Effect of soil leaching and organic matter on Fe$^{2+}$ concentration and rice yields in acid sulfate soils

N Nugroho$^{1*}$, B Kurniasih$^{2}$, S N H Utami$^{2}$, W A Yusuf$^{3}$, I A Rumanti$^{1}$, N Agustiani$^{1}$ and S Margaret$^{1}$

$^{1}$ Indonesian Center for Rice Research, Jalan Raya 9 Sukamandi, Subang, West Java, Indonesia
$^{2}$ Faculty of Agriculture, Universitas Gadjah Mada, Jalan Flora No 1, Bulaksumur, Yogyakarta, Indonesia
$^{3}$ Indonesian Swampland Agricultural Research Institute, Jalan Kebun Karet, Loktabat, Banjarbaru, South Kalimantan, Indonesia

*Corresponding author: nugroho.nurkholis@gmail.com

Abstract. The negative impact of climate change causes extreme weather become unpredictable, leading to flood and drought. In acid sulfate soil, El Nino increases pyrite oxidation which causes sulfate and iron toxicity when flood comes. Iron toxicity in plants is caused by excess concentrations of iron Ferro (Fe$^{2+}$) in the soil solution. This research aims to determine the effect of leaching and organic matter on Fe$^{2+}$ concentration, physiological response and yield of rice in acid sulfate soils. The research was conducted in the Indonesian Swampland Agricultural Research Institute (ISARI) Greenhouse from August to December 2020, using a completely randomized design with three factors. The first factor: actual acid sulfate soil (AASS) and potential acid sulfate soil (PASS), the second factor: waterlogging without leaching (-SL) and soil leaching (+SL), and the third factor: without organic matter (-OM) and with organic matter (+OM). The results showed that soil leaching and adding organic matter decreased Fe$^{2+}$ concentration, thereby increasing root length, relative water content, width of stomata, leaf K and Mg content, root-shoot dry weight, number of grain and crop yield. In comparison to the treatment of without leaching and organic matter, the leaching and organic matter treatment in AASS showed the lowest increase in Fe$^{2+}$ concentration from 123.4 to 241.9 ppm and increased yield from 3.13 to 3.80 ton ha$^{-1}$. Whereas in PASS, the leaching and organic matter treatment showed the highest decrease in Fe$^{2+}$ concentration from 2,298.7 to 686.6 ppm and increased crop yield from 2.39 to 2.77 ton ha$^{-1}$.

1. Introduction

Climate change has a significant effect on crop production. The negative impact of climate change causes extreme weather become unpredictable, leading to flood and drought. In acid sulfate soil, El Nino increases pyrite oxidation which causes sulfate and iron toxicity when flood comes [1]. In waterlogged conditions, Fe$^{2+}$ concentration increases due to the reduction process of ferric (Fe$^{3+}$) to ferrous (Fe$^{2+}$) iron. Rice plants grow optimally at Fe concentration of 100-300 ppm, Fe deficiency at 10-30 ppm, and Fe toxicity at >300 ppm [2]. Iron toxicity in rice plants causes stunted root growth, leaf bronzing, necrosis, and reduced biomass [3].

Innovative technologies for optimizing swamplands in adaptation to climate change include water management and amelioration. Water management is intended to fulfill three purposes that are providing sufficient water for leaching and reducing acidity, reducing excess water during high tide,
and maintaining conditions to avoid over-oxidation. In the acid sulfate soils, channels are constructed to allow sufficient fresh water to support the leaching process [4]. Leaching is done by removing water from the paddy fields, then flood again with high tide. It aims to reduce Fe$^{2+}$, SO$_4^{2-}$, H$^+$ concentrations and soil acidity [5].

The application of organic matter can decrease Fe$^{2+}$ concentration due to the chelating process by organic acids [6]. Besides, it can increase Fe$^{2+}$ concentration lost in the leaching process [7]. This research aimed to determine the effect of leaching and organic matter on Fe$^{2+}$ concentration and rice yield in acid sulfate soils.

2. Method
The research was conducted in The Indonesian Swampland Agricultural Research Institute (ISARI) Greenhouse from August to December 2020, using a randomized block design of three factors with three replications. The first factor was the type of soil, consisting of actual acid sulfate soils (AASS) and potential acid sulfate soils (PASS). The second factor was water management, consisting of waterlogging without leaching (-SL) and soil leaching every two weeks (+ SL). The third factor was the type of organic matter, consisting of non-organic matter (-OM) and with organic matter of 2.5 ton/ha of straw+rush weed compost (+OM). The variety of rice used was Inpara 5.

