Influence of Percolation Patterns and Soil Copper Concentration on Copper Uptake, and Growth and Yield with Copper-Polluted Stratified Paddy Fields

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Abstract: Copper (Cu) was designated as a specific substance in the Agricultural Land Soil Pollution Prevention Act in Japan. It has been known that high Cu concentrations in soil layers reduce rice crop production and thus agricultural practices such as soil dressing have been applied to minimize the damages to crops by copper pollution. In this study, authors investigated the effects of percolation patterns of the under-plowsole and subsoil on growth and yield, and copper uptake of paddy rice. Six stratified paddy field models were constructed to conduct the growth tests under the condition in which the percolation patterns of the under-plowsole and subsoil were in an open and closed system. These models have a plow layer (10 cm thickness) and upper-plowsole (2.5 cm thickness) made with 12.5 cm-thickness of non-polluted soil dressing (3.7 mgCu·kg⁻¹) and an underlying 15 cm-thickness of polluted under-plowsole (7.5 cm thickness) and subsoil whose Cu concentration was higher or lower than Japanese safety standard (approximately 100 mgCu·kg⁻¹, 150 mgCu·kg⁻¹ and 500 mgCu·kg⁻¹, respectively). During the tests, a constant water-ponding system was adopted, and mid-summer drainage was not done. As a result, Cu concentrations of the rice grains were 5% significantly higher in the open system percolation models regardless of the original amount of Cu in the under-plowsole and subsoil. On the other hand, authors did not recognize any significant differences in growth and yield of rice plants among the models. Authors concluded that the Cu concentrations in rice plants are affected by percolation patterns of polluted plowsole and subsoil even though they are covered with non-polluted soil dressing layers.

Key words: Copper, rice plant, percolation patterns, soil dressing.

1. Introduction

Soil contamination by heavy metals is a threat to our health and crop production. In Japan, experiences of serious pollution, such as Itai itai disease caused by cadmium (Cd), caused the waking of the laws which were to prevent heavy metal pollution in 1970's. Cadmium and copper (Cu) are representative of specific substances for regulation [1].

It has been reported that an excess of Cu in soil results in poor growth of rice plants and the upper limit of Cu in soil is specified as 125 mg·kg⁻¹ [2, 3]. In Japan, it is recognized that the history of pollution problems started from Ashio copper mine mineral pollution along Watarase River in 1890s. In the 20th century, Japan experienced severe agricultural land contamination caused by the use of mine waste water for agriculture. It took a long time and made much sacrifice to specify the substances which caused the contamination.

For Cd and Cu contamination in agricultural lands, mixing tillage and soil dressing have mainly been conducted [1, 4]. The adoption of a ponding water condition during growing period has also been recommended in order to minimize Cd and Cu uptake since solubility of these substances decreases under a
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reducing condition [5, 6]. In apple orchards in Japan, Bordeaux mixture, a mixture of copper sulphate and calcium carbonate, has been used for long as a pesticide. It is reported that Cu concentrations in the soil of some apple orchards are 4 to 5 times higher than the Japanese standard of Cu concentration (125 mgCu·kg\(^{-1}\)) [7, 8].

Nowadays, the number of farmers who quit apple farming has been increasing due to a lack of successors, and some of apple orchards are now used for different purposes. Parts of the apple orchards in lowlands were once converted from paddy fields and they are now restored as paddy fields again [9]. The impact on the adjacent paddy fields of the use of Cu-containing agricultural chemicals in apple orchards should be investigated.

Paul, et al. [10, 11] and Sasaki, et al. [12, 13] clarified that in Cd contaminated paddy fields the percolation patterns of the contaminated plowsole and subsoil would affect Cd concentrations in brown rice significantly even if they had soil dressing layers. Paul, et al. [11] also mentioned that the amount of Cu uptake by the rice plants would be affected by percolation patterns, although they had used low-level Cu-containing soil (12.2 mgCu·kg\(^{-1}\)) in their experience. Since solubility of Cu increases under the oxidation condition and decreases under the reduction condition (the same reactions happen in Cd [14]), percolation pattern of stratified paddy fields may have a significant impact on Cu uptake and growth and yields of rice plants in Cu contaminated paddy fields.

