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Trichoderma inoculants and straw compost improved resilience and yield in Cu-contaminated rice paddies

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Abstract. *Cuevas VC, Banaay CGB. 2022.* Trichoderma *inoculants and straw compost improved resilience and yield in Cu-contaminated rice paddies. Nusantara Bioscience 14: 1-9.* Rice paddies in Marinduque, Philippines, are copper-contaminated from tailings of two mining companies formerly operating in the province. At present, paddy-soil copper concentration ranges from 22-386 mg kg^{-1}. Crops suffer from copper toxicity and water stress due to climate-related events. The field study investigated the ability of in situ composted rice straw and *Trichoderma* microbial inoculant (TMI) to mitigate rice productivity constraints. In treated set-ups, rice straw was scattered on the paddy after harvest. Triple 14 mineral fertilizer was mixed with *Trichoderma* compost activator, broadcasted over the straws, and subsequently incorporated into the soil during land preparation. Rice seeds were TMI-coated before sowing. Rice straw composting was not done in control set-ups, and seeds were uncoated. Mineral fertilizers were applied to both set-ups. Furthermore, set-ups were categorized based on soil Cu content, such as normal, moderate, and high. Four replicates were made per season and category. Rice leaves did not show yellowing in treated paddies, indicating adequate N mineralization and plant uptake. The difference in yield was significantly higher (81%) in treated paddies compared to the control. During severe drought conditions, the mean yield in treated paddies was 1.8 t ha^{-1}, while that of control paddies was zero. The yield was significantly correlated with K inputs, mainly by compost in treated paddies. Applying rice straw compost and *Trichoderma* inoculants can be an adaptive strategy for climate change resilience and mitigation of copper toxicity in crops.

Keywords: Copper toxicity, rice, rice straw compost, *Trichoderma* activator, *Trichoderma* microbial inoculant, water stress

INTRODUCTION

Rice straw management is an essential component of rice cropping system sustainability through its conversion to compost. Rice straw is an abundant resource in all rice-growing regions of the world (Pangesti et al. 2012; Hayuningtyas et al. 2013). The national rice production average in the Philippines is around 4 tons ha^{-1} (PSA 2019). With two cropping seasons per year, a hectare of rice land can produce 5.6-8 tons ha^{-1} annually based on a straw-to-grain ratio of 0.7-1.0 (IRRI 2015b). Therefore, farmers can reduce mineral fertilizer inputs by converting rice straws to compost. Chivenge et al. (2020) mentioned that rice straws contain 80, 40, and 30% potassium (K), nitrogen (N), and phosphorus (P), respectively, which are available to the rice plant. Therefore, rice straw compost as a component fertilizer of the rice cropping system can reduce subsequent crop fertilizer requirements.

Furthermore, rice straw compost in soil reduces the impact of heavy metal contaminants on crops. Cuevas et al. (2014) reported that rice straw compost significantly improved soil pH, which decreased the availability of soil copper and significantly increased yield in rice paddies covered with mine tailings in Mankayan, Benguet. Moreover, Cuevas and Balangcod (2020) have found that the build-up of soil organic matter (OM), with a consequent decrease in available Cu, is the driving force for ecological succession in areas covered with mine tailings. In addition to heavy metal contamination in some areas, Philippine agriculture faces a difficult challenge with the current global climate change phenomenon. The Philippines is an archipelago in the tropics, with frequent typhoons yearly. Therefore, the country is vulnerable to extreme weather events (IPCC Ocean and Cryosphere 2019) and weather pattern changes. For example, the El Nino Southern Oscillation typically has a 7-year cycle; however, this duration has shortened, as shown by what the country experienced last 2018-2019, just three years after a similar event in 2015. Reduced rainfall, drought, and stronger-than-usual typhoons characterize an El Niño year. Therefore, agricultural scientists must devise different adaptive strategies to mitigate the effect of such an erratic rainfall pattern. Conversion of rice straw into compost can be one strategy since compost, through an increase in soil organic matter, raises soil water-holding capacity and reduces the impacts of water scarcity on the crop while improving soil structure that supports the crop even in adverse weather conditions (Bot and Benites 2005).