The actual acidic sulfate soils used were taken from abandoned/fallow land in Roham Jaya Village, Wanaraya, Barito Kuala, South Kalimantan. Meanwhile, the potential acidic sulfate soils were taken from intensive rice cultivation in Tanjung Harapan Village, Alalak, Barito Kuala, South Kalimantan. The soil samples were taken at a tillage depth of 0-20 cm. The leaching treatment was carried out by removing the water in the pot until there was no dripping water. The pot was then flooded again by 5 cm using rainwater. The leaching was done once every two weeks. For non-leaching treatment, inundation remained 5 cm during plant growth. The organic matters in the form of straw and rush weed were taken from the acidic sulfate soils of South Kalimantan with a composition of 50% straw and 50% rush weed.

The planting media used were 120 pots containing 8 kg of soil. Fertilization was given in the form of urea of 300 kg ha$^{-1}$, SP36 of 200 kg ha$^{-1}$ and KCl of 100 kg ha$^{-1}$. The observed variables were Fe$^{2+}$ concentration, root length, relative water content, stomatal opening width, leaf N content, leaf Mg content, root dry weight, shoot dry weight, total grain per hill and crop yield.

3. Results and discussion
The potential acidic soil (PASS) could turn into actual acid sulfate soil (AASS) if oxidized due to excessive drought or drainage. Meanwhile, AASS soils could turn into PASS soils with leaching and application of organic matter for a long time [8]. In the AASS, the soil leaching and organic matter treatment (+SL+OM) revealed the lowest increase in Fe$^{2+}$ concentration, namely from 123.35 to 241.9 ppm. On the contrary, in the PASS, the soil leaching and organic matter treatment (+SL+OM) showed the highest decrease in Fe$^{2+}$ concentration from 2,298.72 to 686.6 ppm (Table 1). It proved that leaching could reduce Fe$^{2+}$ concentration [5] and organic matter increased the leachable Fe$^{2+}$ concentration [7].

| Treatment | AASS | PASS |
|-----------|------|------|
|           | 0 DAP | 42 DAP | Δ concentration | 0 DAP | 42 DAP | Δ concentration |
| −SL −OM  | 123.35 | 384.1  | +260.75         | 2,298.72 | 1,165.9 | -1,132.82          |
| −SL +OM  | 123.35 | 383.6  | +260.25         | 2,298.72 | 1,080.5 | -1,218.22          |
| +SL −OM  | 123.35 | 287.7  | +164.35         | 2,298.72 | 1,079.5 | -1,219.22          |
| +SL +OM  | 123.35 | 241.9  | +118.55         | 2,298.72 | 686.6  | -1,612.12          |

Note: −SL: without soil leaching, +SL: with soil leaching, −OM: without organic matter, +OM: with organic matter. DAP: day after planting, AASS: actual acid sulfate soil, PASS: potential acid sulfate soil.
The Fe$^{2+}$ concentration is negatively correlated with root length, relative water content, width of stomata, leaf K content, root-shoot dry weight, total grain and crop yield (Table 2). The decrease in Fe$^{2+}$ concentration due to the soil leaching and organic matter treatment can increase root length, relative water content, stomatal opening width, leaf K content, root-crown dry weight, total grain, and crop yield. The Fe$^{2+}$ concentration is positively correlated with Fe$^{2+}$ toxicity score ($r=0.36$). It could also decrease the iron toxicity score. Score 3 indicated tiller growth and formation were almost normal, old leaves were reddish-brown, purple, or yellow-orange. Meanwhile, score 5 meant that tiller growth and formation were stunted; many leaves changed color. The leaching and organic matter (+SL+OM) treatment had the lowest iron toxicity score compared to other treatments (Table 3).

