# Influence of Intensive Management on Soil Phytotoxic Aluminum Content and Aluminum Distribution in *Phyllostachys praecox*

Renyi Gui[1], Haibao Ji[2], Shunyao Zhuang[2*]

1 Nurturing Station of State Key Lab of Sub-tropical Silviculture, Zhejiang A & F University, 311300, Lin-an, China

2 State Key Lab of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Science, 210008, Nanjing, China

*Corresponding author, email address: syzhuang@issas.ac.cn

## Abstract

Intensive management of Lei bamboo (*Phyllostachys praecox* f. *preveynalis* Chen et Yao) is unique for economic profit, but causes severe soil acidification that may induce serious soil phytotoxic Aluminum (Al) and result in the bamboo degradation. To elucidate its influence on the degradation of Lei bamboo, we evaluated the relationship between soil Al toxicity and the bamboo degradation. Lei bamboos with various planting time were selected from Lin'an county of Zhejiang province, China. The contents of soil acidity, soil phytotoxic Al and total Al in the bamboo bodies were analyzed. Results demonstrated that the soil pH dropped greatly by a maximum of 3 units in the Lei bamboo stand developed from the former paddy field. However, with the planting time soil organic matter content increased to a highest of 64.2 $g \cdot kg^{-1}$ that was 1.5 times of the control. The content of phytotoxic Al increased as well with the bamboo cultivation time. The highest content of 8-hydroxyquinoline extractable Al was 108.0 $mg \cdot kg^{-1}$ that was 10 times of the control. The content of Al in the bamboo roots increased accordingly with the soil phytotoxic Al. However, Al in the other bamboo organs did not increase, indicating a damage of nutrient transport upward from the root in the bamboo due to Al toxicity. Overall, severe soil acidification with intensive management in the bamboo field improved greatly the phytotoxic Al content and then did harm to the bamboo growth. The application of excess nitrogen fertilizer could result in the bamboo degradation, thus an adequate fertilization should be adopted in the intensive management for the bamboo sustainable production.

Keywords: Intensive management · Lei bamboo · Phytotoxic Aluminum (Al) · Soil acidification

# Introduction

Lei bamboo (*Phyllostachys praecox*) has been cultivated extensively in south-east China due to the advantages of its early bamboo shoot harvesting, long harvesting time, delicious shoot, high yield and profit. However, with the increasing plantation time, many bamboo stands showed a severe degradation exhibiting as yield decline, flowering and bamboo rhizome upward-floating in fields (Sun et al. 2009). In present, Lin'an city has a bamboo area of 32,000 $hm^2$ of which the degraded stand accounts for 86.7 %, leafing only 13.3 % in normal (Liu et al. 2010). As reported, the soil with Lei bamboo plantation gets rapidly acidification under the intensive management. Its pH value dropped from 5.57 to 3.20 (Liu et al. 2008; Gui et al. 2013) when the cultivation time was more than 15 years. Compared to the hydrogen ion stress, soil Al dissolved and subsequent toxicity to plant induced by acidification was noted. Accompanied with the hydrogen ion toxicity, the active Al induced by low pH could be much more toxic to plant growth that was paid more attentions on. Therefore, the bamboo soils with low pH may be responsible for such a severe degradation of the bamboo under the intensive management.

