Effect of silica fertilizer on accumulation of phytolith in rice plant and soil

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Abstract. Phytoliths, silica structures formed in plant tissues, significantly contribute to carbon capture by stabilizing organic carbon within their structures and aiding long-term carbon sequestration in soils. Phytoliths play a crucial role in enhancing plant resistance to biotic and abiotic stresses and improving soil properties. This study investigates the impact of two types of silica fertilizers—silicic acid and sodium metasilicate —on the accumulation of phytoliths in rice plants and soil. The experiment was conducted under controlled conditions, with rice plants, RD43 cultivar, receiving applications of either silicic acid or sodium metasilicate at the ratio of 0.33 g/kg-soil. Results indicated a significant increase in phytolith content in both the rice plant tissues (3.76 and 2.79 fold) after applications of silicic acid and sodium metasilicate, respectively. Similarly, in the surrounding soil, accumulations of phytolith contents increased 3.50 and 1.90 fold compared to control soil, without addition of silica fertilizers. Silicic acid was found to be more effective in enhancing phytolith accumulation in rice tissues, while sodium metasilicate showed a greater impact on plant growth and yield. These findings suggest that the type of silica fertilizer used can influence the distribution and accumulation of phytoliths in plants and soils. The study underscores the importance of selecting appropriate silica fertilizers for sustainable rice cultivation and soil management practices.

1 Introduction

Rice cultivation is an important agricultural activity worldwide, providing a staple food to the global population [1-2]. However, it has a significant advert effect, particularly on greenhouse gas emissions. The anaerobic conditions in flooded rice paddies create an ideal condition for the production of methane (CH_4), a potent greenhouse gas that contributes to global warming [3]. Rice cultivation is a significant source of methane releases about 25-100 million metric tons, accounting for 10-12% of total methane emissions globally. The variation in methane release from rice cultivation is due to differences in farming practices, water management techniques, rice cultivars, soil properties and compositions, and climatic conditions [1]. Given methane's high global warming potential, about 28-36 times greater than that of carbon dioxide (CO_2). These methane emissions have a substantial contribution to global greenhouse gas levels and the resultant climate change [4]. Furthermore, in developing countries the rice straws are usually burned on site to prepare the field for next cultivation season leading to uncontrolled release of greenhouse gases and hazardous particles, such as PM10 and PM2.5 [5-6]. Several strategies have been suggested, such as conversions of rice straws to various types of biofuels and biochemical [7], especially biogas, bioethanol and biohydrogen in controlled facilities to reduce the impact to environment [8, 9].

Mitigations of carbon emissions from rice cultivations include improving water management, and adopting sustainable farming practices, and enhancing soil properties. Alternate Wetting and Drying (AWD) method involves periodically draining water out of rice paddies to interrupt the anaerobic conditions that favor methane-producing microbes. Additionally, incorporating amendments of soil's nutritions and compositions like compost and biochar can enhance soil health and structure, leading to better water retention [10, 11]. Using silica fertilizers can promote the growth and strength of plants, it also affects the formation of phytoliths in rice plants and aids in carbon sequestration, contributing to reduction of greenhouse gas emissions [10]. Implementing these practices collectively can

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make rice cultivation more sustainable and environmentally friendly.

Phytoliths are microscopic silica structures that form within plant tissues, mostly as silicon dioxide (SiO_2). Phytoliths are deposited in various parts of the plant, including stems, leaves, roots, and seeds. When plants die and decompose, phytoliths are buried into the soil laters, where they can persist to degradation for thousands of years [12]. The incorporation of carbon into phytoliths primarily occurs through the adsorption of organic molecules on the surfaces of silica nanoparticles as they assemble to form the phytolith structure, so-called phytolith occluded carbon (PhyOC) [12]. Additionally, some carbon compounds are directly incorporated into the silica matrix during its formations and becomes part of the plant's biomass, e.g. improving plant biomass. The formation of phytoliths in plants has several benefits for the plant, including increased resistance to pests and diseases, improved structural integrity, and enhanced drought tolerance [12]. Phytoliths help maintain soil organic carbon levels and prevent the loss of carbon to the atmosphere by contributing to soil stability and reducing erosion. The phytoliths is less susceptible to microbial decomposition and oxidation, which means it is less likely to be released back into the atmosphere as carbon dioxide (CO_2). Instead, this carbon remains stable and sequestered in the soil for extended periods [13]. Therefore, the longevity of phytoliths in plant debris and in soil layers is an important mechanism in the carbon sequestration.

