Role of phytolith occluded carbon of cereales plants for climate change mitigation

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RECEIVED 12.07.2023 ACCEPTED 05.12.2023 AVAILABLE ONLINE 01.03.2024

Abstract: Phytolith-occluded carbon (PhytOC) is highly stable, and constitutes an important source of long-term C storage in agrosystems. This stored carbon is resistant to the processes of oxidation of carbon compounds. In our research phytolith content in barley (Estonia) and oat (Poland) grain and straw was assessed at field trials, with Si as a liquid immune stimulant OPTYSIL and compost fertilisation. We showed that cereals can produce relatively high amounts of phytoliths. PhytOC plays a key role in carbon sequestration, particularly for poor, sandy Polish and Estonian soils. The phytolith content was always higher in straw than in grain regardless of the type of cereals. The phytolith content in oat grains varied from 18.46 to 21.28 mg∙g −1 DM, and in straw 27.89–38.97 mg∙g −1 DM. The phytolith content in barley grain ranged from 17.24 to 19.86 mg∙g −1 DM, and in straw from 22.06 to 49.08 mg∙g−1 DM. Our results suggest that oat ecosystems can absorb from 14.94 to 41.73 kg e-CO 2∙ha−1 and barley absorb from 0.32 to 1.60 kg e-CO 2∙ha−1. The accumulation rate of PhytOC can be increased 3-fold in Polish conditions through foliar application of silicon, and 5-fold in Estonian conditions. In parallel, the compost fertilisation increased the phytolith content in cereals.

Keywords: carbon sequestration, cereals, climate change, compost, phytolith occluded carbon, silicon

INTRODUCTION

Climate change is one of the major environmental issues of the modern world. Global CO₂ emissions for 2022 increased by 1.5% relative to 2021, reaching 36.1·10¹³ kg CO₂ (Liu Z. et al. 2023). New strategies for mitigating climate change are sought to reduce the concentration of CO₂ in atmosphere through carbon sink. Plants play a critical role in the global carbon cycle and are key to climate change mitigation and adaptation. Therefore carbon sequestration in terrestrial ecosystems is a stable carbon sink and can play significant role in mitigate long-term climate warming (Song, McGrouther and Wang, 2016; Song et al. 2017; Liu L. et al. 2023).

Phytoliths are microscopic amorphous silica bodies that form inside tissues of living plants (e.g., cell walls, cell lumina,
and intercellular spaces). They are present in most plants (Sharma, Kumar and Kumar, 2019). Each phytolith shows a different structure and is characteristic of a given plant species. This makes them useful in archaeological studies where radiocarbon dating of phytoliths by means of 14C is commonly applied.

The phytolith content in plant parts varies from <0.5% DM for the majority of dicotyledons to >15% DM in Gramineae (Parr et al., 2010). Differences in phytolith contents between monocotyledonous and dicotyledonous plants primarily result from their ability to take up and accumulate silica (Guo et al., 2015). Even plants of the same species can differ in the phytolith amount produced, depending on the climate and soil conditions, including the silicon (Si) availability in the substrate (Guo et al., 2015; Rehman et al., 2023). During the development of phytoliths in plant tissues, from 0.2 to 5.8% of organic carbon is occluded inside the phytolith forming phytolith-occluded carbon (PhytOC) (Parr and Sullivan, 2005; Parr et al., 2010).

Parr and Sullivan (2011) proposed a detailed methodology for extracting phytoliths from plants. Further research showed that the structure of phytoliths itself is complex, since next to Si, phytoliths additionally contain carbon and nitrogen, as well as other macro- and microelements. Nitrogen content in phytoliths has been previously reported by Jones and Beavers (1963), showing it occurs in low amounts. Hodson et al. (2008) confirmed for wheat that the nitrogen content in phytoliths varied from 0.01 to 0.06% N, depending on the plant parts.

After plant decomposition, phytoliths and phytolith-occluded carbon (PhytOC) may accumulate in soils. Due to high durability of phytoliths, PhytOC can persist in the soil over centuries, or even millennia (Parr et al., 2010), depending on the morphological and chemical structure of the respective phytoliths and the environmental conditions (Nguyen et al., 2019).

