI.

Results and Discussion

Weedy Rice Seed Collection and Characterization

Twenty WR variants were characterized from the collection sites in Pangasinan, Bulacan, Aurora, Tarlac, Pampanga, and Negros Occidental (Table 1). The variants had yellow, dark yellow, golden yellow, and brown grain colors. The pericarp was red to light red and whites, and the awns were yellow to golden yellow and golden brown to light brown. Coloration on the tip of the grains was observed in some variants namely; 4 variants had purple tips, 1 variant had a brown tip, another had a black tip, while the other

Table 1. Weedy rice survey and collection sites in Central Luzon and Negros Occidental.

Weedy Rice Variants	Collection Sites
WR-B 1	Murcia, Negros Occidental; Maria Aurora, Aurora
WR-B 2	San Manuel, Pangasinan; Urdaneta City, Pangasinan; Balungao, Pangasinan; San Miguel, Bulacan
WR-B 3	Maria Aurora, Aurora
WR-B 4	Concepcion, Tarlac;
WR-B 5	San Miguel, Bulacan; Umingan, Pangasin-an; Urdaneta City, Pangasinan; San Felipe, Pangasinan; San Manuel, Pangasinan
WR-B 6	Urdaneta, Pangasinan; San Miguel, Bula-can; Maria Aurora, Aurora
WR-B 7	San Miguel, Bulacan; Concepcion, Tarlac
WR-B 8	Concepcion, Tarlac; Urdaneta, Pangasinan
WR-B 9	Concepcion, Tarlac; San Miguel, Bulacan
WR-B 10	San Miguel, Bulacan; Candaba, Pampanga
WR-B 11	Urdaneta City, Pangasinan
WR-B 12	Murcia, Negros Occidental
WR-B 13	San Manuel, Pangasinan
WR-B 14	Candaba, Pampanga
WR-B 15	Candaba, Pampanga
WR-B 16	San Miguel, Bulacan
WR-B 17	Maria Aurora, Aurora
WR-B 18	Urdaneta City, Pangasinan
WR-B 19	Malasiqui, Pangasinan
WR-B 20	Sta. Barbara, Pangasinan

14 variants had no coloration. Fourteen variants had awn while 6 variants were awnless (Figure 1). The longest grain length was recorded in WR-B14 (11.0 mm), while WR-B1 (6.7 mm) had the shortest grain. The variants with the longest awn were WR-B16 (4-76 mm) and WR-B4 (8-61 mm) (Table 2). The most common variants were WR-B2 and WR-B5, which were observed in five locations, followed by WR-B1, WR-B6, and WR-B8 found in three locations.

The WR reported in the Philippines morphologically looks like cultivated rice. However, it is generally taller, has longer and wider leaves, flowers earlier, and its seeds mature 4 - 5 days earlier than cultivated rice (Guzman, 1996). It produces fewer leaves, tillers, and panicles, and its grains shatter before maturity. In addition, grains are smaller and the pericarp are shorter than those of cultivated rice (Guzman, 1996). Certain WR grains have straw-colored hulls while others are black and with or without awns. Black-hulled grains have the most awns with 30% possessing awns longer than 2 cm (Fajardo and Moody, 1995). Platino (1996) identified four types of WR based on grain color and awns: are awnless with pericarp (44%), awned with red or white pericarp (19%), awnless with white pericarp (13%), and awnless with gold pericarp (6%).

Identification of Resistant Weedy Rice

Figure 2 showed the percent RTD incidence of WR variants at 30 DAS. B10 showed lowest disease incidence in three trials, while B13 and B17 had low incidence in two trials and intermediate incidence in one trial. When inoculated at 45 DAS, B3 had the lowest disease incidence in three trials, while B1, B10 and B13 recorded low disease incidence in two trials and intermediate incidence in the 3rd trial (Figure 3).

All WR variants inoculated with BLB at 30 DAS were susceptible to disease infection (Figure 4). When inoculated at 45 DAS, B4 and B7 had low disease incidence in two trials and intermediate incidence in one trial. Variants B12, B13, and B18 had low disease incidence in 1 trial; however, showed intermediate incidence and susceptibility in other trials (Figure 5).