Soil Al plays a role in mitigation of hydrogen ion toxicity under mild acidic condition, however, a severe acidification enhances Al dissolution from soil minerals to be harmful to plants (Walna et al. 2005). Soils contain a high Al content but only a fraction exists in active form normally (Drabek et al. 2003; Ma et al. 2001). The bioavailability and toxicity of Al in soils are dependent on its distribution in forms or species. Based on the solution chemistry of soil Al, Al species is determined by pH value. When solution pH < 3.5, $[Al(H_2O)_6]^{3+}$ ions are created. The aqua hydroxycomplexes $[Al(OH)]^{2+}$ and $[Al(OH)_2]^+$ are present at pH = 3.5 and the colloid $Al(OH)_3$ exists at pH > 5.0. The $[Al(OH)_4]^-$ species begins to form in solution at pH > 7.0 and becomes predominant at pH 8.0-9.0. The sulphato, fluoro and some organic complexes of Al are also presented in common soluble forms. The Al polymeric hydroxycomplexes are created by the hydrolysis of $Al^{3+}$ ions. With increased molecular mass they can convert to a colloid form (Matúš et al. 2005). As pointed out, the toxicity of soil Al form shows an order as: $Al_{13}$ polymer > $Al^{3+}$ > $Al(OH)^{2+}$ > $Al(OH)_2^+$ > $Al(OH)_4^-$ > $AlSO_4^+$, but Al-F and Al-organic complexes and $Al(OH)_3$ are not harmful to plants (Boudot et al. 1994).

Generally, it is difficult to determine Al species directly in soils. A number of different procedures have been developed to distinguish various Al forms. These analytical procedures often employed in the speciation analysis and fractionation of Al are usually based on size exclusion, kinetic or binding strength discrimination or ion mobility in an electric field. In fact, most toxic Al species in soils is short-term reaction. Therefore, selection of a suitable method to determine Al phytotoxic species is important for the understanding of the effect of acidified Al on the bamboo growth. Current study adopted a method utilizing the complexation of labile Al species by 8-hydroxyquionline (HQN) and salicylic acid (AS) ligand groups. It is relatively simple, rapid and without the need of high-cost instrumentation and suitable for the routine monitoring of mobility, bioavailability and toxicity of Al in the environment (Matúš et al. 2006, 2007).

The increase of phytotoxic Al content due to soil acidification might be responsible for the bamboo withering. However, soil Al phytotoxic species in the bamboo field during various stage of cultivation is still limited. Therefore, this study was conducted to understand soil Al phytotoxic species extracted with HQN and Al accumulation in the bamboo body under the intensive management. The results are expected to be instructive for cultivating bamboo in a sustainable strategy.

# Materials and methods

## *Study site*

The study site was located at Guanghui village (E 119°32′44″, N 30°17′17″) and Hengxu village (E 119°34′25″, N 30°12′35″) of Taihuyuan town, Lin'an city, Zhejiang province of China. It is a main production area of *Phyllostachys praecox* bamboo, where organic material mulching was applied. The region belongs to the north sub-tropical mosoon zone with a hilly landform. The anuual mean rainfall is 1460 mm and the temperature is 15.8 ºC. There is 1939 h of sunshine and 234 d without frost. The sampling site is hilly landscape with an elevation of 150 m. The soil type in Guanghui village is yellow paddy (Stagnic Gleyic Anthrosol, WRB2006) that was derived from quaternary red earth (Typic Haplic Anthrosol, WRB2006) in Hengxu village.

A rice paddy and a series of bamboo stands were selected in this study. The paddy soil was selected as control because of bamboo fields were originated from it. The bamboo planting time involved were 2, 6, 8 and 16 years, respectively, after transplantation.

A technique of organic material mulching was developed and adopted in the Lei bamboo production, using rice straw and bran, sometimes bamboo leaves as the mulching material. Mulching soil surface usually started during the period from November or December to March of next year to increase soil temperature and keep soil moisture in the winter season. The data showed the ground temperature could raise 4-5 °C after mulched with organic materials (Fang et al. 1994). During the process, rice straw was firstly mulched to a height of 10-15 cm from the surface and then rice bran was filled onto another height of 10-15 cm. The total rice straw and bran used in one time commonly reached to 40 and 55 $t \cdot ha^{-1}$. In the next year, the rice straw almost decomposed or mixed into soils, the un-decomposed rice bran layer was removed at March or April. In the next mulching season, the removed rice bran was mixed with new one. The fertilizer was applied three times per year, i.e. mid-May, mid-September and the time before the mulching, respectively. The fertilizer amount was typically about 2.5 $t \cdot ha^{-1}$ (N:P:K=16:16:16) and urea 1.5 $t \cdot ha^{-1}$, sometimes manures with equal nutrient used as well. The use of organic material mulching began from the 5th year after the bamboo transplanting. Because of the bamboo weathering, the farmers began to give up the mulching method after 5 years (10 years after the transplanting).

