CARBON OCCLUSION POTENTIAL OF RICE PHYTOLITHS: IMPLICATIONS FOR GLOBAL CARBON CYCLE AND CLIMATE CHANGE MITIGATION

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Abstract. Phytoliths are silica bodies produced by plants through bio-mineralization process. During such process, occlusion of carbon (C) also takes place within the phytoliths called phytolith occluded C (PhytOC). The PhyOC is highly stable and may substantially contribute to long-term terrestrial C sequestration. The present study aimed to investigate the phytolith and PhytOC contents variability in rice cultivars and its potential for long-term terrestial C biosequestration.The results indicate that dry matter yield of rice cultivars varied from 15.52 to 28.82 g plant^{-1}and, the PhytOC contents of straw, root, husk, and grains range from0.22-0.68%, 0.09-0.22%, 0.43-0.82% and 0.002-0.024%, respectively. The PhytOC content of rice depends on the content of phytoliths and the efficiency of C occlusion within the phytoliths. The C sequestration rates of rice cultivars are approximately 0.05 - 0.12 Mg of C dioxide equivalents (Mg-e-CO_2) ha^{-1} year^{-1}. Assuming maximum phytolith C biosequestration rate of 0.12 Mg-e-CO_2 ha^{-1} year^{-1}, the global annual potential sink rate of PhytOC in soils through rice phytoliths would approximately be 16.4 Tg-e-CO_2. Therefore rice crop may play a significant role in long-term C sequestration through PhytOC.
Keywords: *carbon biosequestration, plant silica, phytolith occluded carbon, rice cultivars*

Introduction

Green house gases (GHGs) mediated global warming and climate change is one of the major global environmental issues of recent decades. Recently it is estimated that global CO_2 emission rate had increased to 3.11×10^{11} Mg per year by 2014. Therefore all mechanisms of carbon (C) sequestration should be explored in order to reduce the concentration of CO_2 in the atmosphere. Land use systems like forest, grassland, croplands, and shrub lands substantially contributes to terrestrial C storage as a major part of C sequestered is again returned to soil as plant residues. Therefore, a minor change in such a big terrestrial C pool may significantly affect the C flux. In this context phytolith occluded C (PhytOC) of plants that has long resident time (millennia) and resist decomposition, fire, animal digestion, etc. can be considered for long-term terrestrial C storage. The presence of silica phytoliths within cereal crops is well documented. But information on C sequestration potential of phytoliths for cereals is meager. Therefore, it is aimed to study the phytolith and PhytOC content variability in rice, a hyper silica accumulator and widely cultivated food crop across the world, to explore its C biosequestration potential within the phytoliths.

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Review of Literature

The PhytOC is an organic C fraction, where C is entrapped within recalcitrant silicified structure called phytoliths. Phytoliths or opal silica is deposits of silica within plant tissues (e.g. cell walls, cell lumina and inter cellular spaces) during the process of biomineralization (Siever and Scott, 1963; Piperno, 1988; Parr and Sullivan, 2005). Compared with other organic fractions PhytOC fraction is very stable and highly resistant against decomposition and may accumulate in soil for several thousands to millennia of years after plant decomposition (Wilding et al., 1967; Wilding and Drees, 1974; Mullholland and Prior, 1993; Prasad et al., 2005; Parr et al., 2010). For example it has been reported that the age of phytoliths in volcanic soils and peat land sediments ranges from 0 to 8000 years (Parr and Sullivan, 2005) and also radio C date of phytolithsindicate13300±450 years old (Wilding, 1967). The C flow in soil plant atmospheric continuum and long-term stability of PhytoC in soil is depicted pictorially in *Fig. 1*. PhytOC plays a major role in soil C cycle (Parr and Sullivan, 2005; Oldenburg et al., 2008) and many researchers emphasized the importance of soil C in climate change (Gifford, 1994; Kosten et al., 2010). Moreover PhytOC can be easily measured in standing vegetation bypassing many of the current issues associated with standard soil C measurement (Parr and Sullivan, 2011).

