

# 1 **Monitoring Environmental Quality in Urban Gardens** 2 **Using Moss Analyses of Heavy Metals and Pigments**

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4 *Urban gardening has become increasingly popular, raising concerns about*  
5 *the safety of food production in urban environments. As direct pollution*  
6 *measurements are often costly and time-consuming, this study evaluated the*  
7 *potential of the moss *Syntrichia ruralis* as a bioindicator of environmental*  
8 *pollution in Tallinn, Estonia. Concentrations of Zn, Cu, Ni, Cd, Pb, Hg, and*  
9 *photosynthetic pigments (chlorophyll a, chlorophyll b, and carotenoids) were*  
10 *measured in moss samples collected from 30 sites, including 22 community or*  
11 *educational gardens, in autumn 2019. Additional pigment measurements from*  
12 *eight sites in spring 2018 and soil heavy-metal data from eleven gardens were*  
13 *included. Long-term PM<sub>10</sub> and NO<sub>x</sub> concentrations were estimated using*  
14 *emission inventories and dispersion modelling. Most heavy metals in moss*  
15 *showed weak relationships with PM<sub>10</sub> concentrations, except for Cu, which*  
16 *was significantly positively correlated with air pollution indicators.*  
17 *Concentrations of Cu, Cd, Ni, and Pb were strongly intercorrelated, and*  
18 *higher soil concentrations of Hg, Cd, and Cu were associated with elevated*  
19 *Hg levels in moss. Pigment content showed weak and inconsistent*  
20 *relationships with heavy metals. Instead, light availability, substrate type, and*  
21 *season had the strongest influence on pigment concentrations. The results*  
22 *suggest that Cu and Hg are the most suitable moss-based indicators of*  
23 *environmental pollution, whereas moss pigment content is not a reliable*  
24 *indicator of pollution in urban gardens.*

25  
26 **Keywords:** *Bioindication, *Syntrichia ruralis*; Bryophyte; Fine particulate*  
27 *matter; Nitrogen oxides*

## 28 29 30 **Introduction**

31  
32 Urban gardening has gained increasing popularity in recent years, raising  
33 questions about the safety of growing vegetables in different urban  
34 environments. Previous studies (e.g. Orru et al. 2011) have shown that  
35 environmental pollution, particularly fine particulate matter containing heavy  
36 metals, poses significant health risks to residents of Tallinn. The few monitoring  
37 stations in the city do not provide sufficient information for citizens to make  
38 informed long-term decisions, such as planning their daily journeys, choosing  
39 places of residence, or deciding whether to grow vegetables themselves, in order  
40 to minimise health risks in urban environments. In addition to the current state  
41 of pollution, it is necessary to know the history of pollution for the decision to  
42 grow vegetables. Considering the limits of extremely time-consuming and  
43 expensive field receptor measurements, could be benefit from the study of  
44 mosses to assess the environmental status of much more localities than it is now.  
45 Therefore, this study explored the use of mosses as a cost-effective bioindicator  
46 for assessing environmental pollution in the vicinity of community and  
47 educational gardens across Tallinn, with the aim of providing preliminary  
48 information on potential contamination risks relevant to urban food production.

## 1 Literature Review

2  
3 As lot of vegetables in markets contain some residuals of pesticides where  
4 the exceedances of the limit values are not uncommon (Padur 2015) then  
5 growing your own crop get more popular and also in cities (Egli et al. 2016).  
6 Urban gardens are also an emerging strategy to increase food access and offer a  
7 solution to fight food insecurity locally (Tims et al. 2021). Community gardens  
8 contribute to sustainable urban development and play a significant role in  
9 improving both individual and community well-being (Huq and Deacon 2025).  
10 At the same time, the question arises whether growing food in the city is safe.  
11 Although advances in cleaner technologies have reduced emissions from many  
12 sources, increasing traffic volumes continue to contribute substantially to  
13 particulate matter (PM) pollution. Heavy metals are the most dangerous  
14 component in PM, which contributed to various estimates of public health  
15 impact on mortality and morbidity (Valavanidis et al. 2008). The presence of  
16 heavy metals in particles from traffic could be one of the explanations to the  
17 results of Pindus et al. (2016) study, where significant health effects (especially  
18 cardiac diseases) associated with traffic particles but did not with wood smoke  
19 particles. Exposure to PM has also been associated with impaired cognitive  
20 performance in humans (Aretz et al. 2021, Künn et al. 2023). Furthermore, heavy  
21 metals bound to atmospheric PM may accumulate in plants and animals, creating  
22 a potential pathway for human exposure through the consumption of  
23 contaminated food products (Li et al. 2013).