Rice farmers do not practice composting rice straw despite the benefits derived from compost. This reluctance is because the usual composting through the heap method is labor-intensive and time-consuming. They also find it difficult to gather animal manure, a nitrogen source for composting. Farmers must also apply large quantities of compost to increase yield (IRRI 2015a). Furthermore, when incorporated into the soil, incompletely decomposed rice straw, followed by flooding of the field, can lead to nitrogen immobilization and cause yield decline. Such conditions can also lead to methane emissions that increase greenhouse gas concentrations (Devevre and Horwâth 2000). On the other hand, rice straw compost can significantly increase crop yield in mine waste-contaminated rice paddies compared to plots without compost (Cuevas et al. 2019). Likewise, the combination of compost and TMI increased yields more than the two factors applied singly. These results show that the harmful effects of using immature compost can be overcome with the proper procedures, and the farmers can derive enormous benefits from the practice. The present field study was conducted in Mogpog, Marinduque, to test whether a simple rice straw composting process and seed-coating with *Trichoderma* microbial inoculant could gain acceptance by farmers and help alleviate the harmful effects of water scarcity and copper toxicity on the crops.

MATERIALS AND METHODS

This study was conducted in Mogpog, Marinduque, Philippines, in 2018-2019, covering two dry and two wet seasons. Marinduque is a small island province located between Mindoro and Quezon provinces. Successive breaches in the tailing ponds in 1993 and 1996 and the intermittent overflow of ponds during heavy rains have led to the transport of copper to agricultural fields downstream (Figure 1). The two companies were extracting copper, and both stopped operations after the 1996 mining disaster. Since then, they have not resumed operations; however, the damage they have brought to the agricultural lands persists today.

Composite soil samples of contiguous paddies were taken from different sites identified by local people to be affected by mine tailings. The surface soil samples were taken at 0-20 cm depth. Samples were analyzed for pH, OM, P, K, and Cu contents. The soil Cu was analyzed as total Cu through the ICP-OES trace metal analysis method using HNO_3-H_2O_2 at a ratio of 7:3 (v/v) for the extraction. Soil pH and soil fertility parameters were analyzed according to Recel et al. (1988). Percentage OM was analyzed using the Walkley-Black method, available P through Bray method 1, and exchangeable K by ammonium acetate extraction (1 N ammonium acetate pH 7.0 with orbital shaking for 30 min). All analyses were done at the Agricultural Systems Institute, Division of Soil Science, College of Agriculture and Food Science, UP Los Baños.

Rice paddies were categorized as normal, moderate, or high based on soil Cu content. Information was taken from the results of soil analysis (Table 1) of samples taken before the start of the first cropping in the 2018 dry season (DS) and with guidance from existing literature (Mackie et al. 2012). The categories were as follows: normal (22-59 mg kg^{-1} Cu), moderate (110-144 mg kg^{-1} Cu), and high (290-386 mg kg^{-1} Cu).

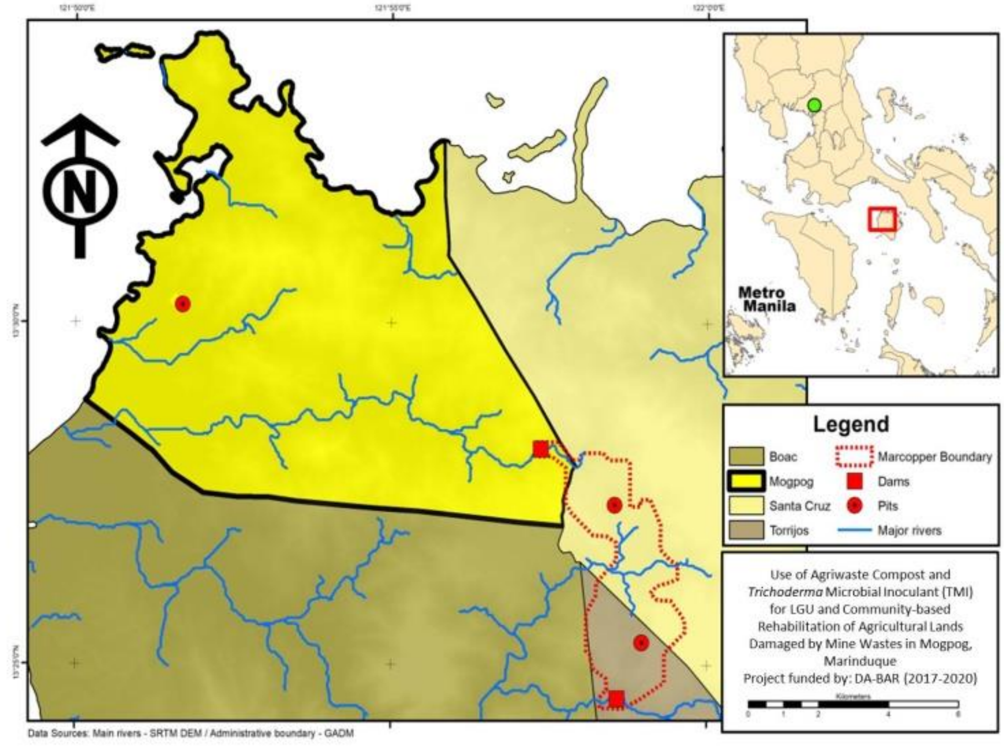

Figure 1. Map of Mogpog, Marinduque, Philippines, showing the locations of mine tailings dams and pits of two copper mining companies