Based on the example of the C–Si bond ($E = 369 \text{ kJ} \cdot \text{mol}^{-1}$; binding length $= 1.87$ Å), it can be expected that the bond is durable in the natural environment. This is supported by a number of arguments. The first one is the binding energy. In the case of bond C–Si, the binding energy is higher than for bond C–N. This means that breaking a longer bond requires greater energy. Another argument is the fact that N and Si atoms have different sizes. The larger the atom, the greater the electron number, and as a result the longer the bond. The third argument is the presence of a free electron pair on the nitrogen atom. The free electron pair improves the reactivity of the compound. Higher reactivity of the compound with durable bonds results in a greater ability to form new groups with different binding lengths and energies. The fourth argument is the reference of elements to the scale of electronegativity on the Pauling scale. Chemical bonds are shifted in the particle towards the more electronegative atom. Based on the example of bond C–Si, the bond will be shifted in favour of the carbon atom (electronegativity of C $= 2.5$, electronegativity of Si $= 1.8$) (Handke, 2008).

A similar dependency concerns bond C–N where the bond is shifted towards the nitrogen atom (electronegativity of C $= 2.5$, of N $= 3.0$).

In recent years, increasingly more attention is paid to potential mitigation of climate change by phytoliths. The process involves durable carbon occlusion on phytoliths. The bond of silicon with carbon is highly resistant to the processes of microbiological biodegradation. Therefore, carbon occlusion on phytoliths naturally allows for an increase in the pool of soil organic carbon by cultivation of agricultural crops.

Soil accumulates from 400 to 1000 times more PhytOC than plant biomass. According to Parr and Sullivan (2005), up to approximately 82% of carbon in some soils may be derived from the decomposition of plants from before 2000 years ago. This suggests that PhytOC can play an important role in long-term carbon sequestration and reduction of CO2 emission in the atmosphere (Song et al., 2016; Song et al., 2022).

Many papers have evidenced that PhytOC shows high potential for sequestration of considerable amounts of atmospheric CO2. Based on Parr, Sullivan and Quirck (2009), the PhytOC content in sugar cane varies from 0.12 to 0.36 Mg e-CO2∙ha$^{-1}$∙y$^{-1}$. Rice is also a plant species able to bind substantial carbon amounts on phytoliths. The index of C sequestration by rice cultivars varies from 0.05 to 0.12 Mg e-CO2∙ha$^{-1}$∙y$^{-1}$. Assuming the carbon accumulation rate in rice phytoliths is 0.12 Mg e-CO2∙ha$^{-1}$∙y$^{-1}$, the global amount of PhytOC for rice in the studied area in China globally would reach 16.4 Tg e-CO2 (Prabajati et al., 2016). In global terrestrial biomes, total phytolith carbon sequestration has been estimated to be $156.7 \pm 91.6$ Tg CO2∙y$^{-1}$ (Song et al., 2017).

It is evident that cultivation of crops producing high phytolith amounts can contribute to the mitigation of climate change through the reduction of CO2 emission to the atmosphere. The content of organic carbon resistant to mineralisation processes in the soil can also be increased, thereby improving the volume of the sorption complex and water capacity of soils. With an increase in Si availability in the substrate, higher accumulation of phytoliths in plant biomass is observed. Therefore, fertilisation with silicon can increase CO2 sequestration through an increased PhytOC amount in plants (Rehman, Malik and Rashid, 2023).

The presence of phytoliths in cereal plants is well documented (Prabha et al., 2022; Wenjuan et al., 2022; Rehman, Malik and Rashid, 2023). The variability of silica accumulation in oat in the conditions of variable fertilisation, however, has not been investigated so far.

Management of the ecosystems to maximise PhytOC production may further enhance the global phytolith carbon sink and contribute to the mitigation of rapid atmospheric CO2 increase and climate warming (Song, McGrouther and Wang, 2016; Song et al., 2017).