24 Air quality in Tallinn is monitored at three permanent stations where several  
25 pollutants, including PM and nitrogen oxides (NO<sub>x</sub>), are regularly measured,  
26 while some heavy metals are randomly measured at one station (Saare et al.  
27 2019, Eesti Keskkonnauuringute Keskus n.d.).

28 Bryophytes lack true roots and a protective cuticle and obtain most of their  
29 nutrients directly from atmospheric deposition. This makes them particularly  
30 sensitive to air pollution and valuable bioindicators for monitoring urban  
31 environmental quality (Vanderpoorten and Goffinet 2009, Govindaparyi et al.  
32 2010, Oishi and Hiura 2017, Plášek et al. 2026). Metals from the atmosphere can  
33 reach the surface of terrestrial bryophytes in solution (precipitation) or in the  
34 form of dry deposition that can later be solubilised or washed away. Even though  
35 terrestrial bryophytes take most of the substances from the atmosphere, soil  
36 contributes significantly to the heavy metals contents (Stanković 2018). Most  
37 bryophyte species are so sensitive to environmental pollution that they do not  
38 grow in contaminated areas at all – e.g 87% of the British and Irish moss species  
39 have no tolerance of heavy metals (Hill et al. 2007). At the same time, those  
40 species that tolerate pollution, collect heavy metals in themselves, which means  
41 that they also express the air quality history. Although mosses can accumulate a  
42 very large amount of heavy metals, it still has an impact on their physiology  
43 (Kaur et al. 2010). Świsłowski et al. (2022) study showed that heavy metals (Cu,  
44 Zn, Cd, Pb, Mn, Fe, and Hg) pollution affected the functioning of photosystem  
45 II in mosses.

1 A often-used indicator of the physiological status and biological activity  
2 (photosynthetic capacity) of plants is the chlorophyll content. However, there  
3 have not been many studies investigating the relationship between the presence  
4 of different heavy metals in bryophytes and the chlorophyll concentration (e.g.  
5 Tremper et al. 2004, Shakya et al. 2008, Tuba et al. 2010). The results of most  
6 of these studies have revealed the reduction in chlorophyll content due to heavy  
7 metals stress, although the degree of the effect depends on the species studied  
8 and the metals tested (Stanković 2018). For example, in the laboratory  
9 experiment of Tremper et al. (2004) used real field amounts of metals on  
10 *Rhytidiadelphus squarrosus* the content of chlorophyll was significantly reduced  
11 by Cu, but not by Pb and Zn, while some other studies with other species reduced  
12 the chlorophyll content by Pb as well as by Zn, and also by Cd (Shakya et al.  
13 2008, Tuba et al. 2010, Stanković 2018). Leblanc and Rao (2008) study showed  
14 the effects of heavy metals on chlorophyll a of moss species *Barbula*  
15 *lambarenensis* so: Va> Cd >Fe >Cu > Pb. In Shakya et al. (2008) experiment all  
16 studied bryophytes species had under heavy metals stress greater amount of  
17 chlorophyll b than that of the chlorophyll-a, indicating that in these bryophytes  
18 heavy metals could induce the conversion of chlorophyll-a to chlorophyll-b  
19 (Stanković 2018). Nevertheless, there are a number of studies on the effects of  
20 metals on bryophytes, but metal concentrations used in the experiments were  
21 often higher than concentrations found in the field. Kaur et al. (2010) study  
22 compared the effect of 7 heavy metals (Cu, Zn, Fe, Hg, Cd, Co and Ni) on the  
23 growth of 7 moss species found that Zn, Cu, Fe are better tolerated than Hg, Co,  
24 Cd and Ni.