## *Sampling method*

Bamboo plot with similar soil position, landform, initial soil fertility and soil basic physiochemical properties before bamboo plantation were selected. The selected planting time was 2, 6, 8, and 16 years, respectively. The paddy soil was regarded as 0 year of bamboo planting time. When planted 16 years, the bamboo stand has degraded in the field. The area of each selected bamboo plot was larger than 100 $m^2$. Due to the shallow root depth of Lei bamboo, the soil profile was separated into 3 layers as 0-10, 10-20 and 20-40 cm, respectively. Before the collection, litters and mulching materials on the soil surface were removed. We selected three sites for sampling with three replicates. Fresh soil samples were air-dried and ground to pass through 2 mm sieve.

During the soil sampling, the bamboo culm density was investigated as well. In the bamboo plot of 2 years, the culm density was about 3,800 culm·$ha^{-1}$, and 23,000, 21,000, 9,900 culm·$ha^{-1}$ in the 6, 8 and 16 years plot, respectively.

Bamboo plant samples were collected in the field. In each plot, 5 new bamboo culms (1 year just for a valid comparison) were destructively collected and various parts of bamboo were separated, including leaf, stem, rhizome and root. These bamboo samples were treated in the lab where samples were washed, oven-dried for 30 min under 105 ºC and then dried to a stable weight under 60-70 ºC. The dried samples were ground to sieve through 0.25 mm filter.

## *Sample analysis*

Soil basic physicochemical properties, including soil pH (Soil:$H_2O$ = 1:2.5), soil organic matter (SOM), capacity of exchangeable cation (CEC), soil electronic conductivity (SEC) and SOM stability ($D_{A400}/D_{A600}$, SSR), were analyzed. Soil pH was determined by electrode method. Soil organic matter was measured with $K_2Cr_2O_7$ oxidation and $FeSO_4$ titration. CEC was extracted by 1.0 M $NH_4Cl$ and measured. SEC was measured using electrode method. SOM stability was represented by the ratio of spectrum absorption of A400 to A600 (Drabek et al. 2003).

Soil phytotoxic Al species were measured using 8-hydroxyquionline extraction. Briefly, 10 g dried soil sample was mixed with 100 mL 1 % 8-hydroxyquionline in 2 % acetic acid solution. The mixture was shaken for 1 h, centrifuged for 20 min using 5000 rpm and then filtered with 0.45 µm. Al in the filtration was determined using ICP-MS after diluted to a suitable concentration. The bamboo samples were digested using microwave method and ICP-MS was also used for Al determination.

## *Data statistics*

The data statistics was conducted using SAS software. The difference of soil properties and Al was tested by ANNOVA one factor deviation. Least square was employed to simulate the analysis relationships among various Al forms.

# Results

## *Soil basic properties changed with bamboo cultivation*

As shown in Table 1, soil pH in paddy soils showed no significant difference between various soil layers in the profile. However, it increased in soil profile and decreased with the bamboo planting time. The lowest pH in bamboo plots was 3.60 that was almost 3 units lower than the paddy soil. This indicated soil acidification was severe when the bamboo planted. After shifted to bamboo fields, soil organic matter (SOM) decreased in the early stage of bamboo plantation. At the late stage (> 3 years of mulching), SOM content increased greatly to 64.2 g·$kg^{-1}$ that was 1.5 times of the control. Obviously, the mulching technique increased SOM due to a direct organic material input. As well, we could find that SOM began to decrease after giving up the method in the 16 years of bamboo plot. Similarly as SOM, the capacity of exchangeable cation (CEC) showed a same trend with the bamboo planting time. SOM enhanced soil CEC and nutrient retention.