Accordingly, the objectives of this research were as follows:
- to study the phytolith and PhytOC content in barley and oat in differentiated fertilisation conditions,
- to explore the potential of C biosequestration within phytoliths in cereals.

**MATERIALS AND METHODS**

Field experiments were established both in Poland and Estonia (Fig. 1). The Polish experiment was set up in April 2022 at the Experimental Station in Skiernickie (51°57'535N, 20°9'254E). It was established on Luvisol soil (IUSS Working Group WRB, 2015) with each experimental plot being 15 m$^2$ in three replicates. The Estonian experiment was implemented in 2021 at the Agricultural Research Centre in Matapera, Viljandi, Estonia (58°20'06.0”N, 25°32'34.8”E). Plots were established on Dystric...
Planosol soil (IUSS Working Group WRB, 2015), with four replicates (20 m² each) for all treatments. The initial soil properties are presented in Table 1.

The soil pH was determined in 1M KCl by the potentiometric method on an automatic pH meter (ISO 10390:2021). Total soil N was determined by the Kjeldahl method (ISO 11261:1995). Total soil carbon was determined by means of the Vario Max analyser CHNS (ISO 10694:1995). Available phosphorus and potassium were determined by the Egner–Riehm method (PN-R-04023) and magnesium by Schachtschabel method (PN-R-04020:1994+A21:2004).

The atmospheric conditions were collected from the weather station localised in Experimental Field in Skierniewice. Mean annual temperature in 2022 reached 9.6°C, and was higher than mean temperature from the multiannual period (1921–2022) by as much as 1.6°C (Fig. 2). Mean temperature in the remaining months of the growing season of oat exceeded the mean temperature from the multiannual period. Mean total precipitation in 2022 reached 605 mm, and exceeded the mean value of the multiannual period by as much as 78 mm. In the growing period (July, August), mean monthly precipitations were higher than the mean value on the 1921–2022 period, providing good conditions for the growth and development of plants.

At the Estonian trial site the climate conditions can be described as continental. The precipitation total was 592.3 mm, being lower than in Poland (Fig. 2). Like in Skierniewice, the most humid month was July, with 125 mm rainfall. Mean air temperature reached 6.6°C, and was as much as three degrees lower than in Skierniewice. On average, temperatures in the period of plant vegetation (months May–September) were from 1.4 to 4.0°C lower in comparison to the Polish experiment.

Spring oat ‘Symphony’ and spring barley ‘Fantex’ were sown in Poland and Estonia, accordingly.

The Polish experiment covered the following fertiliser combinations: control, NPK, NPK + Se, NPK + Si, compost170, compost170 + Se, compost170 + Si, compost120 + Nmin, compost120 + Nmin + Se, compost120 + Nmin + Si. Mineral

Table 1. Characteristic of soil physico-chemical properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Poland</th>
<th>Estonia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil texture (%)</td>
<td>sand 76, silt 8, clay 16</td>
<td>sand 60.9, silt 29.5, clay 9.6</td>
</tr>
<tr>
<td>TOC (g·kg⁻¹)</td>
<td>8.40</td>
<td>10.80</td>
</tr>
<tr>
<td>TON (g·kg⁻¹)</td>
<td>0.76</td>
<td>nd</td>
</tr>
<tr>
<td>pH</td>
<td>4.75</td>
<td>5.70</td>
</tr>
<tr>
<td>P available (mg·kg⁻¹)</td>
<td>38.57</td>
<td>49.60</td>
</tr>
<tr>
<td>K available (mg·kg⁻¹)</td>
<td>70.60</td>
<td>96.50</td>
</tr>
<tr>
<td>Mg available (mg·kg⁻¹)</td>
<td>26.10</td>
<td>135.00</td>
</tr>
</tbody>
</table>

Explanations: TOC = total organic carbon, TON = total organic nitrogen, nd = not determined.

Source: own elaboration.