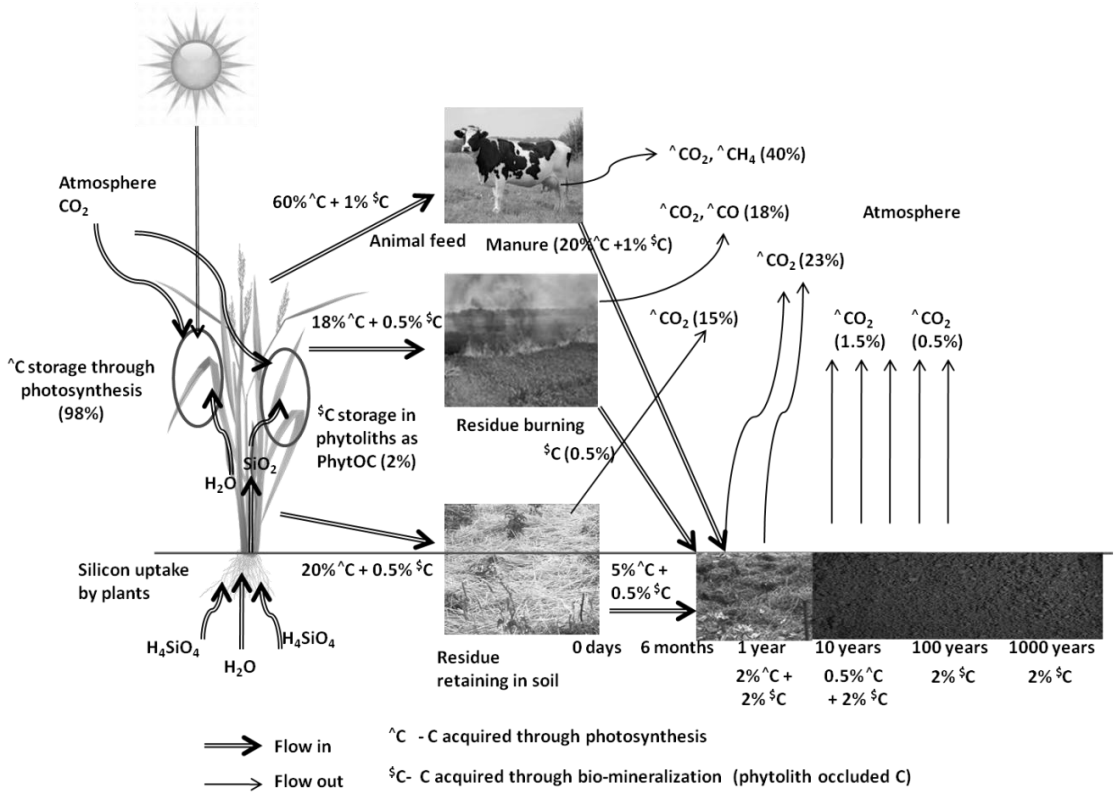

Figure 1. *Carbon flow of soil plant atmosphere continuum and long-term stability of PhytOC in the soil (the ^C fraction which acquired through photosynthesis return back to atmosphere within a short time span of 100 years whereas the $C fraction that entrapped in phytolith can stay in the soil for more than 1000 year)*

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The soil C sequestration rate due to PhytOC under natural vegetation with varying climatic condition varies between 0.4 to 0.9 g C m^{-2} $year^{-1}$ (Parr and Sullivan, 2005). It contributes 15 to 37% of the long term global soil C sequestration rate indicating that PhytOC plays a major role in long term soil C sequestration processes under natural vegetation systems. Also it was demonstrated that the PhytOC yields of crops can be far higher than those of native vegetation (Parr et al., 2009). The PhytOC content and variability in wheat, sugarcane, millet and some bamboo cultivars were extensively studied by many researchers (Parr and Sullivan, 2005, 2011; Parr et al., 2009, 2010; Zuo and Lu, 2011). For example, the phytolith C biosequestration fluxes from millet, wheat, sugarcane and bamboo range up to 0.04, 0.25, 0.36 and 0.71 Mg-e-CO_2-ha^{-1} $year^{-1}$, respectively (Parr and Sullivan, 2005, 2011; Parr et al., 2009, 2010; Zuo and Lu, 2011) and also Song et al. (2013) estimated that global PhytOC sink of croplands is 26.35±10.22 Tg CO_2 $year^{-1}$ and the major contributors of this cropland sinks are rice, wheat and maize, as they are widely cultivated across the world, and play significant role in global cropland C balance (Rajendiran et al., 2012). Bamboo leaf litter has PhytOC yields of upto 0.7 t e-CO_2 ha^{-1} $year^{-1}$ and PhytOC from bamboo and sugarcane grasses has a global potential to bio-sequestrate approximately 1.5 billion t e-CO_2 $year^{-1}$, equivalent to 11% of the current increase in atmospheric CO_2 (Parr et al., 2010). Simply by growing high PhytOC yielding cultivars over low PhytOC yielding cultivars resulted in additional sequestration of C in soil by ~ 5 million t e-CO_2 $year^{-1}$ and 53 million t e-CO_2 $year^{-1}$, for sugarcane (20 million hectares) (Parr et al., 2009)and wheat (214 million hectares) (Parr and Sullivan, 2011), respectively. Hence, this process offers the opportunity to use the plant species that yield high amounts of PhytOC to enhance terrestrial C sequestration.

Rice is currently cultivated on around 164.1 million hectares and it is the stable food source for more than half of the world's population. India has long history of rice cultivation and is accounting for 22% of world production. The current area of rice production in India is around 44 million hectares. Rice is cultivated two to three times in a year because of variability in temperature and irrigation facilities. The presence of silica phytoliths and C sequestration potential of major cereal crop like rice (Li et al., 2013; Guo et al., 2015;), millet (Zuo and Lu, 2011), sugarcane (Parr et al., 2009) and wheat (Parr and Sullivan, 2011) have been reported. Also the process of C accumulation in phytoliths are affected by many factors like location, climate, varieties, pest and disease resistances, fertilizers etc. (Ma et al., 2002; Ding et al., 2005; Meena et al., 2013). Keeping in view of all the above, the objectives of the present study are:

1. To study the phytolith and PhytOC content variability in rice cultivars that cultivated in sub-tropical conditions
2. To screen high phytolith and phytolith occluded C yielding rice cultivars, and
3. To explore the potential of C bio- sequestration within the phytoliths of rice cultivars.

Materials and Methods

Collection of planting material

The seeds of 15 commonly grown rice cultivars of central India were collected from the Department of Plant Breeding and Genetics, Jawaharlal Nehru Krishi Vishwa Vidhyalaya, Jabalpur (India) (*Table 1*).

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Table 1. *Rice cultivars and organs, dry matter yield of rice organs (g per plant), phytolith content of rice organs by dry weight basis (mg g^{-1}), C content of rice phytoliths (%), PhytOC content of organs (%), total dry biomass of rice plant (g) and total estimated PhytOC production in rice phytoliths on the basis of Mg-e-CO_2 ha^{-1} $year^{-1}$ (considering optimum crop stands per ha as 330000 plants by assuming crop spacing with 20 cm x 15 cm as well as 3 season per year) and PhytOC sink rate in soil (Mg-e-CO_2 ha^{-1} $year^{-1}$).*