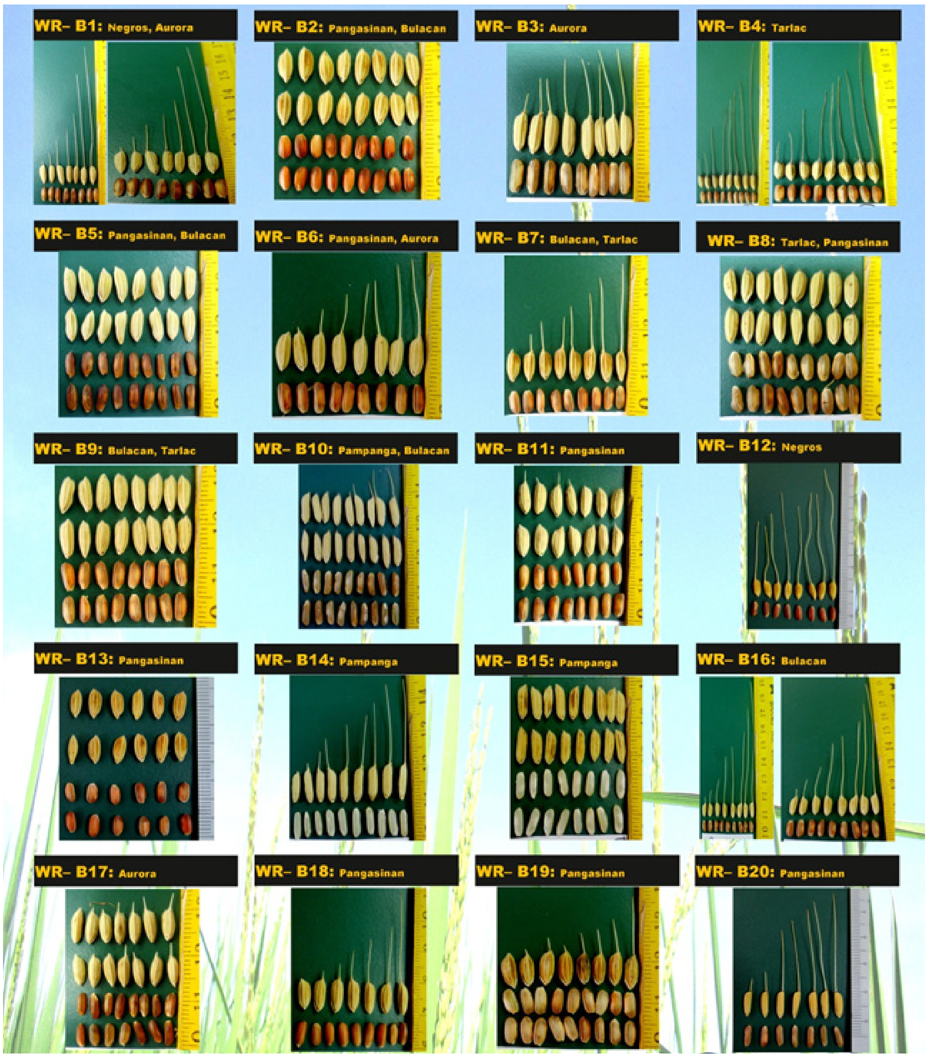


Figure 1. Seeds of 20 weedy rice variants from Central Luzon and Negros Occidental.

Table 2. Morphological characteristics of weedy rice variants.

	Seed Morphology				
Weedy Rice Variants	**Grain Color**	**Pericarp Color**	**Awn Color**	**Grain Length (mm)**	**Awn Length (mm)**
WR-B 1	Yellow w/ purple tip	Red	Light brown	6.7	30-47
WR-B 2	Yellow	Red	None	8.4	none
WR-B 3	Yellow w/ brown tip	Red	Yellow	8.4	0-35
WR-B 4	Brown w/ purple tip	Red	Dark brown	7.8	8-61
WR-B 5	Yellow	Red	None	9.2	none
WR-B 6	Yellow	Red	Yellow	9	0-19
WR-B 7	Yellow	Red	Yellow	8	0-51
WR-B 8	Yellow w/ purple tip	Red	None	7.2	none
WR-B 9	Yellow	Red	None	8.4	none
WR-B 10	Yellow w/ purple tip	Red	Yellow	8.4	0-6
WR-B 11	Yellow	Light red	Yellow	9	0-3
WR-B 12	Golden yellow	Light red	Golden yellow	9	35-49
WR-B 13	Yellow	Light red	None	8.6	none
WR-B 14	Yellow	White	Yellow	11	0-28
WR-B 15	Dark yellow	White	None	8.2	none
WR-B 16	Yellow	Red	Yellow	8.4	4-76
WR-B 17	Yellow	Red	Yellow	7	0-3
WR-B 18	Yellow	Red	Golden yellow	10.3	0-28
WR-B 19	Brown	Light red	Yellow	8	0-14
WR-B 20	Yellow w/ black tip	Red	Golden yellow	9	33.8

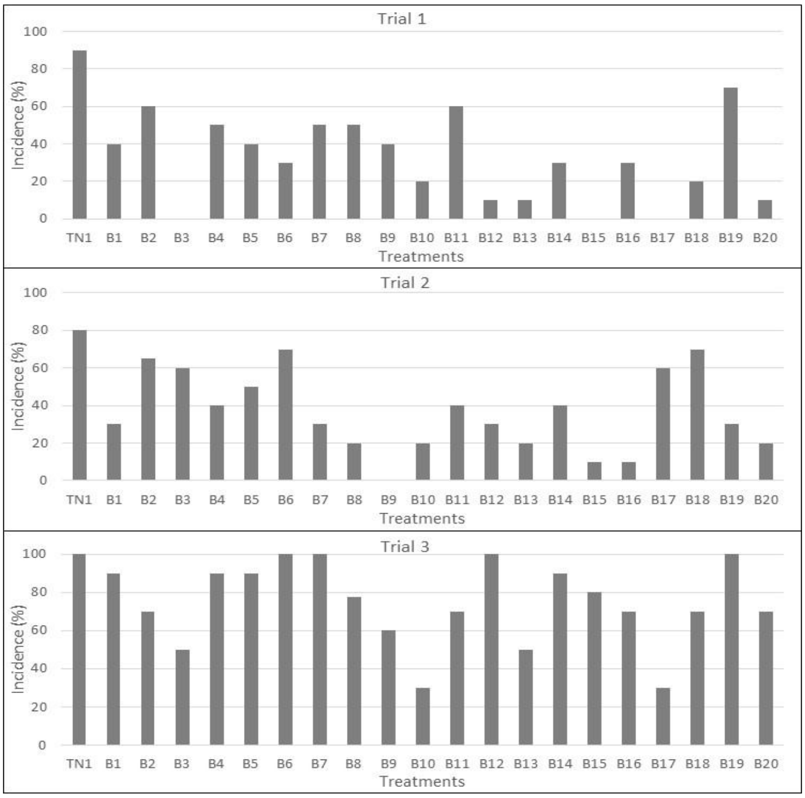


Figure 2. Percent RTD incidence of WR variants and TN1 variety inoculated at 30 DAS from three consecutive trials, 15 days after inoculation.