The soil pH was determined in 1M KCl by the potentiometric method on an automatic pH meter (ISO 10390:2021). Total soil N was determined by the Kjeldahl method (ISO 11261:1995). Total soil carbon was determined by means of the Vario Max analyser CHNS (ISO 10694:1995). Available phosphorus and potassium were determined by the Egner–Riehm method (PN-R-04023) and magnesium by Schachtschabel method (PN-R-04020:1994+A21:2004).

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Spring oat ‘Symphony’ and spring barley ‘Fantex’ were sown in Poland and Estonia, accordingly.

The Polish experiment covered the following fertiliser combinations: control, NPK, NPK + Se, NPK + Si, compost170, compost170 + Se, compost170 + Si, compost120 + Nmin, compost120 + Nmin + Se, compost120 + Nmin + Si. Mineral

Fig. 1. Location of experimental field in Poland (A) and Estonia (B); source: own elaboration

Fig. 2. Weather conditions at the experimental station in Skierniewice, Poland and at the experimental station in Matapera, Viljandi, Estonia; source: own elaboration
fertilisation was applied at the following doses: 100 kg N∙ha⁻¹ – CO(NH₂)₂, 35 kg P∙ha⁻¹ – Ca(H₂PO₄)₂, and 100 kg K∙ha⁻¹ – KCl. The compost was applied at a dose corresponding to 170 and 120 kg N∙ha⁻¹.

The Estonian experiment consisted of the following treatments: N₀ (control), N₀ + Si, N₀ + Si + Se, N₁₀₀, N₁₀₀ + Si, N₁₀₀ + Si + Se, compost⁺₁₇₀, compost⁺₁₇₀ + Si, compost⁺₁₇₀ + Si + Se. Mineral fertilisation was applied as follows: N₁₀₀ – 20 kg∙ha⁻¹ (ASN 26) and 500 kg∙ha⁻¹ (14-14-21 NPK YaraMila).

In both experiments, compost and mineral fertilisation was applied before sowing, selenium was applied in the form of Na₂SeO₄ as foliar fertilisation at a dose of 5.00 g Se∙ha⁻¹ (BBCH 1), and silicon was applied as foliar fertilisation at a dose of 139.8 g Si∙ha⁻¹ as OPTYSIL (INTERMAG Sp. z o.o., Poland) at three growth stages: I: phase 3 of leaves (BBCH 18), II: beginning of stem shooting (BBCH 35), III: end of the flowering phase (BBCH 72).

The compost used in both field trials was produced through composting four organic waste substances, namely municipal sewage sludge, municipal green waste, sawdust, and spent mushroom substrate. The chemical characteristics of compost pellets were as follows: pH 6.7, Corg – 158.7, N – 12.8, S – 1.49, P – 11.05, Na – 1.02, Ca – 84.6, Mg – 5.4 and K – 10.7 g∙kg⁻¹ DM.

After harvest the plant samples (grain and straw) were dried at a temperature of 50°C, and then ground in a laboratory mill (Retsch) at 5000 rpm.

Carbon and nitrogen contents in grain and straw were determined using a CHNS Vario Cube analyser Macro. Contents of phytoliths and PhytOC were determined in grain and straw samples according to Paar and Sullivan (2011). Statistical analyses were conducted with the Statgraphics 5.1 software. The data were subject to variance analysis at a significance level of p = 0.05.

The related calculations were done as per Song et al. (2022).
1. The PhytOC content (mg∙g⁻¹ DM) was calculated using following equation:

\[
\text{PhytOC content of organ} = \text{phytolith content} \times \text{C-content in phytoliths} \tag{1}
\]
where: phytolith content is the weight of phytoliths in unit organ (mg∙g⁻¹ DM), C-content in phytoliths is the weight of C in unit phytolith (mg∙g⁻¹ DM).

2. Phytolith production flux is the total phytolith production in the crop above-ground biomass per ha per year (kg∙ha⁻¹∙y⁻¹), was calculated using following equation:

\[
\text{Phytolith production flux} = \text{phytolith content} \times \text{ANPP} \tag{2}
\]
where: phytolith content is the content of phytolith in crop above-ground biomass (mg∙g⁻¹ DM), ANPP is the above-ground net primary productivity of the crop (kg∙ha⁻¹∙y⁻¹).