25 High nitrogen concentrations can inhibit bryophyte growth. At low to  
26 moderate nitrogen levels, bryophyte growth has been shown to exhibit a  
27 unimodal response to nitrogen availability, although the exact relationship varies  
28 among species (Salemaa et al. 2008).

29 The study focused on *Syntrichia ruralis* (Figure 1), a bryophyte species  
30 commonly found in urban environments and considered one of the most suitable  
31 bioindicators for assessing urban pollution in Estonia (Rajandu et al. 2024).  
32 Owing to its tolerance of environmental stressors, including heavy metal  
33 contamination, *Syntrichia ruralis* has been identified as a particularly suitable  
34 species for indication of heavy metal pollution (Naszradi et al. 2007). It is  
35 relatively easy to identify in the field and occurs on a wide range of substrates,  
36 including soil, concrete surfaces, and asphalt. The species tolerates diverse soil  
37 and moisture conditions and typically thrives in well-lit habitats. This species is  
38 one of the eight selected species by Mallen-Cooper et al. (2023) as being both  
39 abundant and functionally important across temperate and Arctic ecosystems.

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1 **Figure 1.** Moss species *Syntrichia ruralis*.



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## Materials and Methods

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### *Sampling sites and sample collection*

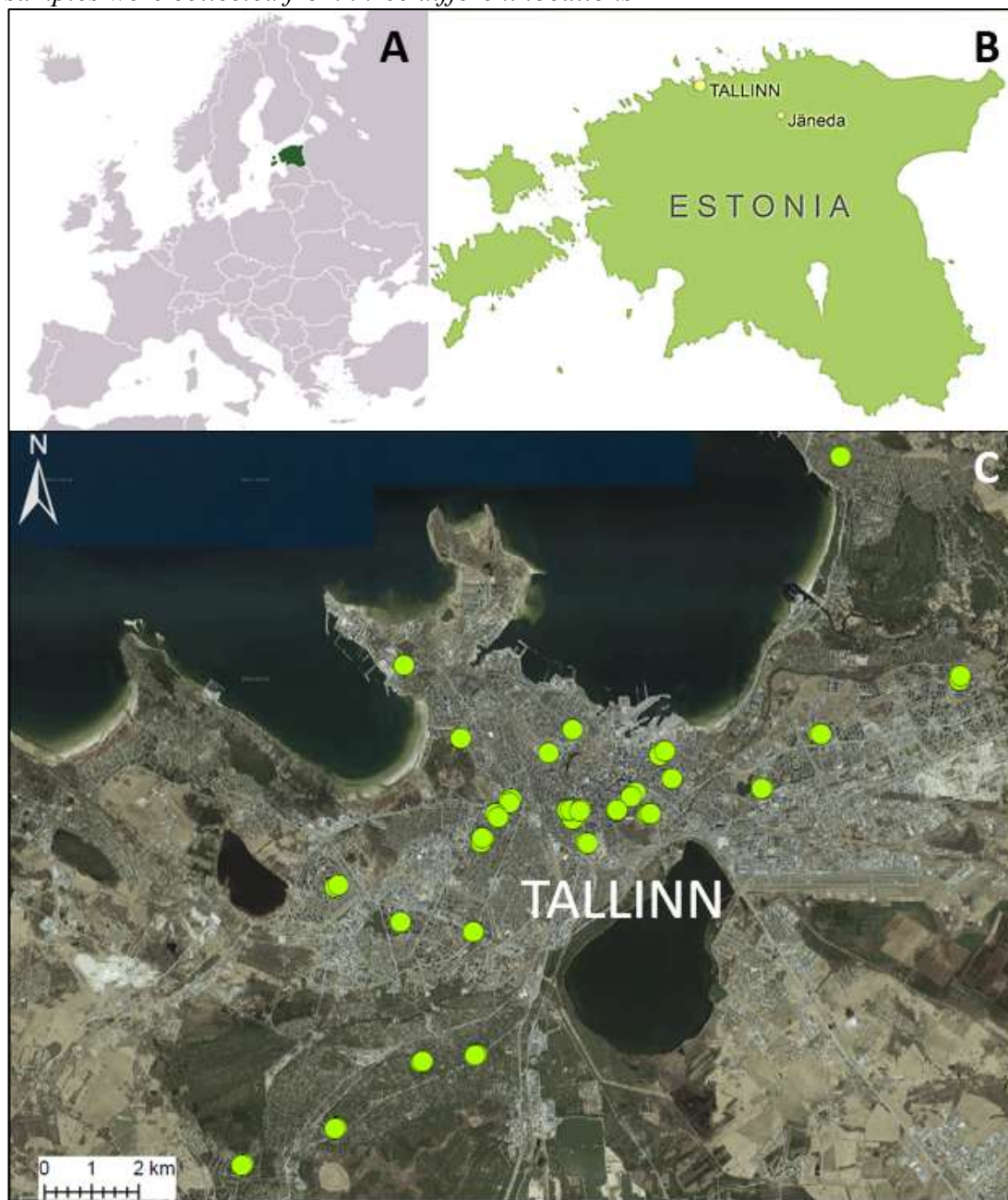
8

9 Thirty study sites were investigated, including 13 community gardens or  
10 potential community garden sites, 9 educational gardens at schools and  
11 kindergartens, 6 reference sites within Tallinn, and 2 control sites located outside  
12 Tallinn in Jäneda (Figure 2). At each sampling site, measurements of light  
13 availability were taken, canopy cover was estimated, the moss substrate was  
14 identified, and the growth surface was classified as either horizontal or vertical.  
15 Concentrations of Zn, Cu, Ni, Cd, Pb, and Hg, as well as chlorophyll a,  