**Table 2.** Correlation between Fe$^{2+}$ concentration with other parameters in the soil leaching and organic matter treatment in acid sulfate soils.

| Treatment | FEC | ITS | RL   | RWC  | WS   | LKC  | LMC  | RDW  | SDW  | NGH  | CY   |
|-----------|-----|-----|------|------|------|------|------|------|------|------|------|
| FEC       | 1   | 0.36| -0.48'| -0.49'| -0.44' | -0.62''| -0.33| -0.57''| -0.60''| -0.80''| -0.83''|
| ITS       | 1   | -0.65'| -0.47'| -0.45'| -0.45' | 0.19  | -0.59''| -0.44' | -0.56' | -0.45'|
| RL        | 1   | 0.52''| 0.38  | 0.36  | -0.17| 0.74''| 0.66''| 0.56''| 0.59''| 0.59''|
| RWC       | 1   | 0.61''| 0.50' | -0.23| 0.54''| 0.54''| 0.56''| 0.56''| 0.63''|
| WS        | 1   | 0.50' | -0.13| 0.62''| 0.52' | 0.56''| 0.56''| 0.56''| 0.63''|
| LKC       | 1   | -0.48'| 0.49' | 0.45' | 0.63''| 0.45' | 0.56''| 0.56''| 0.56''|
| LMC       | 1   | -0.22| -0.38| -0.56''| 0.56''| 0.56''| 0.56''| 0.56''| 0.56''|
| RDW       | 1   | 0.83''| 0.71' | 0.73''| 0.73''| 0.73''| 0.73''| 0.73''| 0.73''|
| SDW       | 1   | 0.62''| 0.65''| 0.65''| 0.65''| 0.65''| 0.65''| 0.65''| 0.65''|
| NGH       | 1   | 0.94''| 0.94''| 0.94''| 0.94''| 0.94''| 0.94''| 0.94''| 0.94''|
| CY        | 1   | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    |

Note: FEC: Fe$^{2+}$ concentration, ITS: iron toxicity score, RL: root length, RWC: relative water content, WS: width of stomata, LKC: leaf K content, LMC: leaf Mg content, RDW: root dry weight, SDW: shoot dry weight, NGH: number of grain per hill, CY: crop yield, ',': correlation is significant at the 0.05 level, ''': correlation is significant at the 0.01 level.

**Table 3.** Iron toxicity scores in leaching and organic matter treatment in acid sulfate soils.

| Treatment | AASS | PASS |
|-----------|------|------|
|            | Scores | Average | Scores | Average |
| -SL -OM    | 3.5   | 4.55   | 3.5   | 4.78   |
| -SL +OM    | 3.5   | 3.89   | 3.5   | 4.55   |
| +SL -OM    | 3.5   | 3.45   | 3.5   | 4.11   |
| +SL +OM    | 3     | 3.00   | 3.5   | 4.11   |

Note: -SL: without soil leaching, +SL: with soil leaching, -OM: without organic matter, +OM: with organic matter, AASS: actual acid sulfate soil, PASS: potential acid sulfate soil

Iron toxicity affected the physiological process in rice plants which decreased the crop yields. Roots were plant organs first affected due to excess iron in the soils. The root growth was stunted due to increased H$_2$O$_2$ production at the root tips [9]. Rice plants on AASS had longer root lengths than those on PASS soils. Soil leaching and organic matter (+SL+OM) treatment provided relatively larger root length than other treatments (Table 4).

Root growth was related to the process of absorbing water and nutrients by plants. Soil leaching and organic matter (+SL+OM) treatment potentially increased the relative water content of the plants. On PASS soils, the treatment of soil leaching and organic matter (+SL+OM) had a relative water content was 84.31%, higher than without soil leaching and organic matter (-SL-OM) 79.11%. In contrast, on AASS soils, the treatment of soil leaching and organic matter (+SL+OM) had a
The relative water content of 87.34% was not different from other treatments (Table 4). The water content in the tissue functioned in the transport of nutrients and assimilates and maintains plant turgor by opening and closing the stomata in the transpiration process. The stomata would open since the guard cells absorbed water [10].

The soil leaching and organic matter (+SL+OM) treatment had wider stomata openings of 9.76 μm on AASS and 8.81 μm on PASS soils, wider than without soil leaching and organic matter treatment (−SL−OM) (Table 4).