The BBCH-scale is used to identify the phenological development stages of plants. The first digit of the scale refers to the principal growth stage. The second digit refers to the secondary growth stage which corresponds to an ordinal number or percentage value. Post-harvest or storage treatment is coded as 99. Seed treatment before planting is coded as 00. The abbreviation BBCH derives from the names of the originally participating stakeholders: “Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie”.

RESULTS

The applied mineral and organic fertilisation caused significant changes in the content of phytoliths in cereals in both the experiments conducted in Poland and Estonia.

For oat in the Polish experiments, the phytolith content in grain varied from 18.46 to 21.28 mg∙g⁻¹ DM (Tab. 1). The phytolith content in straw was multiple times higher, varying from 27.89 to 38.97 mg∙g⁻¹ DM. The applied fertilisation significantly influenced the phytolith content in the plant parts. In treatments with foliar Si fertilisation, the phytolith content was always significantly higher as compared to the other treatments. The highest contents of phytoliths in grain was observed on compost 170 + Si treatment and straw occurred for the compost 170 + Si treatment. The phytolith content was correlated with the PhytOC one. The lowest content of PhytOC in grain was determined in the control treatment with no fertilisation (8.13 mg C∙g⁻¹ phytolith), and the highest (13.66 mg C∙g⁻¹ phytolith) for the NPK + Si treatment.

For spring barley in the Estonian experiments, the phytolith contents in grain were considerably lower as compared to those for oat in Polish field trial; it varied from 17.24 to 19.86 mg∙g⁻¹ DM (Tab. 2). The phytolith content in straw was higher and ranged from 22.06 to 49.08 mg∙g⁻¹ DM. The phytolith content significantly depended on the treatments. The highest phytolith content in grain was determined for the N₀ + Si treatment, and in straw for the compost 170 + Si treatment. The phytolith content was correlated with the PhytOC one. The lowest PhytOC content for grain occurred for the N₁₀₀ + Si + Se treatment (0.43 mg C∙g⁻¹ phytolith), and the highest one for the N₁₀₀ + Si + Se treatment (3.54 mg C∙g⁻¹ phytolith). This PhytOC content was used to compute its equivalent in kg e-CO₂∙ha⁻¹. For grain, the amount corresponded to 2.23–3.88 kg e-CO₂∙ha⁻¹, and for straw to 12.69–37.85 kg e-CO₂∙ha⁻¹, respectively. The total equivalent of carbon accumulated in durable bonds (grain + straw) varied, depending on treatments, from 14.94 to 41.73 kg e-CO₂∙ha⁻¹ (Tab. 2).

PhytOC production flux is the annual PhytOC production by above-ground biomass (kg CO₂∙ha⁻¹∙y⁻¹).

\[
\text{PhytOC production flux} = \text{phytolith production flux} \times \frac{44}{12} \tag{3}
\]
where: phytolith production flux (kg∙ha⁻¹∙y⁻¹) can be calculated from Equation (2), PhytOC content = the content of PhytOC in phytoliths (mg∙g⁻¹ DM), 44/12 = the mass transfer coefficient of CO₂/C.

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Table 1. Content of phytoliths and phytolith-occcluded C (PhytOC) in oat grain and straw cultivated at the Skierniewice experiment, Poland