16 chlorophyll b, and carotenoids, were measured in the moss *Syntrichia ruralis* in  
17 autumn 2019. Mercury concentrations could not be determined at two sites  
18 because insufficient moss material was available. Pigment analyses were  
19 generally conducted using three replicates per study site. For six reference sites,  
20 moss pigment data from a previous survey conducted in spring 2018 were also  
21 available, allowing seasonal and interannual comparisons. Soil heavy metal data  
22 for Zn, Cu, Cd, and Pb were available from eleven of the studied gardens, with  
23 complete soil data for all investigated metals available from eight gardens. Soil  
24 heavy-metal data were collected from eight gardens in 2019 and three in 2023.

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1 **Figure 2.** (A) Location of Estonia in Europe. (B) Study area Tallinn and control  
2 site in a rural area Jäneda. (C) Sampling sites (dots) in Tallinn. At each site,  
3 samples were collected from three different locations



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#### *Heavy metal measurements*

Living parts of moss were washed with ultrapure water, air-dried and lyophilised. All samples were stored at room temperature. Concentrations of Zn, Cu, Ni, Cd, and Pb were measured using flame and graphite furnace atomic absorption spectroscopy (AAS), and Hg was measured using cold-vapour AAS.

## 1 Chemicals and reagents

2 All reagents used were of high purity, and all solutions were prepared in  
3 ultrapure water (Millipore, USA). The Zn, Cu, Ni, Cd, Pb and Hg 1000mg/L  
4 single metal AAS standard solutions were obtained from Honeywell Fluka™.  
5 The reduction solution for cold-vapour AAS analyses was prepared at 25% (m/v)  
6 SnCl<sub>2</sub>·2H<sub>2</sub>O (Merck, Germany) in 20% HCl (v/v) (Merck, Germany). Nitric  
7 acid Suprapur, 68% (Merck) and 35% H<sub>2</sub>O 2(Fluka) were employed for the  
8 digestion of the samples. The applicability of the method to real samples was  
9 demonstrated by the analysis of the CRM testing material LGC6187 (LGC  
10 standards).