Rice cultivar	Name of the organ	Dry weight of organ (g per plant)	Phytolith content (mg g^{-1})	C content of phytolith (% by weight)	PhytOC content of organs (% by weight)	Total dry biomass of rice plant (g)	Total estimated PhytOC sequestration per plant (g-e-CO_2)	Total estimated PhytOC sequestration in rice (Mg-e-CO_2 ha^{-1} $year^{-1}$)	PhytOC sink rate in soil (Mg-e-CO_2 ha^{-1} $year^{-1}$)
MR - 219	Straw	11.89	12.47	3.37	0.420	23.87	0.28	0.094	0.084
	Root	3.55	8.30	2.13	0.177				
	Husk	2.64	14.06	5.67	0.797				
	Grain	5.79	0.26	1.00	0.003				
P - 1121	Straw	9.20	23.62	1.87	0.442	19.97	0.24	0.078	0.070
	Root	4.27	10.70	1.87	0.200				
	Husk	2.21	21.60	3.20	0.193				
	Grain	4.29	0.61	0.87	0.005				
WGL - 32100	Straw	8.71	21.32	2.23	0.475	17.80	0.22	0.074	0.066
	Root	3.06	11.40	1.90	0.217				
	Husk	2.09	24.41	2.40	0.585				
	Grain	3.95	1.42	1.07	0.015				
MTU - 1081	Straw	11.14	22.75	2.20	0.500	24.20	0.28	0.095	0.085
	Root	3.13	7.05	1.70	0.120				
	Husk	3.04	22.06	2.80	0.618				
	Grain	6.73	0.32	0.80	0.003				
JGL - 3844	Straw	8.95	19.24	2.00	0.385	19.06	0.19	0.063	0.057
	Root	3.31	9.17	1.50	0.138				
	Husk	2.05	18.30	3.33	0.610				
	Grain	4.76	1.46	0.83	0.012				

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SUREKHA	Straw	14.62	20.98	2.27	0.476	28.82	0.36	0.118	0.106
	Root	3.95	8.26	2.03	0.168				
	Husk	4.07	19.66	2.63	0.517				
	Grain	6.18	0.14	1.23	0.002				
PRATIKSHYA	Straw	7.30	26.39	2.53	0.668	16.89	0.26	0.086	0.077
	Root	2.96	6.54	2.27	0.148				
	Husk	2.04	21.49	3.80	0.817				
	Grain	4.59	1.94	1.23	0.024				
KAVYA	Straw	8.53	23.33	2.53	0.590	17.60	0.24	0.079	0.071
	Root	2.79	8.45	1.97	0.166				
	Husk	1.98	21.18	2.37	0.502				
	Grain	4.29	1.17	0.93	0.011				
VARALU	Straw	7.61	23.13	1.93	0.446	15.52	0.17	0.055	0.049
	Root	2.42	5.5	1.63	0.090				
	Husk	1.84	15.46	3.21	0.495				
	Grain	3.64	0.41	0.73	0.003				
KRANTI	Straw	11.46	15.72	1.40	0.220	23.21	0.17	0.056	0.051
	Root	2.98	7.2	1.13	0.081				
	Husk	2.73	16.01	4.20	0.672				
	Grain	6.05	1.04	0.70	0.007				
MTU - 1010	Straw	11.88	18.48	2.30	0.425	24.83	0.30	0.099	0.089
	Root	3.26	7.26	1.43	0.104				
	Husk	3.27	13.13	6.30	0.827				
	Grain	6.43	1.15	1.13	0.013				
OR - 1912-24	Straw	9.58	16.33	2.53	0.413	19.96	0.23	0.075	0.068
	Root	2.87	8.51	2.13	0.181				
	Husk	2.49	14.27	4.80	0.685				
	Grain	5.02	0.49	1.30	0.006				
JAGTIAL SANALU	Straw	8.25	20.76	2.27	0.471	16.31	0.19	0.063	0.056
	Root	3.46	10.4	1.77	0.184				
	Husk	1.49	20.3	2.13	0.433				

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	Grain	3.10	0.23	1.07	0.002				
JGL - 3828	Straw	9.11	16.59	2.43	0.403	20.29	0.23	0.075	0.068
	Root	3.47	7.44	1.77	0.132				
	Husk	2.48	13.96	5.90	0.824				
	Grain	5.56	0.73	1.33	0.010				
BPT - 5204	Straw	9.01	14.47	2.90	0.420	17.64	0.22	0.072	0.064
	Root	3.15	8.43	2.20	0.185				
	Husk	1.90	14.52	5.50	0.799				
	Grain	3.99	0.65	1.43	0.009				

Note: Values in the table are a mean of triplicate observations

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These cultivars are raised in the pots under same environmental conditions to eliminate factors that might influence silica uptake and deposition. The greenhouse study was conducted in a "black cotton soil" (Typic Haplusterts) in the Division of Environmental Soil Science, ICAR-Indian Institute of Soil Science (23°18' 33.6" and N, 77°24' 27.2" E and 504 m above mean sea level), Bhopal (Madhya Pradesh), India. It is located in central part of India and has semi-arid and sub-tropical dry summer and cold winter climate with a mean annual air temperature of 25°C and annual average rainfall of 1146 mm. The planted rice cultivars are used for analysis of phytolith and PhytOC content in different organs (straw, husk, grain and root; *Table 1*). The current study compares the PhytOC production variability among the rice cultivars and also contribution of different organs towards this C fraction. After harvest of the crop, plant parts like straw, root, husk and grains were separated and washed with distilled water to remove the dusts accumulated on the plant material. It was allowed to air dry for 2-3 days and then placed in hot air oven at 60°C for 24 hours. The dried plant parts were grounded and passed through 0.02 mm sieve Dry matter yield of straw, root, husk and grain were recorded and these data were used for calculating PhytOC production of each rice cultivar.