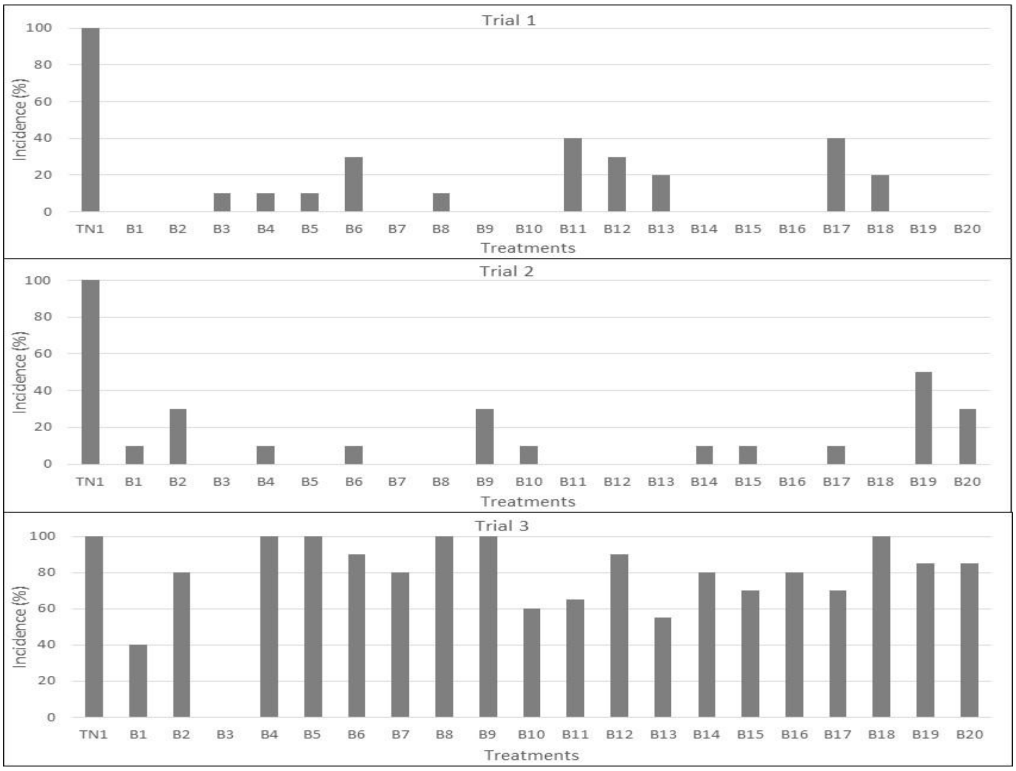


Figure 3. Percent RTD incidence of WR variants and TN1 variety inoculated at 45 DAS from three consecutive trials, 15 days after inoculation.

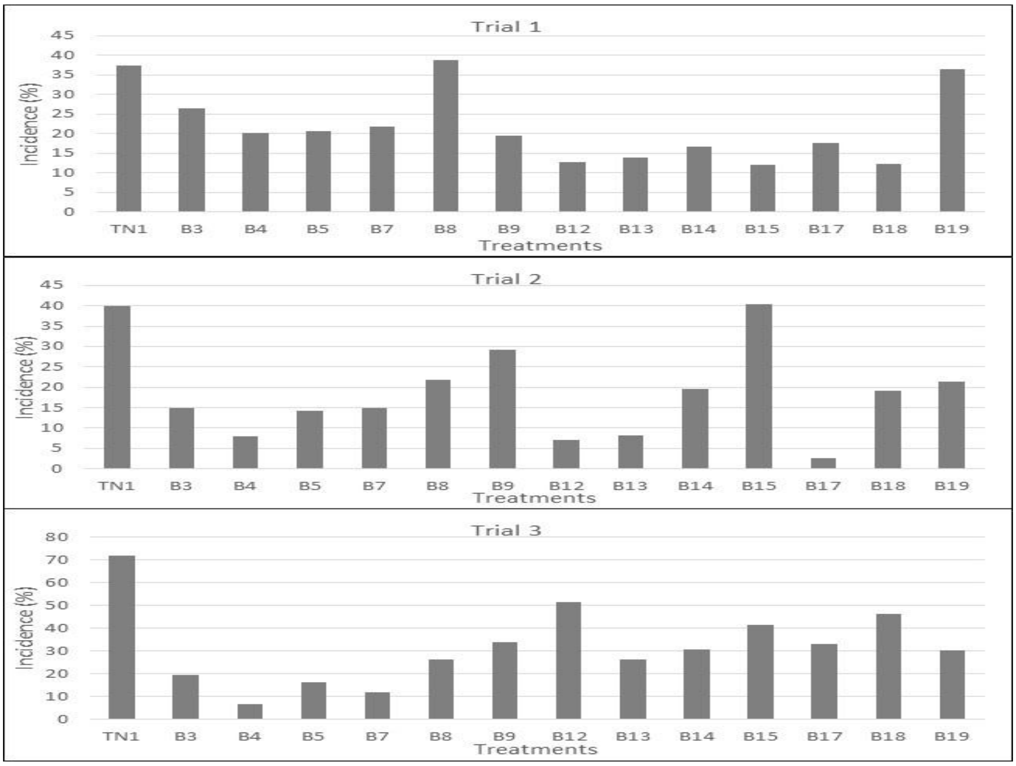


Figure 4. Percent BLB incidence of WR variants and TN1 variety inoculated at 30 DAS from three consecutive trials, 15 days after inoculation.

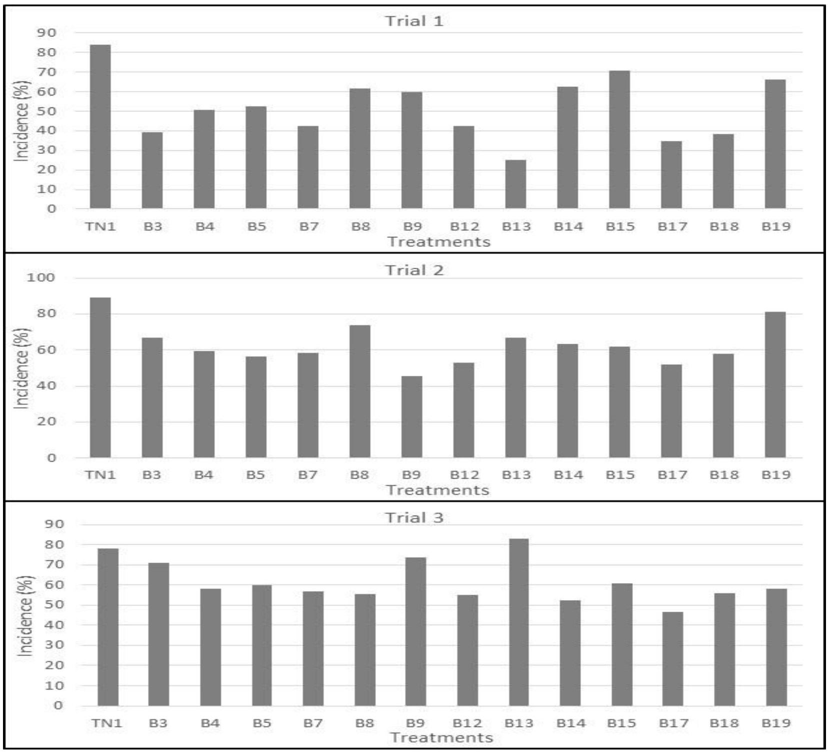


Figure 5. Percent BLB incidence of WR variants and TN1 variety inoculated at 45 DAS from three consecutive trials, 15 days after inoculation.

ANOVA indicates the significant interaction on the combined analysis of 3 trials on WR variants inoculated with RTD at 30 and 45 DAS (Table 3). ANOVA result on BLB inoculation at 30 DAS also indicates insignificant interaction. However, significant interaction is noted at 45 DAS (Table 4).

Table 3. ANOVA results on the combined analysis of three consecutive trials for percent incidence of RTD on WR variants and TN1 variety.