## 11 AAS analysis

12 AAS metal analysis was carried out according to the overall procedure  
13 described in ISO standard EN 14084:2003. Samples were microwave-digested using  
14 Microwave GO (SN: 81801381) equipment according to ISO EN 13805:2002 and  
15 EN13804:2002. Concentrations of Zn, Cu, Ni, Cd, and Pb were determined using  
16 flame and graphite furnace atomic absorption spectrometry (AAS; SpectraAA 220F  
17 and SpectraAA 220Z, Varian). Argon 4.0 was used in the AASG, and an air-acetylene  
18 flame was used for the AASF method. For each sample, two replicate measurements  
19 were made, and the results given in this work are the average concentrations.

20 Hg determination was performed using a CV-AAS system SpectraAA 220F  
21 (Varian). Samples of 0.2–0.3 g were digested in a water bath with 5 mL of nitric  
22 acid (24 h) and 1 mL of hydrogen peroxide (24 h) in a disposable test tube. After  
23 digestion, the samples were diluted with water to 25 mL. The test solution was  
24 transferred to the reaction vessel of the Hg analysis unit, and the mercury content  
25 was measured using continuous-flow cold-vapour-atomic absorption spectrometry.  
26

## 27 *Chlorophyll and Carotenoid Analyses*

28 For pigment analyses, moss samples were collected from three sampling  
29 points within each study site. Samples were kept in dark and cool conditions  
30 during transport, cleaned with distilled water within 24 h of collection, and  
31 stored at –15°C until analysis. The apical 0.5 cm segments of the moss shoots  
32 were used for all measurements.

33 Chlorophyll-a (Chl-a), chlorophyll-b (Chl-b), total chlorophyll (Chl-a+b),  
34 and carotenoid concentrations were determined using an 80% acetone extraction  
35 method modified from Porra et al. (1989). Prior to extraction, samples were  
36 divided into two subsamples. One subsample was oven-dried at 60°C for at least  
37 24 h to determine dry mass, while the second subsample was used for pigment  
38 extraction.

39 Frozen moss tissue was homogenized in a phosphate buffer solution (2.5  
40 mM sodium phosphate, pH 7.8) and extracted with an 80% acetone–20% buffer  
41 solution under dim light conditions. The extracts were centrifuged at 3000 rpm  
42 for 10 min and analysed spectrophotometrically (Shimadzu UV-1800, Japan).  
43 Absorbance was measured at 470, 645, 663 and 750 nm using an acetone-buffer  
44 solution as a blank.  
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1 Concentrations of chlorophyll-a, chlorophyll-b, total chlorophyll, and  
2 carotenoids were calculated from absorbance values and expressed on a dry-  
3 mass basis ( $\text{mg g}^{-1}$  DW). Water content was determined from the difference  
4 between fresh and dry sample mass.

#### 5 6 *Modelled $PM_{10}$ and $NO_x$*

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8 The long-term average concentrations of the air pollutants fine particulate  
9 matter ( $PM_{10}$ ) and nitrogen oxides ( $NO_x$ ) in Tallinn were estimated using the  
10 AEROPOL 5.3 dispersion model (Kaasik et al. 2017), based on meteorological  
11 observations collected at the Tallinn-Harku Meteorological Station between  
12 2015 and 2018. Traffic-related emissions were derived from urban traffic flow  
13 modelling conducted by AS Stratum for the reference year 2017. Emissions from  
14 domestic heating were also included; however, model results indicated that their  
15 contribution to local air pollution levels was relatively minor. This was likely  
16 due to the predominance of district heating in the study area and the location of  
17 most sampling sites near major roads rather than residential areas relying on  
18 wood or coal heating.

19 Within Tallinn, pollutant concentrations were modelled on a spatial grid  
20 with a resolution of 50 m, while a finer 10 m resolution was applied in the city  
21 centre. Model outputs were validated against measurements from three urban air  
22 quality monitoring stations, and regression-based corrections were used to  
23 reduce systematic deviations.