Table 1. The average measurement of soil chemical properties of rice paddies at the start of the study (before DS 2018)

Soil Cu content ($mg\ kg^{-1}$) & category	No. of paddies tested	pH	OM (%)	N (%)	*P ($mg\ kg^{-1}$, Bray)	K ($cmolc\ kg^{-1}$ soil)	Cu ($mg\ kg^{-1}$)
22-59 (normal Cu content)	15	6.1	2.75	0.13	3.03	0.17	37
102-156 (moderate Cu content; contaminated)	11	5.09	2.42	0.14	7.88*	0.25	120
290-386 (high Cu content; severely contaminated)	15	5.32	1.94	0.11	3.13	0.29	290

Note: *Olsen method was used instead of Bray for analysis of P concentration

Trichoderma microbial inoculant (TMI) used in this study is a commercialized product developed at the University of the Philippines from strains isolated from leaf litter of Mt. Makiling in Los Baños, Laguna, Philippines. It consists of two strains of *Trichoderma ghanense* Doi (formerly identified as *T. pseudokoningii* Rifai) and one strain of UV-irradiated *T. harzianum* Rifai mixed in equal proportions. TMI was sold in a 250-g pack; 1 g contains 4.8×10^8 cfu g^{-1}. The *Trichoderma* compost activator used for in situ composting of rice straws is also commercially produced by BIOSPARK Corp. and consists of a local strain of *Trichoderma harzianum*. The farmer cooperators were given workshops on composting and TMI use before the start of the study. A total of 50 farmers maintained treated and the control paddies, while another 50 maintained only treated ones. In treated paddies, rice straw was scattered in paddy fields after harvest, and seeds were coated with TMI before sowing at a rate of 8.3 g kg^{-1}. The *Trichoderma* compost activator was applied to the rice straws scattered in the field after the previous season's harvest. Five kg per 0.43 ha (0.12 g m^{-2} or 12 kg ha^{-1}) triple 14 NPK mineral fertilizer was mixed with a *Trichoderma* activator and broadcasted on the scattered rice straw. The straws' initial C:N ratio was 57, then adjusted to 54 with mineral fertilizer, considering 40.7% C and 0.7% N (Nghi et al. 2020). According to package instructions, the straw was incorporated into the soil during the mechanized land preparation, and rice seeds were TMI-coated before seed sowing. Rice straw composting was not done in the control set-ups, and seeds were not coated with TMI.

Although the farmers were free to plant the inbred rice varieties of their choice, each practiced the same cultural management in treated and controlled paddies. The rice flag leaf greenness was assessed during the grain-filling stage using a Leaf Color Chart (LCC) to gauge leaf N status, reflecting N availability and uptake (Yang et al. 2003). Grain yield was measured according to the total weight of harvested grains divided by the paddy size measured in kg m^{-2} and later converted to t ha^{-1}. Nutrient inputs were computed as g m^{-2} (later converted to kg ha^{-1}) for both treated and control paddies. The N, P, and K contributions of rice straw compost in treated paddies were computed per season using the information from Dobermann and Fairhurst (2002) of 0.5%N, 0.16%P_2O_5, and 1.4%K_2O in dry straw. The amount of rice straw composted was based on the previous season's harvest. Except for DS 2018, the grain harvest in control paddies was used as a basis, assuming it was the harvest before the project started. The grain-to-straw ratio used was 1:1 (Dobermann and Fairhurst 2002). The same treatments and measurements were applied in all seasons covered by the study (DS-WS 2018 and DS-WS 2019).

In 2018, Mogpog received much-reduced rainfall compared to the previous two years (World Weather Online 2020), which persisted until August 2019 (PAGASA 2019). In Mogpog, the severity of water stress was affected by the field location and the distance from the irrigation canal. The crops suffered from water scarcity during the period of observation in addition to copper toxicity. Because these events cannot be controlled, the water-stress factor was considered in the data analysis. Water-stressed paddies were categorized into 6 groups starting with 0-no water stress from sowing to harvest. Level 1 water throughout the cropping period was present but was reduced compared to average years. Level 5 was designated when water was severely reduced throughout the cropping season. All levels between 1 and 5 depended on water availability during the different crop growth stages.

The paired t-test was used to compare rice grain yields, while Tukey's test was used to compare the mineral nutrient inputs of treated and control paddies. The multivariate analysis accounted for differences between treatments, copper levels, water stress, and interactions. In addition, regression analysis was performed to correlate yield parameters such as nutrient inputs, water stress, and soil copper level.