Phytolith extraction and occluded C analysis

The phytolith in plant material was extracted by dry ashing and acid extraction method using muffle furnace (Rovner, 1983; Bowdery, 1989). The carbonates and organic materials in the acid extracts were removed with the help of 10% HCl and 15% H_2O_2, respectively. About 1.0 g of dry plant material was placed in a silica crucible and was heated in muffle furnace at 500°C for 8 hours. Then it was cooled and transferred to test tubes. About 20 ml of 10% HCl was added to test tubes and heated in water bath at 70 °C for 20 minutes. Then it was centrifuged at 3500 rpm for 5 minutes and the supernatant solution was removed. The remaining stuff was rinsed with distilled water and was centrifuged again at 3500 rpm for 5 minutes and the supernatant was decanted. Further 20 ml of 15% H_2O_2 was added and heated in water bath at 70°C for 20 minutes. Then the content was centrifuged at 3500 rpm for 5 minutes and was decanted. Then rinsed with distilled water and centrifuge at 3500 rpm for 5 minutes and decanted, this process was repeated twice. And finally 1 ml of 100% ethanol was added and left overnight to dry. Then dried material was weighed and phytolith was calculated. The separated phytolith was mounted onto microscopic slides in Canada balsam and was observed in microscope at 400x magnification (*Fig 2*). The C content of phytoliths, which extracted from plant materials, was analyzed in CHN analyzer (model FLASH 2000 organic elemental analyzer). The organic C data were monitored with standard soil samples (NC Soil Standard 338 40025 Certif. 133317) and the precision is better than 80%. The C sequestered in different plant parts and the total C sequestered by the rice cultivars were calculated and expressed in CO_2 equivalent basis. The correlation between phytolith content and C content of phytoliths in different plant parts like straw, root, husk and grain was studied.

Estimation of PhytOC production and PhytOC Sink

The production of PhytOC in any plant species is depends primarily on the PhytOC content and dry weight of the material. The PhytOC content of a plant parts is a product of C content in the extracted phytoliths and phytolith content of the plants parts. The

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PhytOC production rate of a plant in an area is estimated from PhytOC content and dry weight of the organs as follow:

$$PhytOC\ production\ rate = \sum_{i=1}^{n} PhytOC\ content_i \times Dry\ biomass_i \times \frac{44}{12} \quad \text{(Eq. 1)}$$

Where, PhytOC production rate is the PhytOC production by a particular plant per hectare per year (Mg CO_2 $ha^{-1}year^{-1}$), PhytOC $content_i$ is the concentration of PhytOC in an organ (wt %), and Dry $biomass_i$ is the dry weight of the crop organs per hectare (Mg ha^{-1} $year^{-1}$), and i =1 to n (number of crop organs). From single plant to per hectare conversion the optimum plant population of 330000 was used in this study by assuming with crop spacing of 20 cm x 15 cm.

The PhytOC sink rate is controlled by the PhytOC production rate and the stability of phytolith in environments. The PhytOC sink rate can be estimated from phytolith production rate and phytolith stability factor as mentioned by Song et al. (2013):

$$PhytOC\ sink\ rate = PhytOC\ production\ rate \times phytolith\ stability\ factor \quad \text{(Eq. 2)}$$

Where, PhytOC production rate may be obtained from *Eq. 1* and the phytolith stability factor is assumed to be 0.9 as most of the phytolith have been proved stable for thousands of years (Meunier et al., 1999; Parr and Sullivan, 2005).

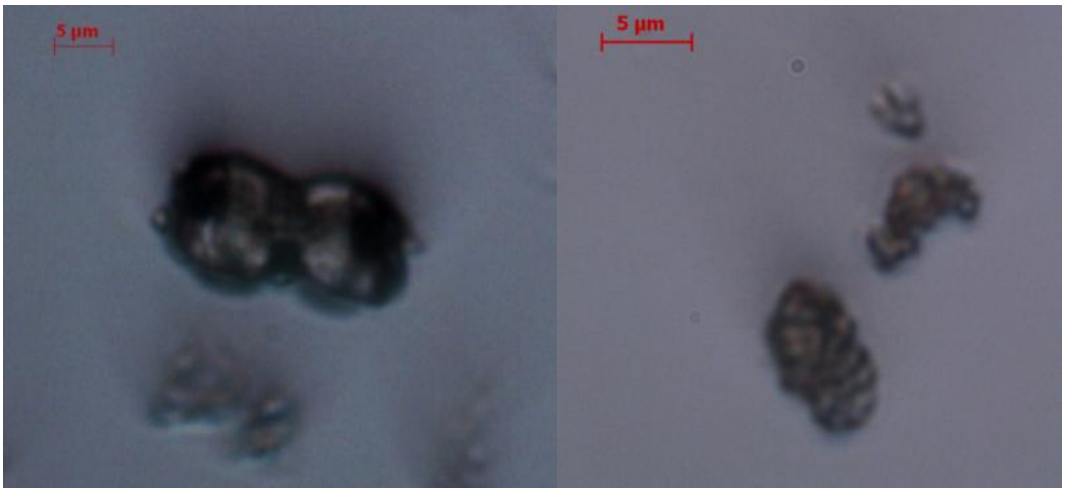

Figure 2. *Morphology of rice phytoliths*

Results

Dry weight of various plant parts straw, root, husk and grain, and total dry matter yield (DMY) of the 15 rice cultivars is presented in *Table 1*. The dry matter yield of rice cultivars vary from 15.52 – 28.82 g per plant. Also the dry biomass of different rice organs such as straw, root, husk and grain range from 7.30 to 14.62 g, 2.42 to 4.27 g, 1.49 to 4.07 g and 3.1 to 6.73 g per plant, respectively. Results indicate that rice straw