24 For sites located outside Tallinn, annual average concentrations of  $NO_x$  and  
25  $PM_{10}$  were estimated using rural background levels measured at the nearest rural  
26 air quality monitoring station in Lahemaa, combined with the contribution of  
27 emissions dispersed from nearby major roads. Rural background concentrations  
28 in Estonia show relatively little spatial variation, ranging from 1.8 to 2.1  $\mu\text{g}/\text{m}^3$   
29 for  $NO_x$  and from 3.9 to 4.5  $\mu\text{g}/\text{m}^3$  for  $PM_{10}$ .

#### 30 31 **Data processing**

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33 Differences between groups were evaluated using one-way ANOVA.  
34 Homogeneity of variances was tested with Bartlett's test, and Welch's ANOVA  
35 was applied when heteroscedasticity was detected. Multiple comparisons were  
36 performed using the Games–Howell post hoc test. Relationships between  
37 variables were assessed using Spearman's rank correlation coefficient  
38 (McDonald 2014). To investigate associations between moss pigments, heavy  
39 metals, and environmental variables, Canonical Correspondence Analysis  
40 (CCA) and General Linear Models (GLM) were performed using CANOCO 5  
41 software (ter Braak and Šmilauer 2012).

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## 1 Results

2  
3 The calculated annual average NO<sub>x</sub> concentrations exceeded 20 µg/m<sup>3</sup> at  
4 reference sites located adjacent to major roads, including areas near the intersection  
5 of Sõpruse and Mustamäe Road and along Liivalaia Road. Elevated NO<sub>x</sub> levels were  
6 also found near educational and community gardens located relatively close to heavily  
7 trafficked roads, including the study sites near Tallinn Co-education Gymnasium,  
8 Tallinn University, and the Rõõmutareke Kindergarten. These sites also exhibited  
9 relatively high modelled PM<sub>10</sub> concentrations. Heavy metal concentrations  
10 exceeded the average across the 30 study sites for all six metals at the Liivalaia  
11 sampling site, where the lead concentration was more than five times higher than  
12 the average, reaching 79.7 µg/g. Other heavily polluted sites with respect to  
13 heavy metals were located near the Põhjala, Telliskivi, and Ameerika  
14 community gardens. At the first two of these locations, concentrations of more  
15 than half of the analyzed metals were 2–3 times higher than the average values  
16 across all study sites. The Põhjala site had the lowest modelled PM<sub>10</sub> and NO<sub>x</sub>  
17 concentrations among the Tallinn sites. Soil Zn concentrations also exceeded the  
18 target value (200 µg/g) in the Ameerika community garden and near the  
19 Rõõmutareke educational garden, reaching 220 and 232 µg/g, respectively.

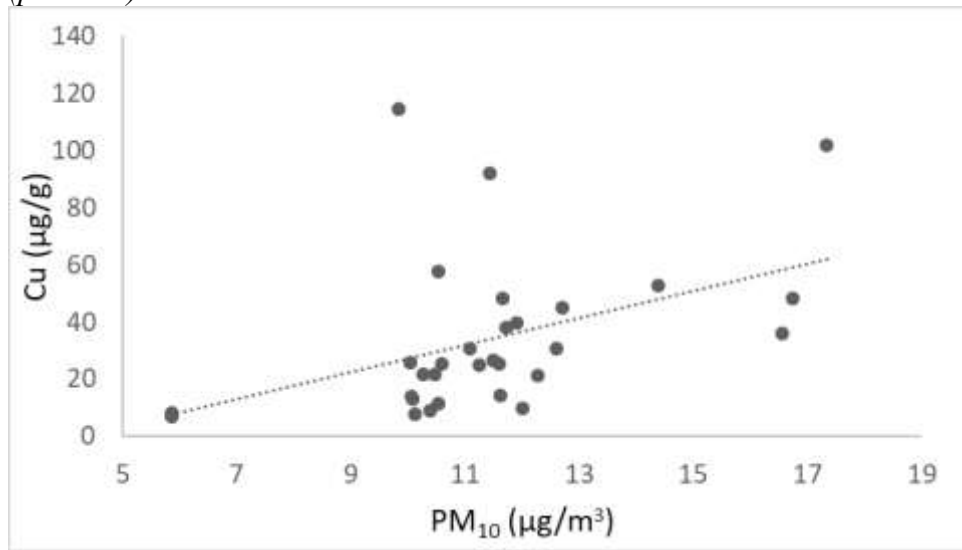
20 Correlation analyses between modelled PM<sub>10</sub> concentrations and heavy  
21 metals contents revealed no statistically significant relationship for most metals,  
22 with the exception of copper, which showed a significant positive correlation  
23 (Table 1, Figure 3). The lowest heavy metal concentrations were found in  
24 Merivälja and near the school gardens of Laagna, Priisle, and Pääsküla, where  
25 concentrations of all analyzed metals were substantially below the overall study-  
26 site averages. Concentrations of Cu, Cd, Ni, and Pb in *Syntrichia ruralis* were  
27 strongly correlated with each another. Among the 11 sites for which soil data  
28 were available, higher concentrations of Hg, Cd and Cu in soil were associated  
29 with greater Hg concentrations in moss (Figure 4).