It has been pointed out that Cu contaminated soil reduces the number of panicles and the ratio of ripening of paddy plants, and causes Cu accumulation in their roots [15, 16]. Shibuya [16] also reported that the yield of brown rice decreased by around 10% with Cu contaminated subsoil (over 200 mgCu·kg\(^{-1}\)) and 15 cm thickness of soil dressing. Those studies, however, did not consider the percolation patterns of the subsoil in stratified paddy fields. Fan, et al. [9] conducted the growth experiments of rice plants with stratified paddy filed models of two different Cu concentrations, 70 mgCu·kg\(^{-1}\) and 250 mgCu·kg\(^{-1}\); Japanese safety standard is 125 mgCu·kg\(^{-1}\). They reported that Cu concentrations in the brown rice of the open type percolation models were significantly higher by 5% than those of the closed type percolation models. In the models with a concentration of Cu (241 mg·kg\(^{-1}\)), the Cu concentration in stems and leaves and roots showed significantly different values between the percolation patterns.

In this study, in order to clarify the effects of percolation patterns on Cu uptake and growth and yield of rice plants in Cu contaminated paddy fields, adding to Fan, et al. [9], authors conducted the growth experiments with the Cu-contaminated stratified paddy field models of 100 mgCu·kg\(^{-1}\), 150 mgCu·kg\(^{-1}\), and 500 mgCu·kg\(^{-1}\), one is below Japanese safety standard and the other two are above the standard.

2. Material and Methods

2.1 Soil Samples

In this study, authors used soils stratified in the same way as Fan, et al. [9]. Table 1 shows physical and chemical properties of the soils (modified Fan, et al. [9]). Non-contaminated soil (Clay loam; International Union of Soil Science) was collected from the plow layer of the paddy field in Kanagi farm of Hirosaki University, Aomori, Japan (hereafter authors call “Kanagi Soil”). Cu contaminated soils were prepared for this study by adding copper chloride (II) hydrate (CuCl\(_2\)·2H\(_2\)O) to the soil (Loam) which had been sampled from plow layer of the paddy field in Bunkyo campus of Hirosaki University, Aomori, Japan (hereafter “Bunkyo soil”) and they were mixed well.

Additionally, 0.1 M HCl extracted-copper concentrations in Kanagi soil and Bunkyo soil were originally 3.7 mgCu·kg\(^{-1}\) and 10.5 mgCu·kg\(^{-1}\), respectively, and by using them, three levels of Cu contained soils, 100 mgCu·kg\(^{-1}\), 150 mgCu·kg\(^{-1}\) and 500 mgCu·kg\(^{-1}\), were made (hereafter “Cu mixed
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Table 1  Physical and chemical properties of the soil (modified by Fan, et al. [9]).

<table>
<thead>
<tr>
<th></th>
<th>Density (g·cm⁻³)</th>
<th>Soil texture</th>
<th>MgO (mg·kg⁻¹)</th>
<th>CaO (mg·kg⁻¹)</th>
<th>K₂O (mg·kg⁻¹)</th>
<th>Cu (mg·kg⁻¹)</th>
<th>T-C (%)</th>
<th>T-N (%)</th>
<th>C/N</th>
<th>OM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanagi Soil</td>
<td>2.58</td>
<td>L</td>
<td>229</td>
<td>531</td>
<td>306</td>
<td>3.70</td>
<td>2.74</td>
<td>0.18</td>
<td>15.40</td>
<td>4.70</td>
</tr>
<tr>
<td>Bunkyou Soil</td>
<td>2.61</td>
<td>CL</td>
<td>219</td>
<td>1,848</td>
<td>373</td>
<td>10.50</td>
<td>3.84</td>
<td>0.26</td>
<td>14.50</td>
<td>6.60</td>
</tr>
<tr>
<td>Gravel</td>
<td>2.68</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.80</td>
<td>0.04</td>
<td>0.01</td>
<td>4.00</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Note: Tukey-Kramer test was performed at 5% level; letter indicates significant difference.

soils”). Cu concentration in the gravel used in the models was 0.8 mgCu·kg⁻¹. Cu mixed soils contain 20 to 100 times higher than the average Cu concentration in soils in non-contaminate paddy fields in Japan (approximately 5 mgCu·kg⁻¹) [1]. TC (Total Carbon) and TN (Total Nitrogen) in the soils were measured by using CN analyzer (Elementar). The organic matter contents, which were calculated with TC percentage, of Kanagi soil and Bunkyo soil were 7.4% and 6.6%, respectively. The gravel was packed as the lower layer of the experimental models since they were designed after the fashion of paddy fields near a river.