In rice cultivation, the use of silica fertilizers to promote plant growth and strength can be particularly beneficial. When silica fertilizers, such as silicon dioxide, silicic acid and sodium metasilicate, are applied to the soil, they elevate the concentration of soluble silica, which is the form that plants can readily absorb [14]. This increased availability of silica in the soil solution facilitates its absorption by the plant roots. Once absorbed, silica is transported through the plant's vascular system to various tissues, including stems, leaves, and seeds. In these tissues, silica is deposited as phytoliths, which are rigid, microscopic silica structures that provide structural support and defense against biotic and abiotic stresses. As a result, more organic carbon is sequestered within phytoliths and deposited in plant tissues, and the overall carbon footprint of rice cultivation is reduced [15]. This approach not only mitigates greenhouse gas emissions but also improves the resilience and productivity of rice crops, contributing to more sustainable agricultural practices. A field experiment of rice cultivation assessed the impact of different silicon sources (diatomaceous earth, silicic acid, and rice husk biochar) on phytolith production and carbon content in rice plants and soil properties. The study found that rice husk biochar significantly increased phytolith and PhytOC content, showing strong correlations with soil organic carbon, nitrogen, potassium, and various forms of silicon [16]. A meta-analysis of over 3500 data points from 87 studies revealed that major rice-producing regions have insufficient Si supply in paddy soils. Si fertilization effectively increased rice yield by an average of 36% and biomass by 39%, with potential increases up to 52% and 46% respectively with higher Si doses. Additionally, Si fertilization enhanced phytolith carbon sequestration potential, although this potential may decline in ancient paddy soils due to slow phytolith migration and dissolution [17].

Given the environmental challenges posed by rice cultivation, there is a growing interest in sustainable agricultural practices that can reduce greenhouse gas emissions while maintaining crop productivity. On a global scale, phytoliths are estimated to sequester between 0.1 and 0.3 gigatons of carbon per year, contributing a small yet significant portion to the global carbon cycle [12]. One promising approach involves the use of silica fertilizers, by promoting the accumulation of phytoliths. Therefore, this study aimed to investigate the effect of silica fertilizers on deposition of phytoliths in plants and soils and evaluate the benefit of boosting rice plant biomass and productivity.

2 Materials and methods

2.1 Preparation of rice cultivation

The rice cultivation experiments were conducted in a controlled environment, a greenhouse, located in Pathum Thani province, Thailand. Rice seeds, RD43 cultivar, are courtesy provided by Pathum Thani Rice Research Center, Thailand. After soaking rice seeds in water for 24 hours to enhance germination, the germinated seeds were transferred to deep planting pots to allow seedlings to grow for 14 days. For fertilizer applications, two types of silica fertilizers, silicic acid and metasodium silicate, were mixed with pot soils with the dosage of 0.33 g/kg-soil. For each treatment, a total of 25 rice seedlings were transferred in to 5 separated pots filled with soils with silica fertilizers, silicic acid (S1) and sodium metasilicate (S2). As a control, 25 rice seedlings were planted in pot soils without supplementation of silica fertilizer (Figure 1). All pots were placed in a greenhouse. To ensure consistent moisture by keeping the soil saturated, mimicking the flooded conditions rice plants naturally grow in, the pots were watering regularly, maintaining a shallow water layer on the soil surface. The progression of rice plant growths and yields were monitors after 100 day-period of cultivation. The plant growth as biomass dried weight were recorded.

2.2 Phytolith quantitations

Rice leave samples were harvested from each treatment after 100 day of cultivation. The leave samples were cut manually into about 1-cm long pieces and dried in 70 ^{o}C for 24 hr until constant dried weight was obtained. Then, all samples were ground by househole blender. Four grams of grounded samples were subjected to muffle furnace operation at 500 ^{o}C, for 8 hr. The samples were hydrolysed by addition of 10% HCl solution in the waterbath at 70 ^{o}C for 20 min. The solid fraction of sample was collected after centrifugation at 3500 rpm, 5 min, and washed with deionized water for 3 times. The

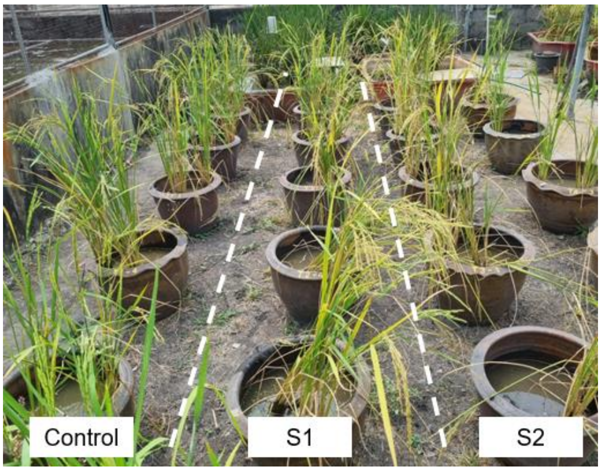

Fig. 1. The growths of rice plants supplemented with silicic acid (S1) and sodium metasilicate (S2)

organic matter in sample was removed by treatment of 15% H_2O_2 solution in the waterbath at 70 ºC for 20 min. The remaining sample pellet was recovered by centrifugation and washed with absolute ethanol. The washed sample was dried in hot air oven at 70 ºC for 24 hr and the dried weight was recorded as phytolith weight in plant sample.