Variable	*P-value*	
	30 DAS	**45 DAS**
Trial	.0000**	.0000**
Treatment	.0000**	.0000**
Trial:Treatment	.0110**	.0000**
CV	29.95%	33.55%

Table 4. ANOVA results on the combined analysis of three consecutive trials for percent incidence of BLB on WR variants and TN1 variety.

Variable	*P-value*	
	30 DAS	**45 DAS**
Trial	0.0131^{ns}	0.0001**
Treatment	0.0847^{ns}	0.0004**
Trial:Treatment	0.5178^{ns}	0.0086**
CV	15.05%	23.66%

WR-B10 from Pampanga and WR-B13 from Pangasinan had the lowest incidence of RTD after three consecutive trials (Table 5). These variants averaged 23 - 26% infection after inoculation at 30 and 45 DAS, compared with susceptible check TN1, which had 94.17% incidence. WR-B3 from Aurora averaged 3% incidence when inoculated at 45 DAS; also rated as intermediate incidence with 36% infection when inoculated at 30 DAS. Resistance against RTD consists of resistance to the vector and/or to the viruses; the latter could further be divided into resistance to virus infection and tolerance to virus multiplication (Nemoto and Habibuddin, 1998). Azzam and Chancellor (2002) asserted that "the tungro virus populations in the field are heterogenous, and that the balance of variants shifts between seasons," indicating strong selection pressure that may result in the breakdown of resistance.

Most of the WR collected had intermediate incidence to RTD with less than 61% infection when inoculated at 30 DAS. Only three variants WR-B2, WR-B6, and WR-B19 were found susceptible. All variants had intermediate incidence when inoculated at 45 DAS. Phenotypic characteristics of WR can be related to its disease resistance. Early maturation of weedy rice collected from Nueva Ecija and Iloilo was reported by Martin et al. (2014) and Donayre et al. (2016), respectively. Nemoto and Habibuddin (1998) reported that RTSV resistance in Basmati 370 showed

Table 5. Average percent RTD incidence of weedy rice variants and TN1 variety from three consecutive trials, 15 days after inoculation.

Weedy Rice Variants	30 DAS		45 DAS	
	Average	Reaction	Average	Reaction
WR-B1	53.3	S	16.7	R
WR-B2	65.0	S	36.7	I
WR-B3	36.7	I	3.33	R
WR-B4	60.0	S	40.0	I
WR-B5	60.0	S	36.7	I
WR-B6	66.7	S	43.3	I
WR-B7	60.0	S	26.7	I
WR-B8	49.2	I	36.7	I
WR-B9	33.3	I	43.3	I
WR-B10	23.3	R	23.3	R
WR-B11	56.7	S	35.0	I
WR-B12	46.7	I	40.0	I
WR-B13	26.7	I	25.0	R
WR-B14	53.3	S	30.0	I
WR-B15	30.0	I	26.7	I
WR-B16	36.7	I	26.7	I
WR-B17	30.0	I	40.0	I
WR-B18	53.3	S	40.0	I
WR-B19	66.7	S	45.0	I
WR-B20	33.3	I	38.3	I
TN1	88.3	S	100.0	S

R - resistant, I – intermediate resistant, S - susceptible.

genetic relationship with the grain width and early maturation.

Resistance in cultivars was due to both antibiosis and non-preference to adult leafhoppers (Hibino et al., 1987). Shibata et al. (2007) suggested that tolerance to tungro viruses and resistance to GLH both contribute to the apparent resistance against RTD in IR 73885-1-4-3-2-1-6 (Matatag 9), although possible involvement of other resistance mechanisms cannot be ruled out.

Wild rice types have also been known to carry different levels of resistance to pests and diseases. With extremely poor plant type, however, they are backcrossed with the improved plant-type line as the recurrent parent to improve the progeny's stand. Three accessions of *Oryza rufipogon* (Acc. Nos. 105908, 105909, and 105910) and one accession of *O. longistaminata* (Acc. No. 110404) with tolerant reaction to the rice tungro bacilliform virus (RTBV) and resistant reactions to the rice tungro spherical virus (RTSV) and the vector green leafhopper (GLH) are presently used as donor and recurrent parents in breeding for tungro resistance (Angeles et al. 2008).

Twelve WR variants had intermediate disease incidence to BLB with less than 26% infection when inoculated at 45 DAS (Table 6). Variant 4 had the least infection of 12% while all variants were susceptible to BLB when inoculated at 30 DAS.

Table 6. Average percent BLB incidence of weedy rice variants and TN1 variety from three consecutive trials, 15 days after inoculation.

Weedy Rice Variants	30 DAS		45 DAS	
	Average	Reaction	Average	Reaction
WR-B1	88.17	S	21.64	I
WR-B2	72.35	S	22.45	I
WR-B3	58.93	S	20.25	I
WR-B4	56.06	S	11.59	R
WR-B5	56.31	S	17.18	I
WR-B6	59.83	S	18.39	I
WR-B7	52.64	S	16.20	I
WR-B8	63.55	S	28.91	S
WR-B9	59.72	S	27.49	S
WR-B10	78.31	S	27.44	S
WR-B11	56.26	S	39.02	S
WR-B12	50.27	S	23.75	I
WR-B13	58.38	S	16.07	I
WR-B14	59.39	S	22.38	I
WR-B15	64.47	S	31.24	S
WR-B16	56.46	S	17.23	I
WR-B17	44.35	S	17.79	I
WR-B18	50.58	S	22.87	I
WR-B19	68.62	S	29.37	S
WR-B20	46.30	S	30.83	S
TN1	84.37	S	49.72	S

R - resistant, I – intermediate resistant, S - susceptible.

Due to the limited material available on the disease-resistant traits of weedy rice (Jia and Dealy, 2018), it is necessary to conduct screenings and related studies to identify the traits that make WR competitive in the field. In a study conducted on blast resistance genes, the sequence analysis of weedy red rice showed several new Pi-ta haplotypes and nearby genomic regions having novel blast resistance genes (Lee et al, 2009 as cited by Jia and Gealy, 2018), which led to the suggestion that weedy red rice may have evolved with novel genetic mechanisms to prevent rice diseases.