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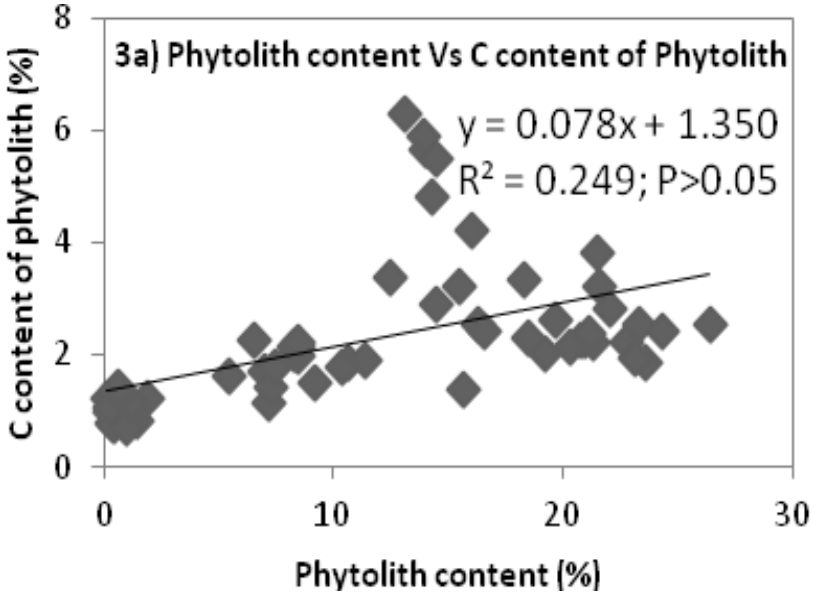
contributes more towards the total dry biomass. The order of rice organs that contributes towards dry matter accumulation in rice cultivars was straw>grain>root>husk.

The microscopic observation of rice pytoliths is very clear and avoid of other impurities (*Fig. 2*). The content of phytoliths in different rice organs varied from 0.14-26.4 mg g^{-1} and there was no clear trend with respect to phytolith content in different plant parts of rice. In some cultivars straw portion has higher phytolith content and in some other cases phytolith content was greater in husk. However in most of the cases straw portion records the highest phytolith content followed by husk, root and grain for rice cultivars (*Table 1*). Also C content of phytoliths of rice organs differs from 0.7-6.3% (*Table 1*). It is observed that C content of phytoliths in sheath is higher than that of straw, root and grain (*Table 1*). Further, substantial variations in PhytOC content were observed in different rice organs ranging from 0.002 to 0.82 mg g^{-1}.

There is weaker positive correlation prevails between phytolith content and C content of phytoliths (R^2 = 0.249, P>0.05) (*Fig.3a*), However there is strong positive correlation exists between phytolith content and PhytOC content (R^2 = 0.694, P<0.05) (*Fig.3b*) as well as C content of phytoliths and PhytOC content of organs (R^2 = 0.760, P<0.01) (*Fig.3c*). Similarly the relationship of phytolith content and C content of phytoliths in different organs show weaker negative correlation in straw (R^2 = 0.139, P>0.05) and grain (R^2 = 0.000, P>0.05), stronger negative correlation in husk (R^2 = 0.721, P<0.05) and weaker positive correlation in root (R^2 = 0.028, P>0.05), respectively (*Fig. 4a*), but correlation between phytolith content and PhytOC content of different organs show strong positive correlation in straw (R^2 = 0.490, P<0.05), root (R^2 = 0.0.662, P<0.05) and grain (R^2 = 0.897, P<0.05) and weak negative correlation in husk (R^2 = 0.245, P>0.05), respectively (*Fig. 4b*). However the correlation between C content of phytoliths and PhytOC content of different organs is positive (*Fig.4c*) for all the organs but stronger for root (R^2 = 0.500, P<0.05) and husk (R^2 = 0.746, P<0.05) and weaker for straw (R^2 = 0.147, P>0.05) and grain (R^2 = 0.072, P>0.05), respectively.



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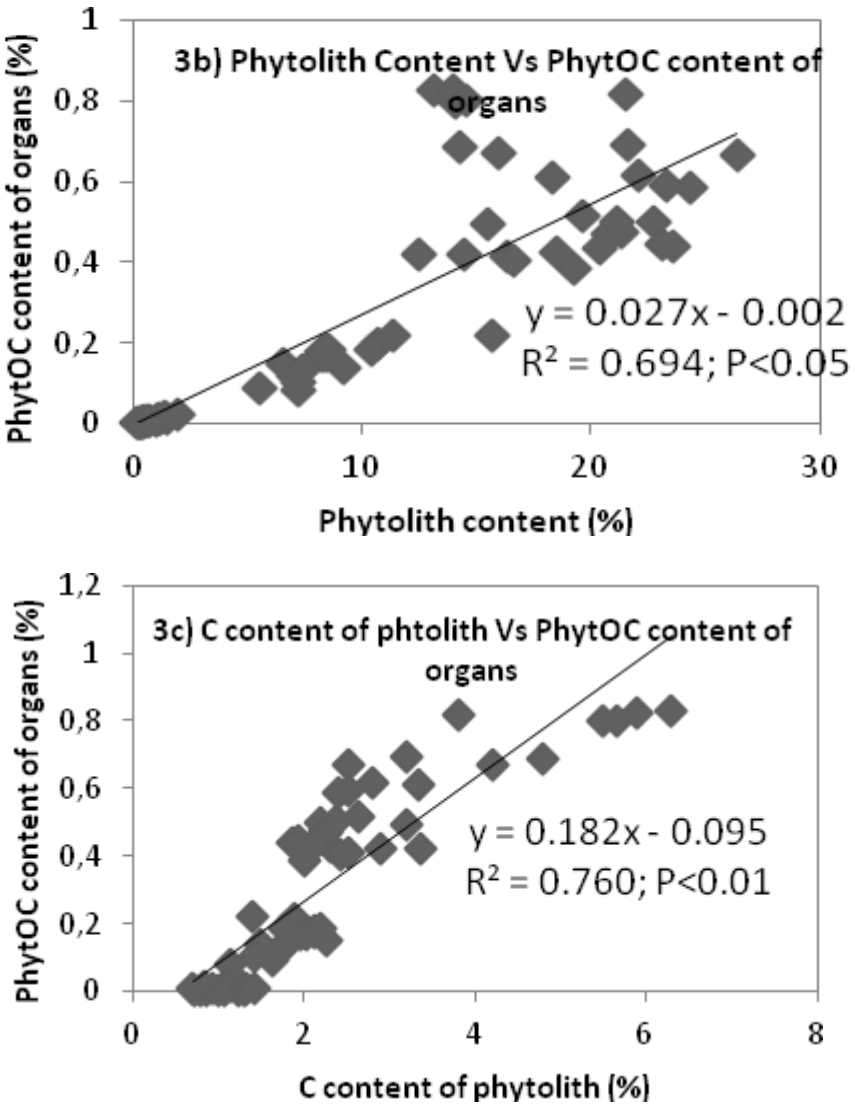
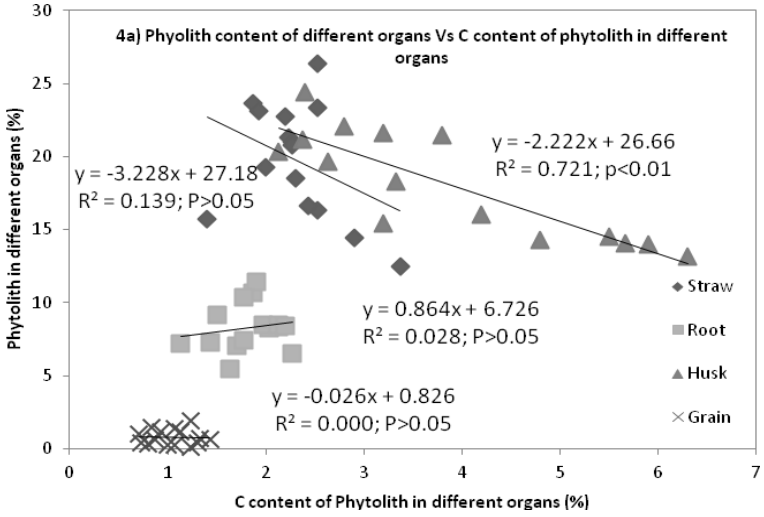