<table>
<thead>
<tr>
<th>Treatment</th>
<th>phytoliths (mg g⁻¹ DM)</th>
<th>C occluded on phytoliths</th>
<th>estimated PhytOC yield (kg e-CO₂ ha⁻¹)</th>
<th>straw</th>
<th>estimated PhytOC yield (kg e-CO₂ ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>phytolith (mg g⁻¹ phytolith)</td>
<td>mg g⁻¹ DM</td>
<td>mg g⁻¹ DM</td>
<td>in yield kg</td>
<td>phytolith (mg g⁻¹ DM)</td>
</tr>
<tr>
<td>Control</td>
<td>19.43a</td>
<td>8.13a</td>
<td>0.16a</td>
<td>0.67a</td>
<td>2.47a</td>
</tr>
<tr>
<td>NPK</td>
<td>19.24a</td>
<td>12.26</td>
<td>0.23d</td>
<td>0.66a</td>
<td>2.42a</td>
</tr>
<tr>
<td>NPK + Se</td>
<td>19.59a</td>
<td>9.52a</td>
<td>0.19b</td>
<td>0.75b</td>
<td>2.76b</td>
</tr>
<tr>
<td>NPK + Si</td>
<td>20.13ab</td>
<td>13.66d</td>
<td>0.28c</td>
<td>1.06d</td>
<td>3.88d</td>
</tr>
<tr>
<td>Compost170</td>
<td>19.28a</td>
<td>9.17a</td>
<td>0.18a</td>
<td>0.64a</td>
<td>2.35a</td>
</tr>
<tr>
<td>Compost170 + Se</td>
<td>18.46a</td>
<td>10.56b</td>
<td>0.20b</td>
<td>0.61a</td>
<td>2.24a</td>
</tr>
<tr>
<td>Compost170 + Si</td>
<td>21.28b</td>
<td>8.69a</td>
<td>0.18a</td>
<td>0.61a</td>
<td>2.23a</td>
</tr>
<tr>
<td>Compost120 + Nmin</td>
<td>19.88a</td>
<td>11.24c</td>
<td>0.22c</td>
<td>0.92c</td>
<td>3.37c</td>
</tr>
<tr>
<td>Compost120 + Nmin + Se</td>
<td>18.63a</td>
<td>10.30b</td>
<td>0.19b</td>
<td>0.65a</td>
<td>2.39a</td>
</tr>
<tr>
<td>Compost120 + Nmin + Si</td>
<td>20.06ab</td>
<td>9.25a</td>
<td>0.18a</td>
<td>0.62a</td>
<td>2.28a</td>
</tr>
</tbody>
</table>

Explanations: values denoted by the same letter, were not significantly differentiated at the level of p = 0.05; DM = dry mass.

Source: own study.
Table 2. Content of phytoliths and phytolith-occluded C (PhytOC) in spring barley cultivated at the Matapera experiment, Estonia

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Content in grain</th>
<th>Content in straw</th>
<th></th>
<th>grain + straw - estimated PhytOC (kg e-CO$_2$ ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>phytoliths (mg g$^{-1}$ DM)</td>
<td>C occluded on phytoliths (mg g$^{-1}$ DM)</td>
<td>PhytOC yield (kg e-CO$_2$ ha$^{-1}$)</td>
<td>phytoliths (mg g$^{-1}$ DM)</td>
</tr>
<tr>
<td>N$_0$</td>
<td>19.35d</td>
<td>0.52</td>
<td>0.010a</td>
<td>0.034a</td>
</tr>
<tr>
<td>N$_0$ + Si</td>
<td>19.86e</td>
<td>0.90d</td>
<td>0.018c</td>
<td>0.058b</td>
</tr>
<tr>
<td>N$_0$ + Si + Se</td>
<td>19.10d</td>
<td>1.25e</td>
<td>0.024d</td>
<td>0.072c</td>
</tr>
<tr>
<td>N$_{100}$</td>
<td>17.24a</td>
<td>0.62c</td>
<td>0.011a</td>
<td>0.052b</td>
</tr>
<tr>
<td>N$_{100}$ + Si</td>
<td>17.39a</td>
<td>0.90d</td>
<td>0.016b</td>
<td>0.076c</td>
</tr>
<tr>
<td>N$_{100}$ + Si + Se</td>
<td>17.55ab</td>
<td>0.43a</td>
<td>0.008a</td>
<td>0.039ab</td>
</tr>
<tr>
<td>Compost$_{170}$</td>
<td>18.69c</td>
<td>0.57b</td>
<td>0.011a</td>
<td>0.034a</td>
</tr>
<tr>
<td>Compost$_{170}$ + Si</td>
<td>19.12d</td>
<td>0.30a</td>
<td>0.010a</td>
<td>0.027a</td>
</tr>
<tr>
<td>Compost$_{170}$ + Si + Se</td>
<td>19.18d</td>
<td>0.46a</td>
<td>0.009a</td>
<td>0.025a</td>
</tr>
</tbody>
</table>