### *Soil phytotoxic Al with extraction method*

Soil Al extracted with 8-hydroxyquionline increased with the planting time (Fig. 1) in the layers of 0-10 and 10-20 cm, however, no significant difference was observed in the layer of 20-40 cm. HQN extracted Al was 108.0 mg·kg$^{-1}$ in the surface layer of the bamboo plot with 16 yr. It was almost 10 times of that in the paddy soil. Soil Al extracted with 8-hydroxyquionline can be regarded as phytotoxic Al (Matúš et al. 2006, 2007). The result indicated that soil acidification induced a great increase of phytotoxic Al in the bamboo soil.

### *Al content in bamboo plants*

According to Table 2, Al content in bamboo was highest in the root with an average of 878.2 mg·kg$^{-1}$, the next was rhizome with 114.0 mg·kg$^{-1.}$ The lowest content was found in stem as 11.98 mg·kg$^{-1}$. At the same time, Al content in roots of bamboo increased with planting time significantly. It was 1072.6 mg·kg$^{-1}$ in 16 years, almost 2 times than in 2 years. However, Al in bamboo stem showed no significant difference and decreased in leaf with planting time.

## Discussion

Lei bamboo soil was acidified dramatically when the organic material mulching technique was applied (Table 1). This was mainly resulted from the high input of chemical fertilizer. The fertilizer application rate reached to 4.0 t·ha$^{-1}$ annually. Some reports found that the excess use of chemical fertilizer was the main reason responsible for soil acidification (Zhao and Xing, 2009; Guo et al. 2010). Under the current intensive management, a large of organic material was mixed and decomposed into the bamboo soil that could mitigate soil acidification in some an extent. However, the occurrence of acidification suggested that chemical fertilizer contributed much more than the organic matter in soils. We also could see that the bamboo soil showed a severe acidification in the plot of 6 years only after using the technique for 2 years.

Soil Al dissolution is controlled by soil pH (Shoji and Fujiwara, 1984). Due to the dramatic acidification, soil phytotoxic Al increased with the bamboo plantation (Fig. 1). According to the Al content extracted by HQN and the soil pH, we could find that they could be expressed as an exponential relationship. When soil pH $< 4.0$, soil phytotoxic Al increased significantly (Fig. 2). It is noticed that the soil pH in the bamboo of 6 years dropped to 3.85 (Table 1), suggesting that phytotoxic Al was already beginning to do harm to the bamboo. The soil pH value fluctuated in the bamboo soil from 8 to 16 years because of the interruption of the organic matter mulching. Moreover, farmers moved sub-layer soil to cover on the surface sometimes due to bamboo rhizome floating up. The mulching technique accelerated soil acidification and enhanced soil Al dissolution to be active forms. The fact that phytotoxic Al accordingly increased with the bamboo planting time might be a main reason responsible for the bamboo withering.

Al content in the bamboo body showed difference in various organs. In the bamboo leaf, Al content decreased from 32.98 mg·kg$^{-1}$ to 19.29 mg·kg$^{-1}$ with planting time from 2 to 16 years. Such a concentration of Al was lower compared to other plants with a mean content of 200 mg·kg$^{-1}$ (Jansen et al. 2002). Al content of bamboo stem was much lower as an average of 11.98 mg·kg$^{-1}$, while Al content was higher in the rhizome and root (Table 2). Al in the rhizome did not show a close relationship with soil phytotoxic Al. In an other word, Al in the rhizome was not related to the bamboo planting time. On the contrast, Al in the bamboo root demonstrated a linear relationship with soil phytotoxic Al and planting time (Fig. 3). Plant root is the most important organ to uptake soil nutrient. Though soil Al is not the necessary nutrient for plant, it will be absorbed by plant root through active and passive ways. Present results showed that Al accumulated in the bamboo root and did not transport up to the ground part, suggesting that a mechanism against Al toxicity was present in the bamboo. As well indicated, the block of Al transportation is one of the important ways for plant to resist Al toxicity (Foy et al. 1978).