Figure 3. *Relationship between 3a) phytolith content and C content of phytolith; 3b) PhytOC of organs and phytolith content; and 3c) PhytOC content of organs and C content of phytolith*



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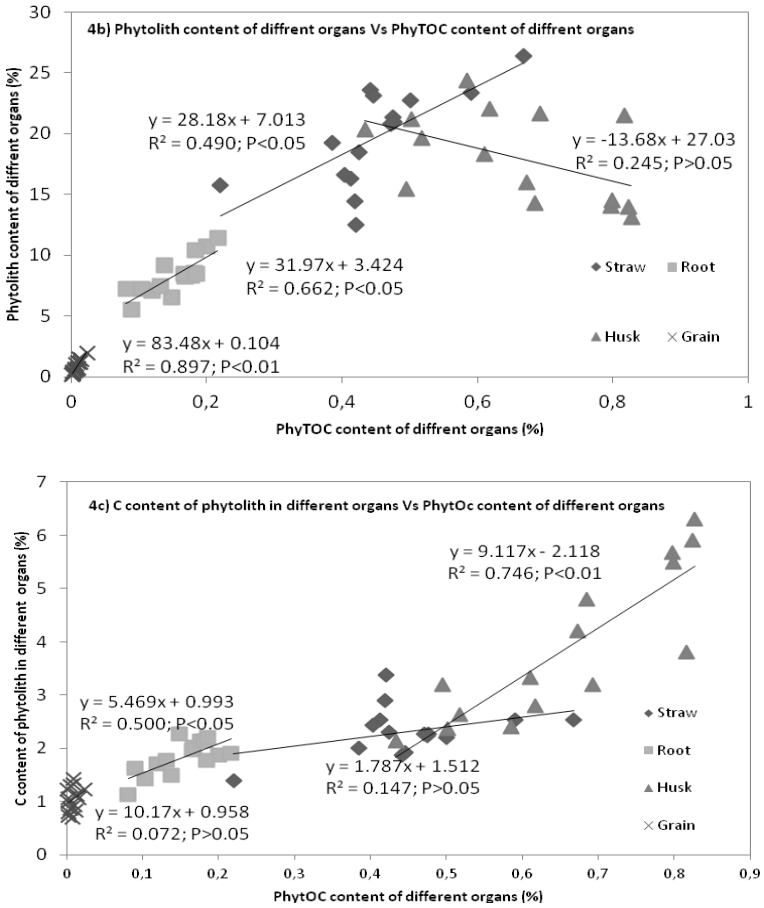

Figure 4.*Correlation of 4a) phytolith content of different organs and C content of phytolith in different organs; 4b) phytolith content of different organs and PhytOC content of different organs; and 4c) C content of phytolith in different organs and PhytOC content of different organs.*

Discussion

Variability of DMY, phytolith and PhytOC content in rice cultivars

Many researchers documented that genotype and environment factors influence DMY of cultivated arable crops (Ying et al., 1998; Khush et al., 2001; Horie et al., 2002; Katsura et al., 2007). In our study, genotypic factor substantially influenced the DMY and significant variations in DMY among the cultivars were observed and similar kinds of results were reported by many workers (Khush et al., 2001; Katsura et al., 2007). The contribution of rice straw towards the total DMY was higher followed by grains, root and husk. The result was in accordance with the results observed by Sun et al. (2008) in rice crop under hydroponic condition.