Explanations as in Tab. 1.
Source: own study.
DISCUSSION

Our study evidenced that oat responds well to foliar Si application by increasing the phytolith content and PhytOC. Significant higher phytolith contents (in the Polish experiment) were determined in oat straw as compared to oat grain. In the Estonian experiment with barley changes in the phytolith content due to fertilisation were considerably lower. Regardless of the field trial, the highest phytolith contents were always recorded for crops fertilised with Si immune stimulant OPTYSIL. Similar results were obtained by Majumdar and Prakash (2020) showing straw management in a rice field affected Si circulation in the environment. Long-term rice cultivation at the same site and leaving straw in the soil promoted the phytolith accumulation in the soil. Rice straw contains as much as 86% of Si absorbed by the plants. Parr et al. (2009) pointed out the strong correlation between the content of phytoliths in the leaf and stem material of wheat, bamboo as well as sugar cane, and the PhytOC content. Similar dependencies were observed by Malik et al. (2021) determining a positive correlation between the contents of silica and phytoliths as well as between phytolith and PhytOC contents. Fertilisation with silicon caused an additional increase in the analysed indices in the cultivation of wheat in comparison to the control treatment (a four-fold increase in comparison to treatments fertilised with silicon). Anjum and Nagabovannil (2021) pointed out that rice cultivars with a longer growing period (>140 days) accumulate significantly higher amounts of phytoliths and PhytOC in straw in comparison to cultivars with a shorter growing period (125 days). Such tendencies were also confirmed by Davamani et al. (2022). They determined that the content of phytoliths and PhytOC in all studied oil palms significantly differed and increased with age. The highest amounts of phytoliths were found in 15-year-old palms and the lowest in 4-year-old palms. According to Qi et al. (2021) the phytolith and PhytOC contents in the biomass of desert steppe of typical dry steppe and typical wet steppe in China significantly differed between species. The dominant species of grasses and sedges were characterised by relatively high content of phytoliths and their content was consider-ably higher in the underground parts (86.44, 58.73 and 76.94 g·kg⁻¹ respectively) than above-ground parts (16.68, 17.94 and 15.85 g·kg⁻¹ respectively). Similar dependencies were obtained for PhytOC of 1.11, 0.72 and 1.02 g·kg⁻¹ respectively in the underground biomass of three types of steppe and 0.68, 0.48, and 0.59 g·kg⁻¹ respectively in above-ground parts.

Oat is a cereal with the highest nutritional requirements for silicon, which is why the amount of phytoliths produced is greater compared to barley. Plants having higher Si uptake levels than water are classified as active (e.g., rice, wheat, and barley), whereas those with similar rates are classified as passive (e.g., oat) and those with lower uptake rates are classified as rejective (Kaur and Greger, 2019).

Our results show that the phytolith and PhytOC contents decrease cultivar dependent both in grain and straw of cereales depending on latitude. This is confirmed by Wenjuan et al. (2022) who showed a strong positive effect of climatic factors related to temperature and precipitation on the production of phytoliths and PhytOC. Based on these authors, the characteristics of distribution of phytoliths and PhytOC in wheat straw and soil showed a decreasing tendency from the South to the North. They also pointed out that physicochemical soil properties such as the Si availability, total carbon (Ctot) and total nitrogen (Ntot) also affect the accumulation of phytoliths in plant parts. Other authors emphasised the phytolith accumulation in plants depending on straw management (Majumdar and Prakash, 2020), application of silicon fertilisation (Guo et al., 2015). All these measures play an important role in C bio-sequestration and mitigation of climate change.