Judged from the appearance of Lei bamboo in the fields, there was no significant difference among the plots in various degradation degrees. The high content of phytotoxic Al did not cause an obvious influence on the bamboo appearance, suggesting that Lei bamboo is highly resistant to Al toxicity. However, phytotoxic Al caused profound consequence in shoot production because few bamboo shoots germinated after 6 years. In order to provide a steady supply of bamboo shoot, farmers usually left a stable percentage of new bamboo in the fields. The declined stand bamboo culms represented a significant bamboo weathering. Accordingly, the increased phytotoxic Al resulted in a damage to bamboo root and ultimately influenced the bamboo growth.

# Conclusions

Bamboo plantation with the organic matter mulching technique resulted in a severe soil acidification. Soil pH value decreased with the bamboo planting time. Accordingly, soil phytotoxic Al (represented by HQN extractable Al) increased as well. Al content in bamboo roots increased with planting time greatly. However, no significant amount of Al was accumulated in the bamboo ground part, indicating a hinder of mineral nutrient transporting from root to upward ground part that might be mainly responsible for the bamboo weathering in growth. Results in this study elucidated that the intensive management with high fertilizer application resulted in a severe soil acidification, and accordingly exerted a great influence on the bamboo growth. The application of excess nitrogen fertilizer was the mainly responsible for the bamboo degradation, thus an adequate fertilization should be adopted in the bamboo management for sustainable production.

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Table 1 Soil basic properties in Lei bamboo fields with various planting time

| Planting time (yr) | Soil depth (cm) | pH | Soil organic matter ($g{\cdot}kg^{-1}$) | Capacity of exchangeable cation ($cmol{\cdot}kg^{-1}$) |
|---|---|---|---|---|
| 0 | 0-10 | 6.53±0.24a | 44.1 ±1.80b | 17.62 ± 0.19c |
| | 10-20 | 6.52±0.31a | 42.9 ± 0.40a | 17.04 ± 0.04c |
| | 20-40 | 6.53±0.24a | 40.1 ± 3.27a | 16.10 ± 0.60a |
| 2 | 0-10 | 4.19 ± 0.11cd | 30.7 ± 1.09c | 15.43 ± 0.26c |
| | 10-20 | 4.40 ± 0.19c | 28.4 ± 1.36cd | 14.67 ± 0.21d |
| | 20-40 | 5.79 ± 0.27b | 19.4 ± 2.19cd | 12.90 ± 0.30cd |
| 6 | 0-10 | 3.85 ± 0.11de | 30.8 ± 3.76c | 18.35 ± 1.13c |
| | 10-20 | 3.90 ± 0.40de | 28.9 ± 2.35cd | 17.03 ± 0.49c |
| | 20-40 | 5.60 ± 0.62b | 25.0 ± 1.47bc | 15.53 ± 0.38ab |
| 8 | 0-10 | 4.30 ± 0.14c | 64.2 ± 9.57a | 22.86 ± 2.76b |
| | 10-20 | 4.21 ± 0.23cd | 37.5 ± 2.03ab | 18.91 ± 1.63b |
| | 20-40 | 5.64 ± 0.11b | 26.1 ± 4.86b | 16.89 ± 1.01a |
| 16 | 0-10 | 3.60 ± 0.06e | 44.2 ± 7.99b | 23.42 ± 2.03b |
| | 10-20 | 4.11 ± 0.20cd | 34.1 ± 7.61bc | 19.47 ± 1.03b |
| | 20-40 | 6.56 ± 0.27a | 15.3 ± 4.33 | 16.41 ± 0.27a |

* Different letters represent the significance of 5%.