The distribution patterns of phytoliths in different plant organs show that straw portion contains most of the phytoliths (60%) followed by husk, root and grain. The similar results and trends were reported by many workers (Li et al., 2013; Guo et al., 2015). In the current investigation, the phytolith content of rice straw varied from 12.46 mg g^{-1} to 26.39 mg g^{-1}. Guo et al. (2015) and Li et al (2013) reported the phytolith

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content of rice leaf varies from 26.85- 37.12 mg g^{-1} and 55.45- 79.27 mg g^{-1}, respectively. When compared to other studies, it gives the impression of low phytolith content, but stem and sheath also parts of rice straw, they contain lower phytolith than that of leaf (Li et al., 2013; Guo et al., 2015). Further the process of phytolith accumulation in a plant is affected by many factors like location, climate, soil type, varieties, management practices, etc. (Parr et al., 2010; Parr and Sullivan, 2011; Meena et al., 2013; Zhao et al., 2015; Guo et al., 2015). The high DMY and silica accumulation in the straw might have resulted in higher phytoliths accumulation in the rice straw compared to other organs (Ding et al., 2005). The high phytolith accumulation in rice straw has additional advantage of being recycled and incorporate into the soil through proper crop residue management may substantially buildup of the phytolith content of the soil (Parr et al., 2010).

It was reported that the PhytOC in bamboo, wheat, sugarcane and millet has no direct relationship with the phytolith content of the plants and mainly depends on the efficiency of the C occluded within the phytoliths during biomineralization process (Parr and Sullivan, 2005, 2011; Parr et al., 2009, 2010; Zuo and Lu, 2011). However the results on C occlusion in the phytoliths from this study are quite different from the above studies. The strong correlation between the phytolith content and the PhytOC content of organs (R^2= 0.694, P<0.05) (*Fig. 3b*), and between the C content of phytoliths and the PhytOC content of organs (R^2= 0.760, P<0.01) (*Fig. 3c*) were observed in the 15 rice cultivars tested. In case of individual organs, between the phytolith content and the PhytOC content each organs (R^2= 0.245- 0.897) (*Fig. 4b*), and between the C content of phytoliths and the PhytOC content of individual organs in 15 cultivars (R^2= 0.072- 0.746) (*Fig. 4c*) show positive correlation. It indicates that the PhytOC content in rice plants might depend on both the phytolith content and C occlusion efficiency of biomineralization process within phytoliths during plant growth. Similarly Li et al. (2013) and Guo et al., (2015) observed the strong positive correlation between the content of phytoliths and the PhytOC content of rice organs, implying that PhytOC content of organs depends not only on the C content of phytoliths but also on phytolith content. Thus all the factors influencing the content of phytoliths and the content of silica occluding C within the phytoliths could result in significant variation of the phytolith and PhytOC content in plants. The findings of Li et al. (2014) were also in concurrence with the findings of the current investigation.

Screening of PhytOC yielding rice cultivars and its application

The estimate shows that the PhytOC flux of rice cultivars is 0.05-0.12 Mg-e-CO_2 ha^{-1} $year^{-1}$ (*Table 1*). Researchers have emphasized that the PhytOC sequestration rate can be improved by selecting cultivars which produce high PhytOC rather than low PhytOC yielding cultivars for cultivation (Parr et al., 2010; Parr and Sullivan, 2011; Song et al., 2013). This study also shows that by selecting high PhytOC yielding cultivar over low PhytOC yielding cultivar for cropping may additionally sequester 0.07 Mg-e-CO_2 ha^{-1} $year^{-1}$ through PhytOC. However cultivars cannot be selected only on the basis PhytOC production, but rather other desirable traits like biomass and yield, climatic factors, location and taste preferences to be considered (Parr et al., 2009). Also in this study it is demonstrated that there is a strong correlation between phytolith content and PhytOC production (*Fig. 3 and 4*), and the DMY also influences the PhytOC production of crops. Hence there is possibility to increase C occlusion potential of phytolith through improving the phytolith content and the DMY of crops by adopting simple management

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practices like nutrient management, regulating silicon (Si) supply, etc. For instance, many reports clearly reveal that the content of phytolith in crops can be enhanced through addition of Si and N fertilizers, straw, organic fertilizer, calcium-magnesium phosphate fertilizers and slags to crops (Bao et al., 1996; Chen et al., 2008; Zhang et al., 2008; Meena et al., 2013; Zhao et al., 2015). In fact phytolith accumulation in plants also may yield some additional advantages to the crop growth such as enhancement of growth and yield, resistance to pest and disease, and increase in shoot rigidity and hardness, etc. (Epstein, 2001) by silicon supplementation. Further Guo et al. (2015) reported that applying Si through basalt powder amendment in rice ecosystem can significantly enhance the phytolith concentration in different rice organs, in turn, substantially improve phytolith carbon sink. Rice is mostly cultivated in resource poor condition in India, as 60% of rice area is under rainfed and grown under poor crop management practices. Therefore, it is likely to enhance PhytOC content through regulating silicon supply, optimization of cropping and fertilization management under various agro-ecosystems across the country (Song et al., 2013; Song et al., 2014).

Moreover the plant phytoliths that present in straw and root are returned directly to soil through plant litter fall or root decomposition and some extent through rice straw as crop residue (Seyfferth et al., 2013; Ngoc Nguyen et al., 2014) and indirectly through burning of crop residues in the field as biochar (Houben et al., 2014; Liu et al., 2014) that is commonly practiced in India by the growers (Venkataraman et al., 2006; Pathak et al., 2010). In contrast, a substantial proportion of phytolith produced in crops is taken from the site during harvest (Meunier et al., 2008). Even some harvested phytoliths are transformed to human and animal waste after food/fodder consumption and returned to soil as amendment or disposed off as a waste into sewage plant systems and surface water bodies (Song et al., 2011). Therefore sustainable management of crop residues may further enhances the phytolith mediated C sequestration potential of terrestrial ecosystems.