Oat cultivation would contribute to sustainable carbon sequestration in the soil. In Polish conditions (oat cultivation covers an area of approximately 500 thous. ha) the compost treatment would induce a PhytOC accumulation estimated to 18.76 kg e-CO₂ ha⁻¹·y⁻¹. Foliar Si application (NPK + Si treatment) would cause a significant (≥2.5-fold) increase in carbon accumulation to 41.73 kg e-CO₂·ha⁻¹·y⁻¹. Potential amounts of accumulated CO₂ depending on the treatments would vary from 9,380 Mg e-CO₂·ha⁻¹·year⁻¹ (compost treatment) to 20,865 Mg e-CO₂·ha⁻¹·y⁻¹ for the NPK + Si treatment. For the crops in North Europe (Estonia), the possibilities of carbon accumulation would be lower due to the much smaller cultivation area, in 2021 reaching 116.39 thous. ha (Trading Economics, no date), and lower phytolith content in grains and straw. Potential amounts of accumulated CO₂ depending on the treatments would vary from 39.5 Mg e-CO₂·ha⁻¹·y⁻¹ (compost treatment) to 130.4 Mg e-CO₂·ha⁻¹·y⁻¹ for the NPK + Si treatment.

The ability of crops to accumulate PhytOC in agricultural ecosystems is confirmed by Wenjuan et al. (2022) who estimated CO₂ accumulation in wheat crops at a level of 7.59·10⁶ Mg, corresponding to 27.83 Tg CO₂. In wheat crops fertilised with silicon in China. Malik et al. (2021) determined a potential of 0.304 Mg e-CO₂·ha⁻¹·y⁻¹. Paar et al. (2009) emphasised that a potential crop permitting long-lasting and durable carbon sequestration is sugar cane that is able to bind approximately 0.66 Mg e-CO₂·ha⁻¹·y⁻¹. Lv et al. (2020) pointed out the vast potential of Moso bamboo (Phyllostachys heterocycla var. pubescens) for carbon sequestration and its richness in PhytOC. The Si application causes a significant increase in PhytOC. Wang and Sheng (2022) evidenced that buck-wheat is a very good plant for carbon sequestration. The average phytolith carbon sequestration rate of Fagopyrum esculentum and Fagopyrum tataricum planting was 2.62·10⁻³ and 1.17·10⁻³ Mg CO₂·ha⁻¹·y⁻¹ respectively.

Our study showed that foliar Si fertilisation should be applied more frequently in the future due to its influence to increase the rate of sequestration of atmospheric CO₂ as well as its contribution to an increase in resistance to stress and increase in yields of crops.

CONCLUSIONS

An addition of Si a liquid immune stimulant (OPTYSIL) has an effect on content of phytoliths and PhytOC in grain and straw of both cereal species. Our data suggest that the future amount of PhytOC in oat and barley fields can be additionally increased through adopting agricultural practices such as optimisation of Si fertilisation. The total equivalent of carbon accumulated in durable bonds (grain + straw) in barley (experiments in Estonia) varied, depending on fertilisation from 0.32 to 1.60 kg e-CO₂·ha⁻¹, and was much higher in oat (experiment in Poland), varying from
14.94 to 41.73 kg e-CO$_2$·ha$^{-1}$. This indicated that oat is a plant species that allocates more silicon in grains and straw than spring barley. Further research on other crop species is required to determine the equivalent of accumulated phytoliths and carbon accumulated in durable bonds and to determine its potential contribution to the mitigation of the greenhouse effect. The method of plowing in and leaving cereal straw in the field can contribute to increasing the amount of stable carbon compounds in the soil (PhytOC).

**FUNDING**

The authors acknowledge the financial support through the partners of the Joint Call of the Cofund ERA-Nets SusCrop (Grant N° 771134), FACCE ERA-GAS (Grant N° 696356), ICT-AGRI-FOOD (Grant N° 862665) and SusAn (Grant N° 696231).

**CONFLICT OF INTERESTS**

All authors declare that they have no conflict of interests.

**REFERENCES**


Davamani V. et al. (2022) “Phytolith-occluded carbon sequestration potential of oil palm plantation in Tamil Nadu,” ACS Omega, 7, pp. 2809–2820. Available at: https://doi.org/10.1021/acsomega.1c05592.


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