2.2 Experimental Design

According to the report by Sasaki, et al. [12], two types of stratified paddy field models were used for the experiment: the open-system percolation model and the closed-system percolation model. Each stratified paddy field model was constructed in an iron box (30 cm × 50 cm × 70 cm) filled with three layers of soil. The first layer (plow layer) was 10 cm depth with non-polluted Kanagi Soil (soil dressing, dry density in puddling condition was 1.04 g·cm⁻³). The second layer (plowsole) was 2.5 cm depth with soil dressing and 7.5 cm depth with polluted soil (Cd mixed soil, dry density at the depth from 10 cm to 12.5 cm and from 12.5 cm to 20 cm were 1.23 g·cm⁻³ and 0.75-0.95 g·cm⁻³, respectively). The third layer (subsoil) was 7.5 cm depth with polluted soil and 35 cm depth with non-polluted gravel (dry density at the depth from 20 cm to 27.5 cm and from 27.5 cm to 55 cm were 0.75-0.95 g·cm⁻³ and 1.40 g·cm⁻³, respectively, those layers were formed by compaction).

The authors defined O-100 and C-100 as the Cu concentration of 100 mg·kg⁻¹ in the each stratified paddy field model (“O” and “C” stand for the open-system and the closed-system percolation, respectively). Similarly, O-150 and C-150 were defined as the Cu concentration of 150 mg·kg⁻¹, O-500 and C-500 were defined as the Cu concentration of 500 mg·kg⁻¹, respectively. The percolation patterns were determined by Sasaki, et al. [17]. The ground water levels of the open-system and the closed-system percolation models were controlled at 57.5 cm and 12.5-20 cm depth, respectively. In the closed-system percolation models, the holes on the side of the iron box were blocked in order to prevent the penetration of the atmosphere. On the other hand, in the open-system percolation models, the holes on the side of the iron box were open in the lower part of the plowsole and the upper part of the subsoil in order to aerate those layers. After the two types of models were prepared, fifteen paddy seedlings (plant length and leaf stage were about 15 cm and about 5.0 leaves, respectively) named “Oryza sativa L., Tsugaru Roman” were transplanted. The paddy seedlings were transplanted by 10 cm intervals. The rate of fertilizer application was of the standardized value (2 g of N, 2 g of P₂O₅ and 2 g of K₂O). The topdressing was not done during the growing period. While the cultivation period, the water ponding condition was constantly adopted and the mid-summer drainage was not done. Transplanting of the paddy seedlings and harvesting were conducted at the end of May and at the middle of September, respectively. The experiment using the stratified paddy field models was conducted in a greenhouse on the university campus.
2.3 Measuring Method

The examination of rice plants was done by the standard method of Iwate Agricultural Experimental Station [18]; authors examined such details as plant length, leafage, the number of stems and panicles, the weight of straw, the number of brown rice and the weight of brown rice. The quantitative analysis of Cu concentrations in foliage, roots (depth of 0-10 cm), brown rice and soils extracted by HCl solution was measured with atomic absorption spectroscopy [19]. Other measurements were also conducted in standard methods used in Japan. The ORP (Oxidation-Reduction Potential) meter (Central Kagaku Co., Ltd., UC-203) was used for measuring oxidation-reduction potential (Eh). ORP sensors were set at each soil layer.

3. Results and Discussion

3.1 Oxidation-Reduction Potential (Eh)

In this study, oxidation and reduction condition was defined as Eh > 300 mV and Eh < 300 mV, respectively, based on Yamane [20]. The temporal changes of Eh are shown in Figs. 1 to 4. The plow layer of O-100 and O-500 in the open system percolation pattern became the reduction layer (under -100 mV), while the plowsole and the subsoil became an oxidation layer (over 300 mV). On the other hand, Eh values measured at each depth of O-100 and O-500 in the closed system percolation patterns gradually decreased after transplanting and Eh of all depths became a reduction layer as under 0 mV. Because these Eh data approximated O-100 and C-100, the results of O-150 and C-150 are omitted here.