RESULTS AND DISCUSSION

The efficiency of rice straw decomposition

Figure 2 shows the crop stand in treated and control paddies with normal soil Cu content one month after transplant during the DS 2018. The figure shows that the observed trend is similar for all other seasons. In control paddies, leaves exhibited yellowing, indicating nitrogen deficiency, while in treated paddies, leaves had normal green color. This status was carried through the grain-filling stage, as shown in the LCC readings presented in Figure 2. Control plants had average LCC readings below three (2.33 and 2.17), while treated paddies had average LCC readings higher than three (3.5 and 3.67). LCC readings of three to four mean that the N content of the leaves was sufficient, and chlorophyll content was also enough for photosynthesis. LCC readings below three mean that the crop is deficient in N (Yang et al. 2003). Data on nitrogen application for treated and the control paddies with normal copper concentration are presented in Table 2. In contrast, data for moderately and severely contaminated paddies are presented in Tables 3 and 4. Tukey's test showed that treated paddies had significantly higher nutrient inputs (combined fertilizers and straw compost) than the control. Tables 2-4 also show that the number of nutrient inputs received by treated paddies under little or no water stress is less than the IRRI-recommended mineral inputs to achieve the grain yield attained in treated paddies. That implies that *Trichoderma* may cause higher nutrient use efficiency since it increases yields despite lower actual mineral inputs. Previous studies have determined that *Trichoderma* spp. can improve nutrient use efficiency and support higher crop yields with fewer mineral fertilizer inputs (Fiorentino et al. 2018; Visconti et al. 2020). In addition, TMI can support the development of greener flag leaves in rice compared to untreated plants (Cuevas 2006; Banaay et al. 2012), as observed in the present study. Flag leaves are important for rice productivity because they directly deliver 50% of photosynthates to the grains (Li et al. 1998; Acevedo-Siaca et al. 2021), thus enhancing grain yield. *Trichoderma* species can increase chlorophyll and photosynthesis-related activities in host plants (Harman and Shoresh 2008a), which is consistent with the observations in this study showing increased greenness of flag leaves and higher grain yield in treated plants compared to the control plants.

The sufficient nitrogen in treated paddies (as indicated by green leaves and >3 LCC readings presented in Figure 2) may have come from the mineral fertilizers applied. The contribution of the rice straw compost since initial test results showed low soil N content (Table 1) and low soil labile amino N. This non-yellowing of leaves showed that the decomposition of rice straw by the scatter method of composting with *Trichoderma* activator plus Triple 14 NPK was sufficient. The activator jump-started the process, while the mineral fertilizer provided the ready source of nutrients for the microbial decomposers during the composting (Cuevas et al. 2019). The *Trichoderma* activator used in the study has been previously shown to effectively accelerate the decomposition process (Cuevas et al. 1988), thus allowing the rapid composting of rice straw in the field. As a result, there was no evidence of N immobilization and mineralization. Guo et al. (2018) mentioned that partially decomposed rice straw returned to the rice field, causing N deficiency and yield decline. Chivenge et al. (2020) added that partially decomposed straw had potentially adverse effects on nutrient availability and the use-efficiency of applied fertilizers for the subsequent crop. However, in this study, there was a higher yield in the treated than in the control paddies, as presented in Tables 2-4. TMI may have also aided in the mineralization of nutrients from the compost. Cuevas (2006) has shown that *Trichoderma pseudokoningii* (= *T. ghanense*, Banaay et al. 2012), a TMI component species enhances nutrient mineralization from organic matter.