Confirmation Trial for RTD and BLB-Resistant Weedy Rice Rice Tungro Disease (RTD)

The pre-selected WR variants showed low RTD incidence with a rating of 0 - 40% infection when inoculated at 30 and 45 DAS. The RTD-infected plants showed a slight shortening of internodes or a 1 - 10% reduction in plant height with no distinct yellow

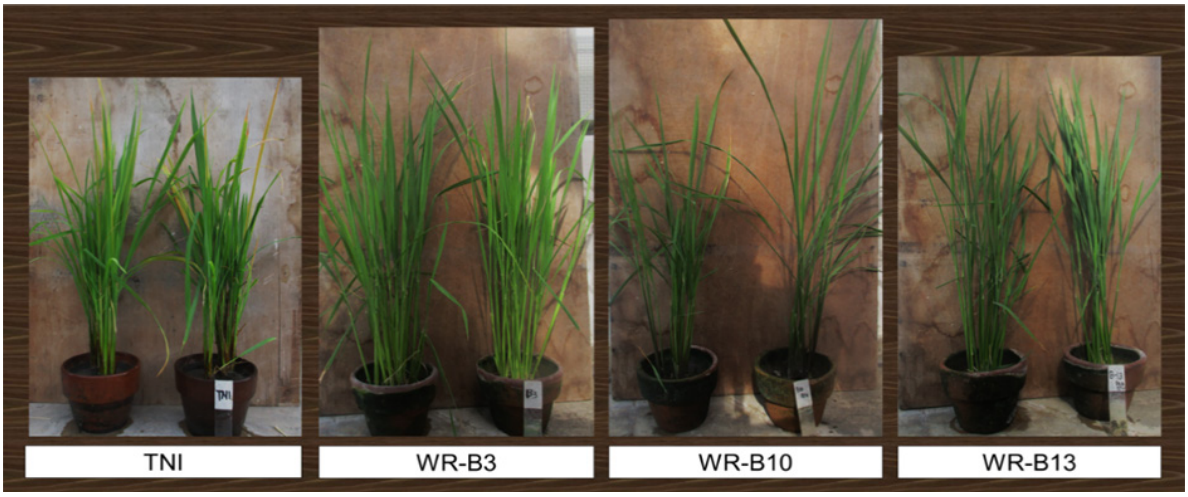


Figure 6. Reactions of weedy rice variants and TN1 variety to RTD.

to yellow-orange leaf discoloration (Figure 6). The variant from Aurora (WR-B3) had the least infection of 0%. Variants that had low disease reaction (0 - 20% infection) regardless of inoculation time were selected to further study for possible rice breeding. Thus, WR-B3 can be among the potential parent materials for breeding RTD-resistant rice (Table 7).

Table 7. Percent incidence of RTD on weedy rice variants and TN1 variety from confirmation trial at 15 days after inoculation.

Weedy Rice Variants	30 DAS		45 DAS	
	Average	Reaction	Average	Reaction
WR-B3	0	R	0	R
WR-B10	40	I	30	I
WR-B13	30	I	10	R
WR-B15	30	I	30	I
TN1	100	S	100	S

R - resistant, I – intermediate resistant, S - susceptible.

Bacterial Leaf Blight (BLB)

Percent incidence ratings from three trials were summarized to determine variants with lowest infection to intermediate reaction to BLB (Table 8). Only WR-B4 had lowest reaction to BLB, while the other 12 selected variants had intermediate reaction. WR-B6, which had an intermediate reaction, was not selected due to the unavailability of viable seeds. The confirmation trial in 2016 dry season shortlisted the 13 variants into only four; three of which had intermediate reaction, while WR-B4 had lowest disease reaction with an average infection of 8.24% when inoculated at 30 DAS. WR-B4 can be recommended for further study to be considered as parent material for breeding to produce a BLB-resistant variety. All WR variants were susceptible to BLB when inoculated at 45 DAS.

Table 8. Percent incidence of BLB on weedy rice variants and TN1 variety from confirmation trial at 14 days after inoculation.

Weedy Rice Variants	30 DAS		45 DAS	
	Average	Reaction	Average	Reaction
WR-B1	25.89	S	53.43	S
WR-B2	43.72	S	61.83	S
WR-B3	24.94	I	51.81	S
WR-B4	8.24	R	59.99	S
WR-B5	24.72	I	64.81	S
WR-B6	13.33	I	64.95	S
WR-B7	27.12	S	47.75	S
WR-B12	31.29	S	65.51	S
WR-B13	49.6	S	61.71	S
WR-B14	48.04	S	54.54	S
WR-B17	48.13	S	81.17	S
WR-B18	46.86	S	42.27	S
TN1	64.85	S	90.72	S

R - resistant, I – intermediate resistant, S - susceptible.

Conclusion

The potential of weedy rice as donor parent was explored and evaluated in this study. Weedy rice has lower incidence of RTD and BLB when infected at an older stage. This affirms its potential as possible source of resistance to develop RTD and BLB-resistant varieties. Further studies on variants WR-B3 for RTD and WR-B4 for BLB can be done and considered as parent materials for breeding RTD and BLB resistant varieties.

Literature Cited

Angeles ER, Cabunagan RC, Tabien RE, Khush GS (2008) Resistance to tungro vectors and viruses. *In* Tiongco ER, Angeles AE, Sebastian LS (Eds.). The Rice Tungro Virus Disease: A Paradigm in Disease Management (pp 93-114). Philippines: Philippine Rice Research Institute

Arashi A (1974) Consideration of Red Rice in Japan. Tokyo: Yusankaku

Azmi M, Abdullah MZ, Mislamah B, Baki BB (2000) Management of weedy rice (*Oryza sativa* L.) The Malaysian experience. *In* Baki BB, Chin DV, and Mortimer M. (Eds.). Wild and weedy rice in rice ecosystems in Asia—A review (pp 91-96). Philippines: International Rice Research Institute

Azzam O, Chancellor TCB (2002) The Biology, Epidemiology, and Management of Rice Tungro Disease in Asia. Plant Disease **86**(2): 88

Azzam O, Cabunagan RC, Chancellor T (2000) Methods for evaluating resistance to rice tungro disease. IRRI Discussion paper series no. 38. Philippines: International Rice Research Institute

Baltazar AM, Janiya, JD (2000) Weedy rice in the Philippines. *In* Baki BB, Chin DV, Mortimer M (Eds.). Wild and weedy rice in rice ecosystems in Asia—A review (pp 75-78). Philippines: International Rice Research Institute

Chauchan BS (2013) Management Strategies for Weedy Rice in Asia. Philippines: International Rice Research Institute

Delouche JC, Labrada R, Rosell CH (2007) Weedy Rices: Origin, Biology, Ecology, and Control. Rome: Food and Agriculture Organization of the United Nations