**Table 4.** Root length, relative water content, width of stomata, leaf K and Mg contents in leaching and organic matter treatment in acidic sulfate soils.

| Treatment       | Total root length (cm) | Relative water content (%) | Width of stomata (μm) | Leaf K content (%) | Leaf Mg content (%) |
|-----------------|------------------------|---------------------------|-----------------------|--------------------|--------------------|
| AAAS            |                        |                           |                       |                    |                    |
| −SL−OM          | 395.5±28.8             | 83.24±0.65                | 8.78±0.36             | 0.53±0.04          | 0.123±0.01         |
| −SL+OM          | 427.9±32.5             | 85.39±4.45                | 9.44±0.24             | 0.56±0.08          | 0.147±0.01         |
| +SL−OM          | 388.9±20.3             | 85.05±2.88                | 8.96±0.53             | 0.58±0.04          | 0.133±0.01         |
| +SL+OM          | 453.1±61.3             | 87.34±2.51                | 9.76±0.58             | 0.56±0.01          | 0.140±0.01         |
| PAAS            |                        |                           |                       |                    |                    |
| −SL−OM          | 355.3±14.8             | 79.11±0.63                | 8.46±0.11             | 0.46±0.05          | 0.163±0.02         |
| −SL+OM          | 357.6±2.9              | 82.58±2.29                | 8.90±0.68             | 0.51±0.04          | 0.167±0.03         |
| +SL−OM          | 367.3±20.1             | 84.45±1.63                | 8.66±0.17             | 0.49±0.04          | 0.147±0.01         |
| +SL+OM          | 394.0±80.0             | 84.31±0.91                | 8.81±0.27             | 0.47±0.05          | 0.173±0.01         |

Note: −SL: without soil leaching, +SL: with soil leaching, −OM: without organic matter, +OM: with organic matter. AASS: actual acid sulfate soil, PASS: potential acid sulfate soil.

The absorption of nutrients by plants was related to root growth. The lowest K content was in non-leaching and non-organic matter treatment (−SL−OM), but not different from other treatments (Table 4). Soil leaching and organic matter increased the leaf K content, but the increase was not significant. K played a role in opening and closing stomata [10] and transporting assimilates from leaves to all plant tissues [11].

Leaching and organic matter also increased the leaf Mg content. The leaching and organic matter (+SL+OM) treatment on AASS soils had leaf Mg content was 0.14%, higher than other treatments. On the other hand, on PASS soils, the leaching and organic matter (+SL+OM) treatment had Mg content was 0.17%, not different from non-leaching and non-organic matter treatment (−SL−OM) (Table 4). Mg was a chlorophyll-forming element. Rice plants with iron poisoning would experience a decrease in chlorophyll content [12].

Stomata and chlorophyll played a direct role in the photosynthesis process to produce organic compounds as assimilates from inorganic compounds with the help of solar energy. These organic compounds were used by plants to grow and develop [13]. Increased stomata opening and chlorophyll-forming elements due to leaching and organic matter could increase plant dry weight. This was evidenced by the increase in root and shoot dry weight in the soil leaching and organic matter treatment. Root dry weight in the soil leaching and organic matter treatment (+SL+OM) on AASS soils was 10.83 gram, higher than non-leaching and non-organic matter treatment (−SL−OM) of 6.76 gram. In contrast, on PASS soils, the soil leaching and organic matter treatment (+SL+OM) had root dry weight of 5.82 grams, not different from other treatments. Shoot dry weight on PASS soils increased to 15.47 grams and 23.40 grams on AASS soils, heavier than in non-leaching and non-organic matter (−SL−OM) (Table 5).
Table 5. Root and shoot dry weight, total grain per hill, and crop yield in leaching and organic matter treatment in acidic sulfate soils.

| Treatment | Root dry weight (g) | Shoot dry weight (g) | Total grain per hill | Crop yield (ton ha⁻¹) |
|-----------|---------------------|----------------------|----------------------|----------------------|
| AAAS      |                     |                      |                      |                      |
| −SL −OM  | 6.76±1.51           | 18.17±1.86           | 1033.58±26.99        | 3.13±0.11            |
| −SL +OM  | 8.04±0.96           | 20.23±1.46           | 1136.53±21.25        | 3.45±0.39            |
| +SL −OM  | 7.00±2.24           | 15.50±3.46           | 1149.42±19.84        | 3.46±0.31            |
| +SL +OM  | 10.83±1.89          | 23.40±2.71           | 1193.81±26.17        | 3.80±0.25            |
| PAAS      |                     |                      |                      |                      |
| −SL −OM  | 4.96±0.59           | 10.80±0.26           | 854.31±49.30         | 2.39±0.30            |
| −SL +OM  | 4.94±2.48           | 14.60±3.62           | 839.18±30.21         | 2.43±0.11            |
| +SL −OM  | 4.69±0.59           | 15.73±2.45           | 887.00±29.86         | 2.53±0.10            |
| +SL +OM  | 5.82±1.97           | 15.47±1.67           | 927.43±27.31         | 2.77±0.22            |

Note: -SL: without soil leaching, +SL: with soil leaching, -OM: without organic matter, +OM: with organic matter. AASS: actual acid sulfate soil, PASS: potential acid sulfate soil.