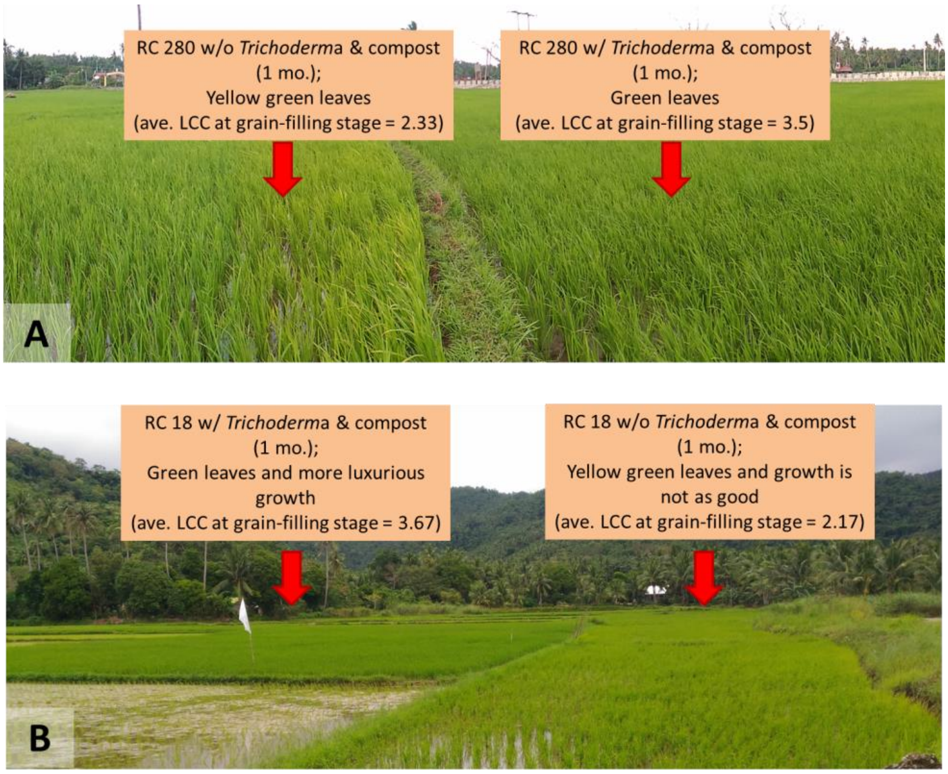

Figure 2. Comparison of standing rice crop during the 2018 dry season with the leaf color chart (LCC) readings for the same crop stand at the grain-filling stage. A. Farmer's field at Anapog-Sibucao with normal (42 mg kg^{-1}) soil Cu content and B. Farmer's field at Ino with Cu-contaminated soil (122 mg kg^{-1}); both sites are located in Mogpog, Marinduque, Philippines

Table 2. Comparison of yield, mineral fertilizers, and seasonal water stress level during the four seasons crop of 2018-2019 for paddies with normal Cu content (22-59 mg kg^{-1})

Seasons	Mean water stress level	Treated (w/ rice straw compost + TMI)				*Recommended mineral inputs for the attained yield in treated paddies (kg ha^{-1})			Control (no rice straw compost, no TMI)			
		Mean yield (t ha^{-1})	Mean nutrients applied (fertilizer + compost) (kg ha^{-1})						Mean yield (t ha^{-1})	Mean mineral fertilizer applied (kg ha^{-1})		
			N	P	K	N	P	K		N	P	K
DS 2018	1	5.7	45	19	19	57	14	36	4.5	39	5.0	5.0
WS 2018	3	3.4	58	21	21	34	8.5	21	1.9	48	11	11
DS 2019	5	2.2	44	48	4.8	22	6.2	14	0	0	0	0
WS 2019	1.6	3.8	42	10	10	38	9.5	24	2.1	22	3.5	3.5
Ave		3.8	47	13.7	13.7	38	9.0	22.8	2.1	28	5.0	5.0

Note: *IRRI (2015a,b)-Steps to successful rice production. Data are the mean of 4 replicates

Table 3. Comparison of yield, mineral fertilizers, and seasonal water stress level during the four seasons crop of 2018-2019 for paddies with moderate Cu content (110-144 mg kg^{-1})

Seasons	Mean water stress level	Treated (w/ rice straw compost + TMI)				*Recommended mineral inputs for the attained yield in treated paddies (kg ha^{-1})			Control (no rice straw compost, no TMI)			
		Mean yield (t ha^{-1})	Mean nutrients applied (fertilizer + compost) (kg ha^{-1})						Mean yield (t ha^{-1})	Mean mineral fertilizer applied (kg ha^{-1})		
			N	P	K	N	P	K		N	P	K
DS 2018	1.75	2.3	40	9.5	9.5	23	6.0	14	2.2	32	1.0	1.0
WS 2018	0	6.4	39	11.4	11.4	64	16	40	4.7	35.5	7.0	7.0
DS 2019	5	1.1	29	7.0	7.0	10	2.5	6.3	0	0	0	0
WS 2019	0.8	3.7	48	10	10	37	9.0	22	2.3	52	9.0	9.0
Ave		3.5	39	9.5	9.5	30	7.5	20	2.3	30	4.0	4.0

Note: *IRRI (2015a,b)-Steps to successful rice production. Data are the mean of 4 replicates

Table 4. Comparison of yield, mineral fertilizers, and seasonal water stress level during the four seasons crop of 2018-2019 for paddies with high Cu content (290-386 mg kg^{-1})