Table 2 Al content in different organs with various planting time of Lei bamboo fields ($mg{\cdot}kg^{-1}$)

| Plant time (yr) | Leaf | Stem | Rhizome | Root |
|---|---|---|---|---|
| 2 | 32.98±6.928a | 11.94±3.526a | 107.0±31.25bc | 594.2±58.60c |
| 6 | 22.99±8.566b | 13.06±2.549a | 116.1±29.97b | 805.4±103.3b |
| 8 | 21.26±5.043b | 12.65±3.795a | 146.1±62.66a | 1040.5±135.3a |
| 16 | 19.29±6.952b | 10.25±2.855a | 86.76±30.20c | 1072.6±140.5a |

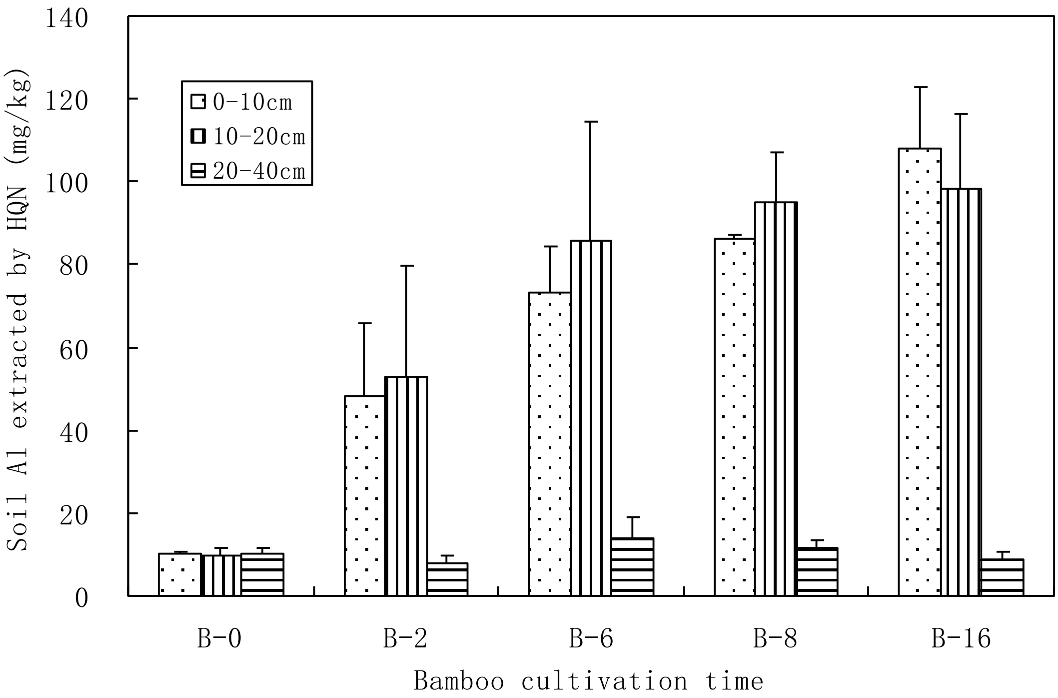


Fig. 1 Soil 8-hydroxyquinoline extractable Al in Lei Bamboo fields with various planting time