Soil samples were collected from the pots of each treatment at the same day of rice harvesting. Soil samples were dried in hot air oven at 70 °C for 24 hr until constant dried weight was obtained. Five grams of dried soil samples were washed with 5% Calgon solution and samples were placed in ultrasonication bath for 10 min at ambient temperature. The samples were recovered by centrifugation at 3000 rom for 2 min, and washed with deionized water for 3 times. Organic matters in soil samples were oxidized by addition of 30% H_2O_2 solution in waterbath at 70 °C, 20 min, and samples were washed with deionized water for 3 times. Samples were subsequently hydrolysed by 30% HCl solution at 70°C, 20 min, and samples were washed with deionized water for 3 times. The samples were disintegrated again by mixing in 5% Calgon solution and samples were placed in ultrasonication bath for 10 min at ambient temperature, and followed with washing 3 times. The phytolith contents in soil samples were collected in supernatant fraction after density-assisted centrifugation in $ZnBr_2$ solution at the density of 2.35 g/ml and the dried weight of phytolith was recorded.

2.3 Characterization of soil phytoliths by x-ray diffraction (XRD) analyses

An X-ray diffractometer (Model: SmartLab x-ray diffractometer, Rigaku, USA) was used in the determination of the crystalline structure of untreated and pretreated Napier grass. The biomass was scanned at 2θ ranging from 5º to 50º with a scan speed of 4º/min [18-19].

3 Results and discussion

This study selected two types of silica fertilizers, silicic acid (H_4SiO_4) and sodium metasilicate (Na_2SiO_3), for applications to soil used for rice cultivation in greenhouse. The main difference between silicic acid and sodium metasilicate lies in their form and solubility. Silicic acid is a highly soluble form of silica and is directly bioavailable to plants. In contrast, sodium metasilicate needs to dissolve and release silicic acid before plants can absorb it, which might delay its effectiveness but can offer a more prolonged supply of silicon [20-21]. Additionally, silicic acid can be applied as a foliar spray, allowing for rapid absorption through the leaves, providing a quick boost of silicon to support critical growth stages. Sodium metasilicate is widely used due to its relatively lower cost and ease of handling by dissolving it in water during watering to the plants [20-21].

In this study, after 100 days of rice cultivations, the plant above-ground biomass, rice seeds and soil samples were collected to represent the harvesting stage of growth. Phytoliths in above-ground-part of rice samples and soils in the planting pots were extracted and their weights were measured (Figure 2). In plant samples, both silicic acid and sodium metasilicate influenced on increase of phytolith depositions for 3.76 and 2.79 fold times, respectively, compared to control set (without silica fertilizer). Similarly, the phytolith contents extracted from soil samples were higher than control set for 3.50 and 1.90 fold time with application of silicic acid and sodium metasilicate, respectively. Therefore, this result supported that applications of silica fertilizers in rice cultivation promote depositions of phytoliths in plant biomass and soil, although the abundance of phytoliths in soil samples are lower than plant biomass. This could be explained that during the growth of plants, they actively absorb silica from the soil and deposit it within their cells, resulting in a high concentration of phytoliths within the plant biomass. Once the plants die and decompose, these silica structures are released into the soil [22]. However, in this experiment, the soil samples were freshly prepared, therefore there is no decomposed plant biomass as found in nature, which possibly leads to deviant behaviour from nature.

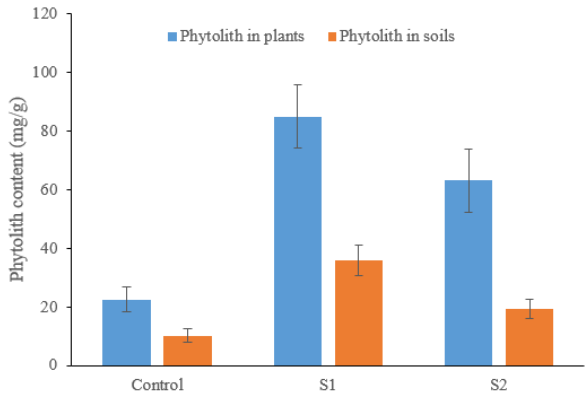

Fig. 2. The phytolith weights extracted from rice plants and soils

To observe the effect of silica fertilizer applications on growth and yield of rice cultivation, the dried weights of above-ground part and seeds were recorded (Figure 3). The results showed that both silica fertilizers enhanced the dried weights of above-ground part and seeds compared to control set, especially when using sodium metasilicate. The exact mechanisms by which carbon is incorporated into phytoliths, resulting in increase of plant biomass, are still a subject of ongoing research, but it is clear that organic carbon becomes immobilized within the phytolith structure during its formation. This observation could be due to the properties of sodium metasilicate, including slow-release of silica and its alkalinity to adjust soil acidic condition [23].