Seasons	Mean water stress level	Treated (w/ rice straw compost + TMI)				*Recommended mineral inputs for the attained yield in treated paddies (kg ha^{-1})			Control (no rice straw compost, no TMI)			
		Mean yield (t ha^{-1})	Mean nutrients applied (fertilizer + compost) (kg ha^{-1})						Mean yield (t ha^{-1})	Mean mineral fertilizer applied (kg ha^{-1})		
			N	P	K	N	P	K		N	P	K
DS 2018	4.2	1.0	40	9.0	9.0	10	2.5	6.3	0.5	33	4.0	4.0
WS 2018	2.2	4.7	58	12	12	47	11.8	29.4	2.2	52	10	10
DS 2019	5	1.9	51	11.7	11.7	18	4.5	11.2	0	0	0	0
WS 2019	1.25	4.2	20	7.0	7.0	42	10	26	1.2	17.5	4.0	4.0
Ave		2.9	42.3	9.9	9.9	29.3	7.2	18.2	1.0	25.6	4.5	4.5

Note: *IRRI (2015a,b)-Steps to successful rice production. Data are the mean of 4 replicates

Furthermore, since the field was not flooded after harvest, the rice straw decomposition process was aerobic. After the wet cropping season in October/November, intermittent rain from the North-East monsoon allowed rapid decomposition in three to four weeks before the next cropping. Dobermann and Fairhurst (2000) have reported that this moist aerobic stage minimizes the adverse effects of anaerobic decomposition at the early stage of rice seedling growth. On the other hand, after the dry cropping season in April or May, the interval for the next cropping was too long (usually up to six to eight weeks) since farmers usually wait for the field to be fully saturated by rain before the start of mechanized land preparation. In this case, the activator and mineral fertilizer mixture were applied only after the first heavy rains. This practice helps ensure the proper decomposition of rice straws and avoids the harmful effects of partially decomposed straws. Figure 3 shows that, during the initial season of the study (DS 2018), in treated paddies with normal Cu content, rice straw compost added a mean of 1.9 g m^{-2} N, 0.6 g m^{-2} P, and 5.3 g m^{-2} K. In general, NPK inputs from in situ composted rice straw is higher during the wet seasons (2018 and 2019) than the dry seasons because the amount of rice straw scattered in the field before the start of wet seasons is based on dry season biomass in uncontaminated control plots (with little to no water-stress), which are usually higher than wet season biomass.

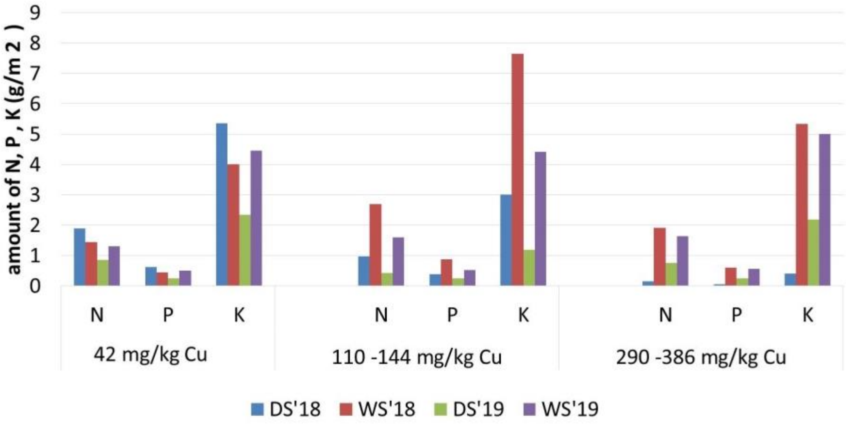

Figure 3. The amount of N, P, and K minerals contributed by the in situ composted rice straw in the compost and *Trichoderma*-treated rice paddies with different levels of soil Cu

The addition of compost to soil has both short-term and long-term benefits. Short-term benefits include the provision of NPK, enrichment of beneficial microorganisms, promotion of soil health, and provision of micronutrients like Zn, which was absent in mineral fertilizers (Bot and Benites 2005; Banaay et al. 2013; Tambone et al. 2013; Tits et al. 2014). In addition, the compost nutrients are slow-release and are less likely to be subject to leaching (IRRI 2020). Long-term benefits include improving soil physicochemical properties such as increased water holding capacity, soil aeration, and soil organic carbon (Bot and Benites 2005; Tits et al. 2014; Memoli et al. 2017). Incorporating rice straws in the paddy soil also provides ecosystem services since compost serves as a habitat and food for soil invertebrates and other soil organisms, thus increasing biodiversity (Chivenge et al. 2020). These soil organisms also participate in energy flow and nutrient cycling, providing stability to the agroecosystem (Kibblewhite et al. 2008).