Donayre DKM, Martin EC, Casimero MC (2016) Incidence, growth, and agronomic characteristics of weedy rice variants from Iloilo province, Philippines under field and screenhouse conditions. IAMURE International Journal of Ecology and Conservation **19**:37-52

Biodiversity International (2007) Descriptors for wild and cultivated Rice (*Oryza spp.*) https://www.bioversityinternational.org/e-library/publications/detail/descriptors-for-wild-and-cultivated-rice-oryza-spp/

Fajardo FF, Moody K (1995) Rice off-types in Central Luzon, Philippines. Int. Rice Res. Notes **20**: 9-10

Ferrero A (2003) Weedy rice, biological features and control. *In* Labrada, R. (Ed.). Weed Management for Developing Countries: Addendum 1. (pp 89-107). Rome: FAO

Guzman, MP (1996) Germination, Life Cycle, and Gross Morphology of Two Types of Weedy Rice (*Oryza sativa* L.). (Unpublished Dissertation). Visayas State College of Agriculture, Philippines

Hibino H, Tiongco ER, Cabunagan RC, Flores ZM (1987) Resistance to rice tungro-associated viruses under experimental and natural Conditions. The American Phytopathological Society **77(**6): 871-874

Jia Y, Gealy D (2018) Weedy red rice has novel sources of resistance to biotic stress. The Crop Journal **6**(5): 443-450

Khush GS, Angeles E, Virak PS, Brar DS (2004) Breeding rice for resistance to tungro virus at IRRI. SABRAO Journal of Breeding and Genetics **36**(2): 101-106

Khush GS, Ling, KC (1974) Inheritance of resistance to grassy stunt virus and its vector in rice. Journal of Heredity **65**: 134-136

Khush GS (1977). Disease and insect resistance in rice. Advances in Agronomy **29**: 265-341

Lee S, Constanzo S, Jia Y, Olsen K, Caicedo A (2009) Evolutionary dynamics of the genomic region around the blast resistance gene Pi-ta in AA genome *Oryza* species. Genetics **193**: 1315-1325

Luat NV (2000) Integrated weed management and control of weeds and weedy rice in Vietnam. *In* Baki BB, Chin DV, Mortimer M. (Eds.). Wild and weedy rice in rice ecosystems in Asia - A review (pp 1-3). Philippines: International Rice Research Institute

Martin EC, Donayre DKM, Casimero MC (2014) Prevalence, agronomic characteristics and biology of weedy rice variants of Nueva Ecija. IAMURE International Journal of Ecology and Conservation **12**: 86-99

Moody K (1994) Weedy forms of rice in Southeast Asia. Paper presented at the Padi Angin Workshop, May 18, 1994. Penang, Malaysia

Morishima H, Sano Y, Oka HI (1984) Differentiation of perennial and annual types due to habitat conditions in the wild rice *Oryza perennis*. Plant Syst. Evol **144**: 119-135

Natarajkumar P, Sujatha K, Laha GS, Viraktamath BC, Reddy CS, Mishra B, Balachandran SM, Ram T, Srinivasarao K, Hari Y, Sundaram M (2010) Identification of a dominant bacterial blight resistance gene from *Oryza nivara* and its molecular mapping. Rice Genetics Newsletter **25**: 54-55

Nemoto H, Habibuddin H (1998) Mechanism and inheritance of resistance to rice tungro disease in rice varieties Basmati 370 and IR 50. Jpn. J. Trop. Agr. **42** (2): 111-118

PhilRice [Philippine Rice Research Institute] (2016) Pinoy Rice Knowledge Bank. https://www.pinoyrice.com/rice-varieties/

Platino ND (1996) Survey and Characterization of Different Types of Weedy Rice in Baybay, Leyte. (Unpublished Dissertation). Visayas State College of Agriculture, Philippines

Pyon JY, Kwon WY, Guh JO (2000) Distribution, emergence, and control of Korean weedy rice. *In* Baki, BB, Chin, DV, and Mortimer, M. (Eds.). Wild and Weedy Rice in Rice Ecosystems in Asia - A review (pp 37-44). Philippines: International Rice Research Institute

Rathore M, Singh R, Kumar B, Chauchan BS (2016) Characterization of functional trait diversity among Indian cultivated and weedy rice populations. Sci Rep **6**. https://doi.org/10.1038/srep24176

Ravelo GB, Abdula SE, Truong XH, Batay-an EH, D.A. Tabanao, M.G.M. Babb, and L.S. Sebastian (2008) The tungro-resistant Matatag lines in the Philippines. *In* ER Tiongco, ER Angeles, LS Sebastian (Eds.). The Rice Tungro Virus Disease: A Paradigm in Disease Management. Philippines: Philippine Rice Research Institute and Honda Research Institute Japan Co. Ltd

Royal Horticultural Society (RHS) (1986) R.H.S. Colour Chart (Edn. 1,2). London: Royal Horticultural Society

Sato YI (2000) Origin and evolution of wild, weedy, and cultivated rice. *In* Baki BB, Chin DV, Mortimer, M (Eds.), Wild and Weedy Rice in Rice Ecosystems in Asia - A review (pp 7-15). Philippines: International Rice Research Institute

Second GA (1991) Report on *Oryza officinalis* as a weed and a new genome. A weed which appeared last year. Report on observation made by Dr. Gerard Second on a trip to San Jose area (Occidental Mindoro), weekend of Oct 19-20, 1991. Philippines: International Rice Research Institute

Shibata Y, Cabunagan RC, Cabauatan PQ, Choi I (2007) Characterization of *Oryza rufipogon*-derived resistance to tungro disease in rice. Plant Disease **91**(11):1386-1391

Tateoka T, Pancho JV (1963) Report on exploration for wild rice species of *Oryza* in the Philippines. https://shigen.nig.ac.jp/rice/oryzabase/ebook/ricereport/part1/en/#136

Watanabe H, Vaughan DA, Tomooka N (2000) Weedy rice complexes: Case studies from Malaysia, Vietnam, and Surinam. *In* Chin DV, Baker B, and Mortimer M (Eds.). Wild and Weedy Rice in Rice Ecosystems in Asia: A Review (pp 25-34). Philippines: International Rice Research Institute

CALL FOR PUBLICATION

Rice-Based Biosystems Journal

SCOPE

The Rice-Based Biosystems Journal encourages publication of original research and review articles that have impact on applied and integrated rice and rice-based cropping systems in a particular ecosystem. The Journal provides information on rice-based researches on soil and crop management, crop protection, crop improvement, grain quality, farm machinery, resource use efficiency, plant biology, nutraceuticals, food value-adding systems, biofertilizers, biopesticides, biomaterials, and system analysis and simulation. It also covers the economics, social, and communication systems that influence the landscape of rice and rice-based cropping systems.