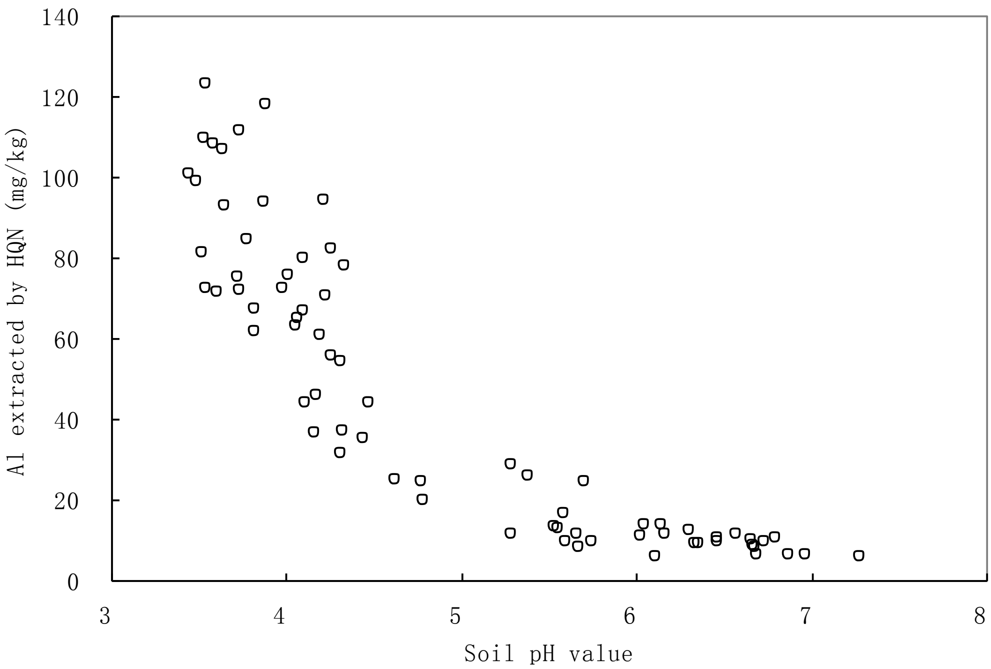


Fig. 2 Relationship between soil Al extracted by HQN and soil pH value

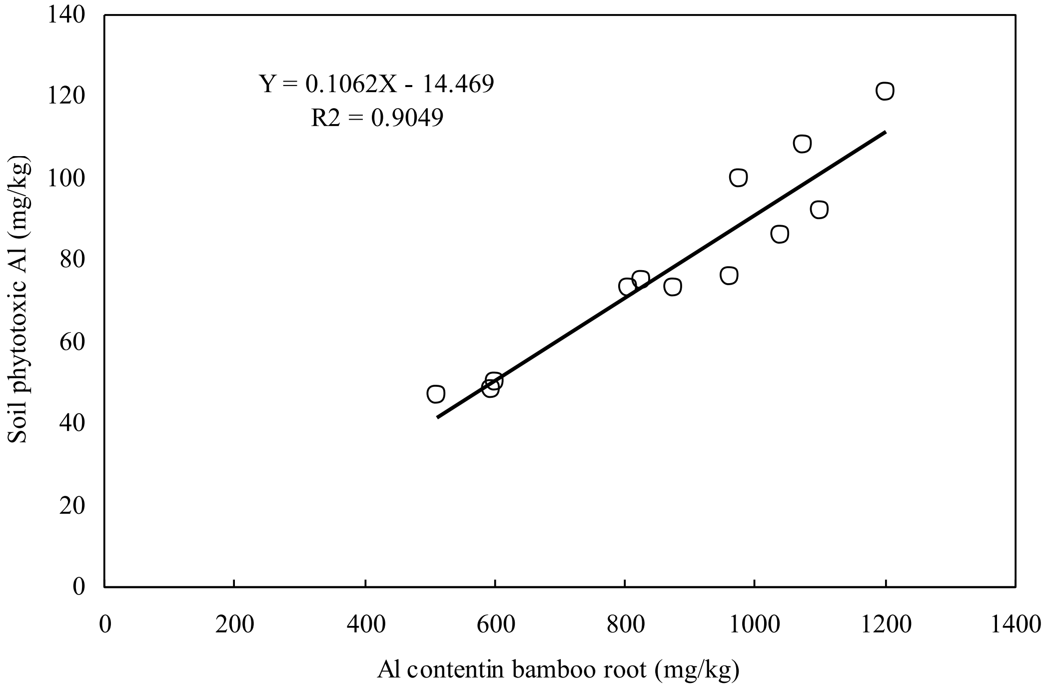


Fig. 3 Relationship between Al in bamboo root and soil phytotoxic Al