In this result, the contaminated soil layer became an oxidation layer in three models of O-100 to O-500. However, in the model of C-100 to C-500, the same layer became a reduction layer. It is pointed out that the uptake of Cu in rice is influenced by oxidation-reduction environment [5]. However, the Eh value of the oxidation layer represented in Fig. 3 was lower than that in Fig. 1, and it seemed that the Eh measured below the plowsole had a weak reduction condition represented in Fig. 4. This is thought to be due to the fact that the packing dry density of the soil layer model was somewhat higher and also that the soils used in the experiment were not the same kind. However, details are not clear and the issue needs further examination.

![Fig. 1 Temporal changes of Eh in the stratified paddy field model (O-100).](image-url)
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Fig. 2 Temporal changes of Eh in the stratified paddy field model (C-100).

Fig. 3 Temporal changes of Eh in the stratified paddy field model (O-500).

Fig. 4 Temporal changes of Eh in the stratified paddy field model (C-500).
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Table 2  The results of Cu concentration in rice plants.

<table>
<thead>
<tr>
<th>Model</th>
<th>Rice grains (n = 7)</th>
<th>Roots of plow layer (n = 5)</th>
<th>Stems and leaves (n = 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mg·kg⁻¹)</td>
<td>(mg·kg⁻¹)</td>
<td>(mg·kg⁻¹)</td>
</tr>
<tr>
<td>O-100</td>
<td>3.9 ± 0.4ᵃ</td>
<td>16.4 ± 1.3ᵃ</td>
<td>1.2 ± 0.4ᵃ</td>
</tr>
<tr>
<td>C-100</td>
<td>3.3 ± 0.1ᵇ</td>
<td>14.9 ± 0.7ᵃ</td>
<td>1.2 ± 0.1ᵃ</td>
</tr>
<tr>
<td>O-150</td>
<td>4.7 ± 0.7ᵇ</td>
<td>19.8 ± 1.6ᵇ</td>
<td>1.8 ± 0.4ᵇ</td>
</tr>
<tr>
<td>C-150</td>
<td>3.4 ± 0.3ᵇ</td>
<td>20.2 ± 0.9ᵇ</td>
<td>1.1 ± 0.4ᵇ</td>
</tr>
<tr>
<td>O-500</td>
<td>3.7 ± 0.2ᵇ</td>
<td>15.3 ± 1.2ᵇ</td>
<td>2.1 ± 0.1ᵇ</td>
</tr>
<tr>
<td>C-500</td>
<td>2.8 ± 0.1ᵈ</td>
<td>16.3 ± 0.9ᵈ</td>
<td>1.4 ± 0.2ᵇ</td>
</tr>
</tbody>
</table>

Note: Tukey-Kramer test was performed at 5% level; letter indicates significant difference. The numerical value of ± shows standard deviation.

3.2 Copper Concentration in Rice Plants

The results of Cu concentration in rice plants are listed in Table 2.

(1) Rice Grains: Cu concentration in brown rice (n = 7) was ranged from 2.8 to 4.7 mg·kg⁻¹. The tendency of Cu concentrations due to the difference in percolation type was O-100 > C-100, O-150 > C-150 and O-500 > C-500. These were similar to the Cu concentrations indicated by Asami [1]. However, in his study, there was no demarcation in the percolation types. In our study, Cu concentrations in the rice grains of the open system percolation models were significantly higher by 5% than the ones of the closed system percolation models. Paul, et al. [11] reported that the significant difference was observed in Cu concentrations in brown rice due to differences in percolation patterns. In the same study, the Cu concentrations in brown rice ranged from 2.5 to 4.2 mg·kg⁻¹, even though the Cu concentrations were low at about 10 mg·kg⁻¹. Taking these results also into consideration, authors can suggest that the Cu concentrations ranging from 10 to 500 mg·kg⁻¹ in the lower layer did not give a significant difference in Cu concentrations in brown rice. From the above results, it was confirmed that the difference in Cu concentrations in brown rice was made due to the difference in percolation types. This was similar to the results of the Cd contaminated soil experiment conducted by Sasaki, et al. [12, 13].