AUTHOR'S GUIDELINES

1. Submission and Acceptance of Manuscripts

Manuscripts are submitted to Rice-Based Biosystems Journal: rbbj.philrice@gmail.com. Manuscripts should be formatted as described in the Rice-Based Biosystems Journal Author Guidelines and follow the PhilRice style guide. When preparing your file, please use Times New Roman as font type, and 12 as font size for the text. Please do not use Japanese or other Asian fonts. Do not use automated or manual hyphenation. With your submission, you will have to complete, sign, and send the Copyright Transfer Agreement. Authors may provide names of potential reviewers for their manuscript. Authors must inform the editorial assistant of any possible conflict of interest capable of influencing their judgement, and if necessary, a disclaimer will be included. Revised manuscripts must be submitted two weeks after the authors are notified of conditional acceptance pending satisfactory revision. Authors resubmitting manuscripts should follow the same procedures as for submission of new manuscripts. If accepted, papers become the copyright of the journal. Photos and tables must be high resolution scans (JPEG at 300 dpi).

2. Requirements for Manuscripts

2.1. Language

The language of publication is English.

2.2. Format

The first page should contain the name and address of the institute where the work has been done, the title of the paper, name(s) and initial(s) of the author(s), the e-mail address of the corresponding author, and the number of figures and tables.

The main text shall be preceded by an abstract, which is always in English and contains the background for the research undertaken, reference to the material and methods used, as well as main results and conclusions. It should not exceed 220 words. Up to seven 'keywords' should be added. A short version of the title (running title) should also be given.

The main text should be divided into the following sections: Introduction, Materials and Methods, Results and Discussion, Conclusion, Recommendation, Acknowledgment, and Literature Cited. Facts explained by tables or figures need no lengthy explanation in the text. Numerical material should be submitted only after statistical processing.

The manuscript comprises a printout of the text and a list of all figures and tables with their captions and titles on a separate piece of paper. In anticipation of the online edition, we ask that you convey the essential information within the first 60 characters of the captions. Each figure, table, and bibliographic entry must have a reference in the text. The preferred position for the insertion of figures and tables should be marked on the margin of the text of the manuscript. Any corrections requested by the reviewer should already be integrated into the file. The text should be prepared using standard software (Microsoft Word). Please do not include footnotes.

2.3. Length

The manuscript should be typed double spaced with a 4 cm left margin. Manuscripts, including figures and tables, should not exceed 25 printed pages. The publication of shorter papers may be given priority.

2.4. Units, Abbreviations, and Nomenclature

All units and measures must conform to the international standard-system (SI). Botanical genus and species names should be set in italics.

2.5. Illustrations and Tables

The number of tables and figures should be kept to the minimum necessary, and have a maximum of 13 cm in height and 17 cm in width. All figures should include reproducible copies marked with the author's name, short title, and figure number. Figures submitted as electronic file should be saved in PNG instead of JPEG for better quality. Powerpoint and Word graphics are unsuitable for reproduction.

Submit high-contrast photographic materials suitable for reproduction. Images should be of high quality with respect to detail, contrast, and fineness of grain to withstand the inevitable loss of contrast and detail during the printing process.

Scanned figures (usually in JPEG format) should have a resolution of 300 dpi (halftone) or 600 to 1200 dpi (line drawings) in relation to the reproduction size. You may submit figures in color or black and white. Graphs with an x and y axis should not be enclosed in frames; only 2-dimensional representations. Place labels and units.

Captions for the figures should give a precise description of the content and should not be repeated within the figure. Tables should be created with the table function of a word processing program. Spreadsheets are not acceptable.

2.6. References

The literature cited should be arranged alphabetically and contain: the author's surname, first name and middle initial, year of publication, title of paper, name of journal, volume number, and first and last page number of the publication.

Bibliographic references to books or other established publications should contain: author's surname, first name and middle initial, year of publication, and edition, publishing house and place of publication. The name of the author and the date of publication should be included within the text. If more than one publication of the same author appeared in one year, these should be marked by small letters after the year, e.g., 2015a; 2015b. References to publications by more than two authors should be cited as follows: Luna et al. (2015) or (Luna et al., 2015).

3. Copyright

If your paper is accepted, the author identified as the formal corresponding author for the paper will receive an email.

4. Proof Corrections and Offprints

The corresponding author will receive an e-mail with the laid out publication. A working e-mail address must therefore be provided for the corresponding author. Further instructions will be sent with the proof. We will charge for excessive changes made by the author in the proofs, excluding typesetting errors.

5. Submission and Acceptance of Research Notes

A research note is a short discussion on key research findings and advances on a particular theory, study, or methodology that does not sum up to a full research article. The format and guidelines of a research note resembles that of a full-length manuscript except for the number of words, figures and/or tables. A 3000 to 4000-word paper with an abstract and a maximum of 2 figures and/or 2 tables may be submitted as a research note.

6. Submission of Invited Papers

The Editorial Team can invite a member of the Advisory Board and Editorial Board of the Rice-Based Biosystems Journal or an expert to submit a paper in line with the theme of the volume to be published. Invited papers may be in the form of a full paper, research note or a review article. A review article gives information on a particular field of study, recent major advances and discoveries, significant gap in the research, current debates, and ideas or recommendations for future advances.

At least one expert on the subject matter will review the invited paper. Instructions for submitting a full paper and research note are in numbers 1-5 of the author guidelines.

6.1 Format

The Abstract consists of 220 words or less that summarizes the topic of the review. The current challenges and perspective on the topic are addressed, with significant conclusion and recommendations.

The Introduction states the purpose of the review. It presents a short background of the nature of the problem and its aspects of being resolved. The limitations of current solution or studies are included.

The Body presents the current studies and major advances or discoveries and impact on the present situation of the problem. Evaluation of studies such as applicability and availability of the methods used to certain areas and situation or statistical significance are elaborated.

The Conclusion summarizes the overall or major impacts and main points of the current studies. Recommendations for future advances of the research on the subject matter are presented.

The Literature Cited follows the instructions in number 2.6 of the author guidelines.