Phytoliths are microscopic silica structures that form within the cells of many plants, primarily composed of silicon dioxide (SiO_2). Besides silicon dioxide, phytoliths often contain trace amounts of organic carbon, remnants of plant tissue, or other organic matter associated with the plant. Additionally, phytoliths may include trace elements, such as aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), potassium (K), sodium (Na), and phosphorus (P) [24]. The specific composition of these elements can vary depending on the plant species, soil composition, and environmental conditions, providing valuable insights for reflecting the growth conditions of the plants. To understand the utilization of silica fertilizer in soil by rice plants, the compositions of silica derivatives of soil phytoliths were analyzed by using XRD. In this study, 4 silica derivatives were identified, including quartz (SiO_2), halloysite ($Al_2Si_2O_5(OH)_4$), kaolinite ($Na_{0.3}Al_4Si_6O_{15}(OH)_6 \cdot 4H_2O$), and alum ($NaAl(SO_4)_2(H_2O)_{12}$), with various abundances in each soil samples (Table 1).

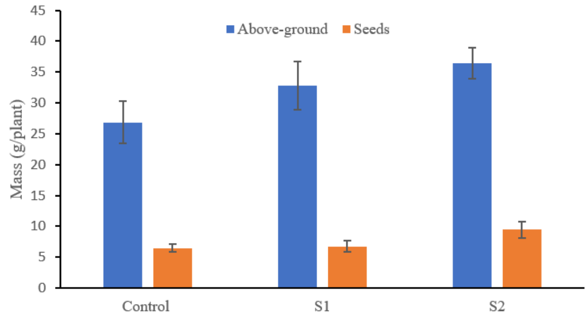

Fig. 3. The biomass of rice cultivation under treatment of silica fertilizer

Table 1. Composition of phytoliths extracted from soil samples

Sample	Silica-derivatives in soil phytoliths (%)*			
	Quartz	Halloysite	Kaolinite-montmorillonite	Alum-Na
Control	33.3	21.7	35.8	9.2
S1	35.6	22.5	41.6	0.37
S2	39.7	2.16	32.6	25.6

*Quartz: SiO_2, Halloysite: $Al_2Si_2O_5(OH)_4$, Kaolinite-montmorillonite: $Na_{0.3}Al_4Si_6O_{15}(OH)_6 \cdot 4H_2O$, Alum-Na: $NaAl(SO_4)_2(H_2O)_{12}$

Among 4 derivatives, quartz was found with the major composition of soil phytoliths in control and treatment soils. Sodium metasilicate affected to have the most deposition of quartz, whereas silicic acid promoted kaolinite-montmorillonite. Quartz, halloysite, kaolinite, and alum are integral to the soil's silica content, influencing the availability of silica for plant uptake and subsequent phytolith formation [25]. Unlike crystalline silica forms such as quartz, the silica in phytoliths is in an amorphous state, often referred to as opal-A. Quartz, being a crystalline form of silica, is not found within phytolith structures themselves. However, both quartz and phytoliths can coexist in the soil, reflecting the silica-rich environment from which plants draw their nutrients. Quartz provides a primary source of silica through weathering, while clay minerals like halloysite and kaolinite, which are composed of aluminum silicates, release silica more gradually. Alum affects soil pH and nutrient dynamics, indirectly impacting silica availability [24, 25]. Together, these components contribute to the complex interactions between soil, plants, and the formation and recycling of phytoliths.

4 Conclusion

The study concludes that the application of silica fertilizers significantly influences the accumulation of phytoliths in both rice plants and soil. Specifically, silicic acid enhances phytolith formation within rice plant tissues more effectively than metasodium silicate, while sodium metasilicate contributes to a higher phytolith content in the soil. These findings highlight the potential of silica fertilizers to improve plant resilience and soil quality through increased phytolith accumulation. Additionally, the study underscores the importance of selecting the appropriate type of silica fertilizer to optimize phytolith production, which can contribute to carbon sequestration and sustainable agricultural practices. Future research should explore the long-term effects of these fertilizers on plant health, soil properties, and carbon capture efficiency to further refine agricultural strategies for environmental sustainability.

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