The higher grain yield in rice plants was due to increased root and shoot growth which contributed to the remobilization of carbon reserves from vegetative tissue to grain [14]. The leaching and organic matter (+SL+OM) treatment gave total grain of 1,193.81 on AASS soils and 927.43 on PASS soils, higher than non-leaching and non-organic matter treatment (−SL−OM) (Table 5). Compared to non-leaching and non-organic matter (−SL−OM), the soil leaching and organic matter treatment (+SL+OM) on AASS soils increased crop yields from 3.13 to 3.80 ton/ha, while on PASS soils, it increased from 2.39 to 2.77 ton ha⁻¹. The leaching and organic matter could increase crop yields by 15-21%. The crop yield was negatively correlated with Fe²⁺ concentration (r = -0.83). When Fe²⁺ solubility increased, the rice yield decreased [15].

4. Conclusion
The soil leaching and application of organic matter reduced Fe²⁺ concentration, thereby increasing root length, relative water content, width of stomata, leaf K content, leaf Mg content, root dry weight, shoot dry weight, total grain per hill and crop yield. In comparison to the treatment of without soil leaching and organic matter, the soil leaching and organic matter treatment in actual acid sulfate soil showed the lowest increase in Fe²⁺ concentration from 123.4 to 241.9 ppm, and increased crop yields from 3.13 to 3.80 ton ha⁻¹. Meanwhile, in potential acid sulfate soil, the soil leaching and organic matter treatment showed the highest decrease in Fe²⁺ concentration from 2,298.7 to 686.6 ppm and increased crop yields from 2.39 to 2.77 ton ha⁻¹. The soil leaching once every two weeks and organic matter amendment of 2.5 ton ha⁻¹ are climate change mitigation technologies to reduce Fe²⁺ concentration and increase rice yields in the acid sulfate soils.

References
[1] Maftu’ah E, Annisa W and Noor M 2016 Jurnal Sumberdaya Lahan 10 103-14
[2] Mahender A, Swamy B P M, Anandan A and Ali J 2019 Plants 8 1–34
[3] Zhang L, Li G, Wang M, Di D, Sun L, Kronzucker H J and Shi W 2018 New Phytologist 1 1–16
[4] Wignyosukarto 2013 Irrig. and Drain. 62 75–81
[5] Ar-riza I, Alwi M, and Nurita 2015 J. Agron. Indonesia 43 105–10
[6] Susilawati A and Nursyamsi D 2013 Jurnal Sumberdaya Lahan 1 27–37
[7] Alwi M, Sabiham S, Anwar S, Suwarno and Achmadi 2010 Jurnal Tanah dan Iklim 32 83–94
[8] Nursyamsi D, Raihan S, Noor M, et al A 2014 Pedoman Umum Pengelolaan Lahan Sulfat Masam Untuk Pertanian Berkelanjutan (Jakarta: Badan Penelitian dan Pengembangan Pertanian)
[9] Reyt G, Boudouf S, Boucherez J, and Briat J 2015 *Molecular Plant* **8** 439–53
[10] Singh R, Chaurasia S, Gupta D, Mishra A and Soni P 2014 *Journal of Environmental Science, Computer Science and Engineering & Technology* **3** 1228-34
[11] Subandi 2013 *Pengembangan Inovasi Pertanian* **6** 1-10
[12] Pereira E G, Oliva M A, Rosado-Souza L, et al 2013 Plant Sci **201-2** 81-92
[13] Mashud 2007 *Bulletin Palma* **32** 52-9
[14] Zhang Z, Zhang S, Yang J and Zhang J 2008 *Field Crops Res* **108** 71-81
[15] Suswanto T, Shamshuddin J, Omar S R S and Mat P 2007 *Malaysian Journal of Soil Science* **11** 1–16.

**Acknowledgment**

This work was supported in part by National Priority Research (Prioritas Riset Nasional), Contract No. 07/E1/PRN/2020 for Dr. Indrastuti Apri Rumanti and by study and research grant from the Ministry of Agriculture of Indonesia. We thanks to all team of swampy research at Indonesian Center for Rice Research (ICRR) and Indonesian Swampland Agricultural Research Institute (ISARI).