(2) Stems and Leaves: Since the Cu concentrations in the stems and leaves of every percolation model became less than 2 mg·kg⁻¹, statistically significant differences were not observed in the Cu concentrations. However, significant differences were observed in the percolation models of O-150 > C-150 and O-500 > C-500. Although migration of Cu was small, there was a possibility that a significant difference in Cu concentrations might be made in stems and leaves in the contaminated soil of the lower layer in more than 125 mg·kg⁻¹. It is speculated that the differences between low and high Cu concentrations in the soil are causing this difference.

(3) Roots: Cu concentrations in roots (n = 7) ranged from 14.9 to 20.2 mg·kg⁻¹. High Cu concentrations observed in the percolation model of O-500 (15.6 mg·kg⁻¹) were not very different from those observed in the models of O-100 (16.4 mg·kg⁻¹). Any significant differences in Cu concentrations were not observed between different percolation system models. Even if there is no significant difference in the Cu concentrations in roots, however, it is presumed that there is a difference in the migration mechanism to the aerial part.

Cu concentrations in the rice plants were in the order of roots > brown rice > stems and leaves, and the ratio was 12:3:1. This order was similar to that of Shibuya [16] and Paul, et al. [11] who used rice plants, and to those of Li, et al. [21] who used soybeans. It was predicted that these results were due to the transport characteristics of Cu and Cd in the rice plants. The behavior of Cu concentrations in brown rice is presumed to be almost constant even if Cu concentrations in the soil rise in the same way as the
Table 3 Parameters of rice plant growth (n = 8).

<table>
<thead>
<tr>
<th>Model</th>
<th>Plant length (cm)</th>
<th>Leaf age (leaf)</th>
<th>Weight of dry straw (g·hill⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-100</td>
<td>94.3 ± 3.6⁴</td>
<td>14.0 ± 0.0⁴</td>
<td>11.6 ± 2.4⁴</td>
</tr>
<tr>
<td>C-100</td>
<td>99.9 ± 2.8⁴</td>
<td>14.4 ± 0.5⁴</td>
<td>13.9 ± 2.8⁴</td>
</tr>
<tr>
<td>O-150</td>
<td>101.6 ± 4.5⁴</td>
<td>14.0 ± 0.0⁴</td>
<td>13.0 ± 1.9⁴</td>
</tr>
<tr>
<td>C-150</td>
<td>99.1 ± 2.8⁴</td>
<td>14.0 ± 0.0⁴</td>
<td>13.5 ± 2.4⁴</td>
</tr>
<tr>
<td>O-500</td>
<td>101.0 ± 6.1⁴</td>
<td>15.0 ± 0.0⁴</td>
<td>11.8 ± 2.8⁴</td>
</tr>
<tr>
<td>C-500</td>
<td>101.3 ± 2.9⁴</td>
<td>15.0 ± 0.0⁴</td>
<td>12.6 ± 2.3⁴</td>
</tr>
</tbody>
</table>

Note: Tukey-Kramer test was performed at 5% level; letter indicates significant difference. The numerical value of ± shows standard deviation.

Table 4 Parameters of rice plant yield (n = 8).

<table>
<thead>
<tr>
<th>Model</th>
<th>The weight of one panicle (g)</th>
<th>No. of Panicles (Panicles/hill⁻¹)</th>
<th>The percentage of ripening (%)</th>
<th>The number of brown rice per unit hill (grains/hill⁻¹)</th>
<th>The 1,000 grain weight of brown rice (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-100</td>
<td>2.2 ± 0.6⁴</td>
<td>8.5 ± 1.7⁴</td>
<td>94.0 ± 2.2⁴</td>
<td>553.3 ± 133.2⁴</td>
<td>19.2 ± 0.6⁴</td>
</tr>
<tr>
<td>C-100</td>
<td>2.2 ± 0.3⁴</td>
<td>9.5 ± 2.5⁴</td>
<td>93.6 ± 2.8⁴</td>
<td>710.4 ± 170.4⁴</td>
<td>19.3 ± 0.6⁴</td>
</tr>
<tr>
<td>O-150</td>
<td>2.0 ± 0.2⁴</td>
<td>8.8 ± 0.7⁴</td>
<td>93.8 ± 1.4⁴</td>
<td>642.9 ± 103.9⁴</td>
<td>18.9 ± 0.3⁴</td>
</tr>
<tr>
<td>C-150</td>
<td>2.2 ± 0.3⁴</td>
<td>8.9 ± 2.3⁴</td>
<td>94.3 ± 2.3⁴</td>
<td>670.4 ± 128.1⁴</td>
<td>19.6 ± 0.3⁴</td>
</tr>
<tr>
<td>O-500</td>
<td>2.4 ± 0.4⁴</td>
<td>7.0 ± 1.4⁴</td>
<td>97.5 ± 0.6⁴</td>
<td>579.4 ± 99.7⁴</td>
<td>22.8 ± 0.5⁴</td>
</tr>
<tr>
<td>C-500</td>
<td>2.6 ± 0.2⁴</td>
<td>7.1 ± 1.7⁴</td>
<td>97.4 ± 0.7⁴</td>
<td>621.3 ± 149.5⁴</td>
<td>23.2 ± 0.8⁴</td>
</tr>
</tbody>
</table>