Effect of nutrient inputs, water stress, and Cu level on rice yield

Multivariate tests showed highly significant differences in yield ($p<0.001$) among treatments (control vs. TMI + rice straw compost), Cu levels ($p=0.009$), and water stress levels ($p<0.001$). There were also significant interactions of Cu level × water stress ($p<0.001$) and treatment × water stress ($p=0.02$). However, the treatment × Cu level interaction was not significant ($p=0.84$). Treated paddies in all seasons and all soil Cu levels had significantly higher yields than the control. The yield was positively correlated with N, P, and K ($p= 0.01$). The overall mean yield in all treated paddies was 3.6 t ha^{-1}, while that of control was 1.9 t ha^{-1}. Thus, the overall mean increase in yield of treated paddies vs. control was 81% (Table 5). The higher concentration of nutrients from mineral fertilizers and rice straw compost resulted in better performance of treated paddies and was responsible for higher yield, especially during severe drought. The plant growth-promoting effects of TMI are also responsible for the higher yield (Cuevas 2006; Banaay et al. 2013). *Trichoderma* can increase crop yield through systemic effects on plants that include increases in the following: carbohydrate metabolism, photosynthetic rate, stomatal conductance, transpiration, internal CO$_2$ concentration, water use efficiency, plant height, tiller number, leaf number, panicle number, root length, root weight, and chlorophyll *a* and *b* content (Shoresh and Harman 2008a,b; Doni et al. 2014; Doni et al. 2017; Harman et al. 2019). *Trichoderma* also functions as an agent of biocontrol, natural decomposition, bioremediation, stress tolerance, and biofertilizers by helping rice plants take up nutrients from the soil (Debnath et al. 2020; Zin and Badaluddin 2020).

Table 5. Yield increase of rice in treated (with rice straw compost + *Trichoderma* microbial inoculant) and control set-ups

Set-ups	**Mean rice yield (t ha^{-1}) in four seasons under different soil Cu content categories**			**Overall mean yield in all seasons for all soil Cu levels**
	Normal Cu content (22-59 mg kg^{-1})	**Moderate Cu content (110-144 mg kg^{-1})**	**High Cu content (290-386 mg kg^{-1})**	
Treated	4.08	3.75	2.87	3.57
Control	2.31	2.43	1.08	1.96
	% increase in Treated vs. the Control			81

Table 6. Differences of the mean of N, P, K inputs (in kg ha^{-1}) for treated and control paddies regardless of soil Cu concentration levels and water-stress levels, and IRRI-recommended rates for attained yield

Set-ups	N*	P*	K*	Yield* (t ha^{-1})
Treated (with Rice straw compost + TMI)	54.9 a	14.8 a	43.3 a	0.33 a
IRRI Recommendation to attain the yield observed in treated plants (for paddy fields without heavy metal contamination and water stress)	32.9 b	8.3 b	21.1 b	0.33 a
Control	25.4 b	4.5 c	4.5 c	0.18 b

Note: * In a column, means followed by a common letter are not significantly different at a 5% level of significance by Tukey's test

Tables 2-4 show data on nutrient inputs and the corresponding yields per season at different levels of soil copper. The tables also present IRRI-recommended levels of mineral fertilizers for the attained yield in treated paddies. These recommended fertilizer rates need to be added to attain a particular target yield, given that the soil type in Mogpog is clay loam (Municipality of Mogpog 2017). Close inspection of the data revealed that, in several cases, treated paddies had levels of N and P that were close to the IRRI-recommended rates for these nutrients. However, mineral K fertilizer was insufficient. For example, in treated paddies with normal Cu levels during the DS 2018 (Table 2), the K fertilizer applied was only 19 kg ha^{-1}, whereas the required K to attain the actual yield was 36 kg ha^{-1}. Similarly, the yield in treated Cu-contaminated paddies during WS 2018 was 6.4 tons ha^{-1}, but the K fertilizer applied was only 11.4 kg ha^{-1}, whereas the required K to achieve this yield was 40 kg ha^{-1}. These computations mean that the actual yield was supported by a K source other than the mineral fertilizer. Therefore, the additional K must have come from the rice straw compost (Figure 3). Tukey's test in Table 6 shows that the treated paddies had higher N, P, and K levels with combined mineral fertilizer and rice straw nutrients than the control paddies.