EDITORIAL POLICY

Authors should:

- designate a corresponding author who will be responsible in coordinating issues related to submission and review, including ensuring that all authorship disagreements are resolved appropriately;
- submit original work that has been honestly carried out according to rigorous experimental standards;
- give credit to the work and ideas of others that led to their work or influenced it in some way;
- declare all sources of research funding and support;
- submit manuscripts that are within the scope of the journal by ensuring that they abide by the journal's policies and follow its presentation and submission requirements;
- explain in a cover letter if there are special circumstances when the manuscript deviates in any way from a journal's requirements or if anything is missing and ensure that the manuscripts do not contain plagiarized material or anything that is libelous, defamatory, indecent, obscene or otherwise unlawful, and that nothing infringes the rights of others;
- ensure they have permission from others to cite personal communications and that the extent, content, and context have been approved;
- provide details of related manuscripts they have submitted or have in press elsewhere; and
- check the references cited to ensure that the details are correct.

Authors should not:

- submit the same or a very similar manuscript to more than one journal at the same time, present their work, or use language, in a way that detracts from the work or ideas of others;
- be influenced by the sponsors of their research regarding the analysis and interpretation of their data or in their decision on what to, or not to publish and when to publish;
- divide up the papers inappropriately into smaller ones in an attempt to increase their list of publications;
- be involved in 'ghost' or 'gift' authorship;
- use information privately obtained without direct permission from the individuals from whom it was obtained;
- make exaggerated claims about the novelty or significance of their findings;
- misrepresent or inappropriately enhance their results by any means;
- make significant changes to their manuscript after acceptance without the approval of the editor or journal editorial office; and
- submit a manuscript that has been rejected by one journal to another journal without considering the reviewers' comments, revising the manuscript, and correcting presentational errors.

Philippine Rice Research Institute
Central Experiment Station
Maligaya, Science City of Muñoz, 3119 Nueva Ecija

We are a government corporate entity (Classification E) under the Department of Agriculture. We were created through Executive Order 1061 on 5 November 1985 (as amended) to help develop high-yielding and cost-reducing technologies so farmers can produce enough rice for all Filipinos.

With our "Rice-Secure Philippines" vision, we want the Filipino rice farmers and the Philippine rice industry to be competitive through research for development work in our central and seven branch stations, coordinating with a network that comprises 59 agencies strategically located nationwide.

We have the following certifications: ISO 9001:2015 (Quality Management), ISO 14001:2015 (Environmental Management), and OHSAS 18001:2007 (Occupational Health and Safety Assessment Series).

PHILRICE CENTRAL EXPERIMENT STATION Maligaya, Science City of Muñoz, 3119 Nueva Ecija
Tel: (44) 456 -0277 • Direct line/Telefax: (44) 456-0354

BRANCH STATIONS:
PhilRice Batac, MMSU Campus, Batac City, 2906 Ilocos Norte; Telefax: (77) 772-0654; 670-1867; Tel: 677-1508 Email: batac.station@philrice.gov ph
PhilRice Isabela, Malasin, San Mateo, 3318 Isabela; Mobile: 0908-875-7955; 0927-437-7769; Email: isabela.station@philrice.gov.ph
PhilRice Los Baños, UPLB Campus, College, 4030 Laguna; Tel: (49) 536-8620; 501-1917; Mobile: 0920-911-1420; Email: losbanos.station@philrice.gov.ph
PhilRice Bicol, Batang Ligao City, 4504 Albay;Tel: (52) 284-4860; Mobile: 0918-946-7439; Email: bicol.station@philrice.gov.ph
PhilRice Negros, Cansilayan, Murcia, 6129 Negros Occidental; Mobile: 0949-194-2307; 0927-462-4026; Email: negros.station@philrice. gov.ph
PhilRice Agusan, Basilisa, RTRomualdez, 8611 Agusan del Norte; Telefax: (85) 343-0768; Tel: 343-0534; 343-0778; Email: agusan.station@philrice.gov.ph
PhilRice Midsayap, Bual Norte, Midsayap, 9410 North Cotabato; Telefax: (64) 229-8178; 229-7241 to 43 Email: midsayap.station@philrice.gov.ph
PhilRice Field Office, CMU Campus, Maramag, 8714 Bukidnon; Mobile: 0916-367-6086; 0909-822-9813

SATELLITE STATIONS:
Mindoro Satellite Station, Alacaak, Sta. Cruz, 5105 Occidental Mindoro • Mobile: 0917-714-9366; 0948-655-7778
Samar Satellite Station, UEP Campus, Catarman, 6400 Northern Samar • Mobile: 0948-754-5994; 0929-188-5438
Zamboanga Satellite Station, WMSU Campus, San Ramon, 7000 Zamboanga City • Mobile: 0910-645-9323; 0975-526-0306

Liaison Office, 3rd Floor. ATI Bldg, Elliptical Road, Diliman, Quezon City; Tel/Fax: (02) 8 920-5129

www.philrice.gov.ph www.pinoyrice.com | 0917-111-7423 | DA-PhilRice | prri.mail@philrice.gov.ph | PhilRice TV

SOCOTEC ISO 9001 ISO 14001 OHSAS 18001

CALL FOR PAPERS

The Rice-Based Biosystems Journal is a peer-reviewed online and an open-accessed journal in The University Library of University of the Philippines Diliman, and Cagayan State University Library. It is managed by the Philippine Rice Research Institute (PhilRice) through a competent editorial team, reputable advisory and editorial boards, and invited referees. The journal encourages publication of original research and review articles that have impact on and are interconnected with rice and rice-based crops. It publishes rice and rice-based research studies on soil and crop management, crop protection, crop improvement, grain quality, farm machinery, resource use efficiency, plant biology, nutraceuticals, food value-adding systems, biofertilizers, biopesticides, biomaterials, and systems analysis and stimulation. It also covers the economics, social, and communication systems that may influence the landscape of rice and rice-based production. For your submission, you can email your manuscript to rbbj.philrice@gmail.com with subject and file format as: RBBJ_Title_Surname.doc. For more information about the journal, please visit www.philrice.gov.ph/grants/call-publication/.

RICE-BASED BIOSYSTEMS JOURNAL
Volume 8 • February 2021

CALL FOR PAPERS

visit www.philrice.gov.ph/grants/call-publications/

Mailing address:
PhilRice Central Experiment Station
Science City of Muñoz, 3119 Nueva Ecija

Philippine Rice Research Institute
Central Experiment Station
Maligaya, Science City of Muñoz, 3119 Nueva Ecija