Note: Tukey-Kramer test was performed at 5% level; letter indicates significant difference. The numerical value of ± shows standard deviation.

behavior of Zn concentrations reported by Shibuya [16].

3.3 Growth and Yield of Rice Plants

The results of this experiment in for the growth and yield of rice plants are shown in Tables 3 and 4, respectively.

(1) Growth of rice plants: The average plant height (n = 8) of each model was almost equal, and it was between 94.3 to 101.3 cm (Table 3). Leafage of each model was ranged from 14.0 to 15.0, showing little difference between them. Total straw weight was 11.6-13.9 g·hill⁻¹. No significant difference was observed in the plant height, leafage and total straw weight regardless of the percolation patterns. Previous research by Shibuya [16] reported that Cu concentrations in the Cu polluted soil layer had an influence on the growth of rice plants. In this study, however, the influence of the Cu concentrations on the growth of rice plants was not noticeable, which may have resulted from the application of soil dressing. A similar result was obtained by Fan, et al. [9].

(2) Yield of rice plants: The number of panicles per unit hill in each model was between 7.0 and 9.5 hill⁻¹ (Table 4). Likewise, weight of one panicle and the number of grains of brown rice per unit hill were between 2.2 and 2.6 g·panicle⁻¹ and between 553 and 710 grains·hill⁻¹, respectively. In addition, the percentage of ripening and the 1,000 grain weight of brown rice were between 93.6 and 97.5% and between 18.9 and 23.2 g, respectively. No significant differences were found in any of the items of the models in different percolation types, which also agreed with the results of Fan, et al. [9]. Paul, et al. [10] reported that yield components of the closed-system percolation model were significantly higher than those of the open-system percolation model although their experiment was conducted by using a different soil type for Cd polluted soil layers.
Shibuya [16] reported that Cu concentrations had an influence on the number of panicles and the percentage of ripening. In this study, however, the influence of the Cu concentrations on the growth of rice plants was not remarkable, which may be attributed to the application of soil dressing. Shibuya [16] also reported that the yield of brown rice decreased by about 10% under a Cu concentration condition of higher than 200 mg·kg⁻¹ with a 15-cm thick soil dressing. Authors inferred, however, that Cu concentration did not cause a remarkable difference in the yield of rice plants if they were within the range of Cu concentrations adopted in this study and that of Fan, et al. [9].

4. Conclusion

Using six types of Cu-polluted stratified paddy field models, authors conducted an experiment to clarify the effects of percolation patterns in the sub-layer (both plowsole and subsoil) on the Cu concentrations in rice plants and their growth and yield. The models had a 15-cm thick Cu polluted soil layer and a 12.5-cm thick non-polluted soil dressing. For the Cu polluted soil layer, three different Cu concentrations of 100 mg·kg⁻¹, 150 mg·kg⁻¹ and 500 mg·kg⁻¹ were prepared.

The results of our experiment showed that in the open system percolation models the sub-layers became oxidation layers and in the closed system percolation models the sub-layers became reduction layers. Cu concentrations in the brown rice of the open system percolation models were significantly higher by 5% than those observed in the closed system percolation models. However, there was little significant difference in the growth and yield of rice plants between the percolation patterns.

Under the above conditions, difference in percolation patterns of the stratified paddy field models little affected the growth and yield of rice plants, while it had an influence on Cu concentrations in the rice plants.

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