Estimated C biosequestration within the phytoliths of rice

Based on the available records for planted area of rice in India from 1950 to 2010 (*Fig. 5a*), we have estimated the trend of possible lowest and highest CO_2 sequestration of rice phytoliths though PhytOC from 1950-2010 (*Fig. 5b*). It shows that between 1.94×10^6 to 4.66×10^6 Mg-e-CO_2 year^{-1} is occluded within the rice phytoliths in India. Considering the largest flux of PhytOC sequestration (0.12 Mg-e-CO_2 ha^{-1} year^{-1}) in this study, our results estimate that the rice phytoliths have potentially occluded around 2.84×10^8 Mg-e-CO_2 during the past 60 years. In 2010, the rice planted area of the world was around 155 million ha (IRRI, 2011). Applying the largest flux of PhytOC in rice phytoliths, the global annual potential sink rate of PhytOC in soils through rice phytoliths would approximately be 1.64×10^7 Mg-e-CO_2. The annual CO_2 occlusion within the rice phytoliths per unit area is comparatively lower than that of other plants like bamboo, wheat and sugarcane (*Table 2*), based on the total area of rice production, the global CO_2 sink rate (1.64×10^7 Mg-e-CO_2 year^{-1}) in rice phytoliths is greater than that is reported for bamboo leaf litter (1.40×10^7 Mg-e-CO_2 year^{-1}) (Parr et al., 2010), and sugarcane (0.65×10^7 Mg-e-CO_2 year^{-1}) (Parr et al., 2009) (*Table 2*). When rice residues returned to soil, phytoliths are released into soil after rice straw decomposition. The phytoliths from rice is very stable and can be stored in soil for more than thousands of years (*Fig. 1*) (Cao et al., 2006, 2007; Zheng et al., 2003). For example, rice phytoliths could be found intact in ancient paddy soils for 6280 years (Cao et al., 2007).

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Hence, the PhytOC can be considered as an important soil organic C fraction and play an important role in global C cycle and long-term C sequestration (Parr and Sullivan, 2005; Parr et al., 2010) and also in mitigation of climate change (Parr and Sullivan, 2005, 2011; Parr et al., 2009, 2010, Zuo and Lu, 2011). Therefore, it is very important to further estimate the potential of PhytOC in rice and other cultivated arable crops under various climatic, soil and management conditions.

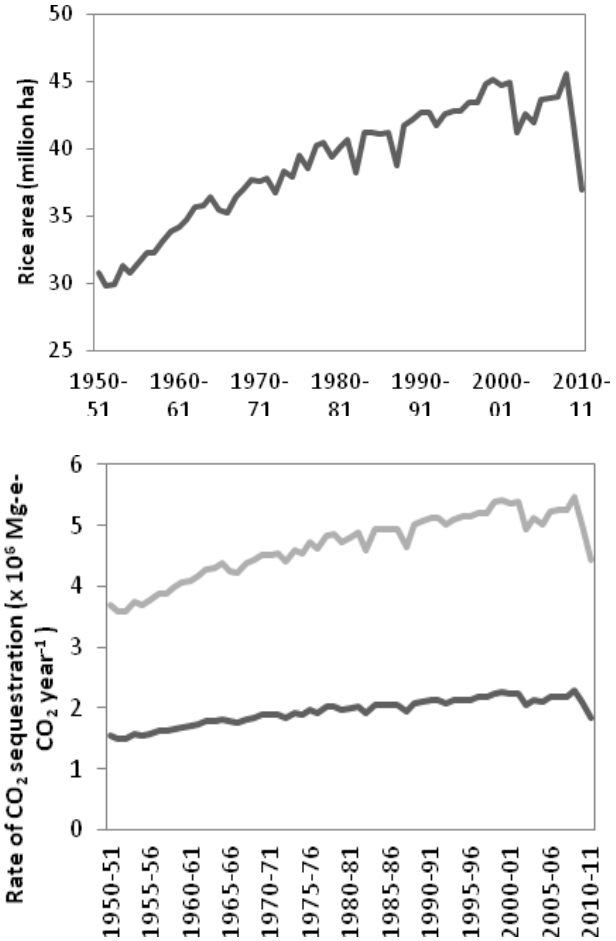

Figure 5. *5a) The fluctuation trend of rice cultivated area during 1950-2010 in India; 5b) Estimated lowest and highest CO_2 sequestration rate through phytoliths of rice plants from 1950 to 2010 in India.*

Table 2.*Comparison of PhytOC content in plant tissues, estimated PhytOC storage fluxes (Mg-e-CO_2 ha^{-1} year^{-1}) and global PhytOC sink rate (Mg-e-CO_2 year^{-1}) in different plants.*

Plant species	PhytoC content of dry material (%)	PhytOC storage fluxes (Mg-e-CO_2 ha^{-1} year^{-1})	global PhytOC sink rate (Mg-e-CO_2 year^{-1})	References
Rice	0.02-0.68	0.05-0.12	1.64×10^7	This study
	0.04-0.28	0.03-0.13	1.75×10^7	Li et al. (2013)
Bamboo	0.24-0.52	0.01-0.71	1.40×10^7	Parr et al. (2010)
Sugarcane	0.31-1.54	0.12-0.36	0.65×10^7	Parr et al. (2009)
Wheat	0.06-0.60	0.01-0.25	4.77×10^7	Parr and Sullivan (2011)
Millet	0.04-0.27	0.01-0.04	0.24×10^7	Zuo and Lu (2011)

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To sum up, the PhytOC, an environmentally stable C fraction, can be retained for several hundreds or thousands of years and has the potential to contribute terrestrial C sequestration. Rice, a well known silica accumulator, is a widely cultivated crop across the world and occludes C within their phytoliths. The C sequestration rates of rice phytoliths are approximately 0.05-0.12 Mg-e-CO_2 ha^{-1} $year^{-1}$depending upon the variation in DMY, Phytolith and PhytOC contents among the rice cultivars. The estimated global annual potential sink rate of PhytOC in soils through rice phytoliths would approximately be 1.64 x 10^7 Mg-e-CO_2. Therefore rice crop may play a significant role in long-term C sequestration and climate change through the PhytOC. The C sink potential of the rice phytoliths can be further enhanced by optimization of cropping and fertilizer management practices including regulation of silicon supply for crops. Also plant breeding and biotechnological tools can be applied to improve the traits which are responsible for the higher occlusion of C in the phytoliths of rice.

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