In the present study, the yield obtained from treated paddies was higher than in the control set-ups, indicating more significant nutrient support from inputs computed from the IRRI formula. Dobermann and Fairhurst (2002) reported that when mineral fertilizers and rice straw compost are used, nutrient reserves in the soil, such as N, P, K, and Si, are constant and may even be increased. The data and computations implied that decomposition and mineralization from the compost led to significant improvements in soil nutrient status. Chivenge et al. (2020) also supported these results and noted that rice straw incorporation could reduce mineral fertilizer inputs, supporting a greater yield. Regression analysis showed that water stress and soil Cu level had a highly significant adverse effect on rice yield (p= 0.01). However, as shown in Table 7, at zero to mild water stress level 1, the mean yield was not affected significantly in treated paddies. At the mean water stress level of 2, the average yield did not differ significantly from 0-1 and 3 levels. At water stress levels 3-5, the effect of reduced water was observed in yield reduction. However, the treated paddies performed much better than the control despite the reduction in yield. At severe drought (level 5) DS 2019, mean yields were 2.4, 1.1, and 1.9 t ha^{-1} in treated paddies with normal, moderate, and high Cu content, respectively. Meanwhile, all the corresponding control paddies had 0 yields (Tables 2-4). Such improved performance of treated paddies may be attributed to the effect of additional soil organic matter from rice straw compost, which improves soil aeration and water holding capacity (Craswell and Lefroy 2001) as well as the increase in mineral nutrients (Dobermann and Fairhurst 2002) and effects of *Trichoderma* treatment through positive influences on both nutrient-use efficiency and photosynthesis-related activities (Doni et al. 2014, 2017; Harman et al. 2019; Debnath et al. 2020).

Based on the data presented, the overall effect of soil copper on yield was low. The yield was reduced by 0.00005 and 0.00009 per unit increase in soil Cu for treated and control paddies, respectively. However, among severely contaminated paddies, there was a significant difference in yield between paddies with 290 mg kg^{-1} Cu and paddies with 386 mg kg^{-1} Cu. The former had an overall mean yield of 3.30 t ha^{-1}, while the latter had an overall mean yield of 2.6 t ha^{-1}. This difference was only observed among already severely contaminated sites, which means that Cu concentrations may already be at a level where Cu toxicity is manifested as significant yield reduction or the Cu threshold for phytotoxicity has been reached. The present study results indicate that significant yield reduction can be observed only at high Cu concentrations. Xu et al. (2006) observed that different concentrations of copper, i.e., 100 mg kg^{-1}, 300-500 mg kg^{-1}, and 1,000 mg kg^{-1} reduced rice yield by 10%, 50%, and 90%, respectively.

Table 7. Effect of water stress level on the yield of rice grown in Cu-contaminated paddy fields

Water stress level	Yield* (t ha^{-1})	
0	4.85	a
1	4.74	a
2	3.97	ab
3	2.54	bc
4	1.98	cd
5	0.88	d

*In each column, means followed by a common letter are not significantly different at the 5% level by Tukey's test

Likewise, in vegetables, significant yield reduction due to copper toxicity was observed only above 150 mg kg^{-1} soil copper concentrations (Yang et al. 2002), which is beyond the moderate category in this study. Alternatively, this low effect of Cu on yield may have been due to the inherent adaptation of the rice varieties farmers preferably use. Eduardo-Marquez et al. (2018) have observed that local rice varieties in Vietnam grown in paddy soil near open-pit coal mines contaminated with heavy metals like Cu have developed adaptations to contaminants. Rice plants have developed trace metal protection mechanisms by sequestering metals in roots or combining them with deprotonated organic acids, proteins, and polysaccharides (Eduardo-Marquez et al. 2018). It is also possible that microbial communities have adapted to heavy metal stress (Hoostal et al. 2008) and consequently confer incidental benefits for the crops.

The effect of rice straw compost and TMI use on paddies contaminated with Cu-rich mine tailings was tested by Cuevas et al. (2019) in Mankayan, Benguet. The field trial results showed that 2 kg m^{-2} application significantly improved yield and number of productive tillers. This rate was found to be optimum for rehabilitating Cu-contaminated paddies. Yield in paddy fields with TMI alone was higher when compared to the field without amendment. Yield with TMI + compost was consistently higher than paddies with TMI alone. The use of TMI in rice cropping was already suggested by Cuevas (2006), which showed that the inoculant helped make nutrients such as P and Zn more available to rice crops, increasing crop yield.

In conclusion, this two-year study showed that in situ composting by scattering the rice straws on the paddy field after harvest and inoculating with a *Trichoderma* activator mixed with triple-14 NPK mineral fertilizer is a method that farmers easily implement. Moreover, over four seasons, 100 farmers carried out the field experiment in Mogpog, Marinduque. The results showed no yellowing in treated paddy rice leaves, indicating the sufficient decomposition of straw. Furthermore, results revealed that the overall yield increase in treated paddies of 81% was significantly higher than the control. The increase in yield was due to higher mineral fertilizers that farmers applied and from nutrient contributions from rice straw compost, especially K element, and the use of TMI. This study also exhibited that using rice straw compost and TMI resulted in a modest yield even under severe water stress. Therefore, it can be an adaptive strategy for erratic rainfall patterns associated with climate change phenomena, in addition to helping alleviate the effect of Cu toxicity on crop productivity.

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