30  
31 **Table 1.** Correlation matrix with the Spearman's correlation coefficients.  
32 Statistically significant correlations are marked with bold ( $p < 0.05$ ). NO<sub>x</sub> - the  
33 modelled indicator of nitrogen oxides and PM<sub>10</sub> - the modelled indicator of fine  
34 particles below 10µg (particulate matter).

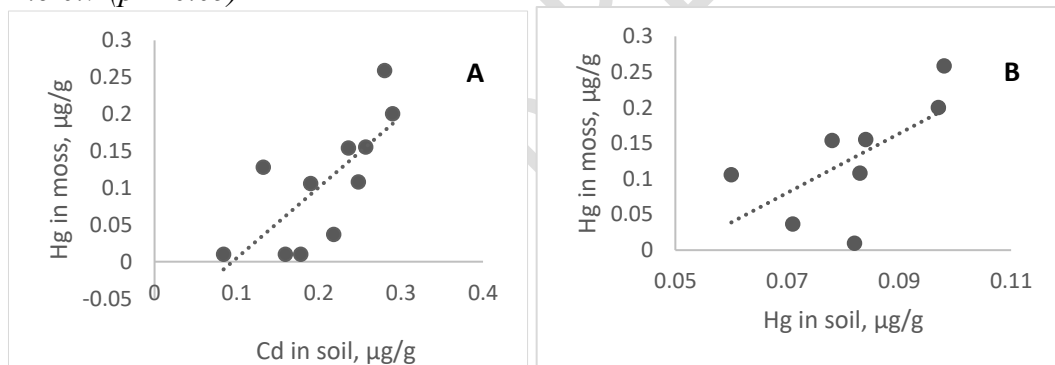
	Zn	Cu	Ni	Cd	Pb	Hg	NO <sub>x</sub>	PM <sub>10</sub>
Zn (µg/g)	1							
Cu (µg/g)	<b>0,42</b>	1						
Ni (µg/g)	<b>0,46</b>	<b>0,73</b>	1					
Cd (µg/g)	0,33	<b>0,49</b>	<b>0,56</b>	1				
Pb (µg/g)	0,27	<b>0,52</b>	<b>0,65</b>	<b>0,40</b>	1			
Hg (µg/g)	-0,13	0,19	0,04	0,28	0,23	1		
NO <sub>x</sub> (µg/m <sup>3</sup> )	0,09	<b>0,50</b>	0,23	0,19	0,18	-0,01	1	
PM <sub>10</sub> (µg/m <sup>3</sup> )	0,16	<b>0,52</b>	0,25	0,17	0,21	-0,11	<b>0,95</b>	1

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1 **Figure 3.** Correlation between fine particles  $PM_{10}$  and Cu. Spearman's rho 0.5  
2 ( $p < 0.05$ ).



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4  
5 **Figure 4.** (A) Correlation between Cd in soil and Hg in moss. Spearman's rho  
6 0.7 ( $p < 0.05$ ). (B) Correlation between Hg in soil and Hg in moss. Spearman's  
7 rho 0.7 ( $p < 0.05$ )

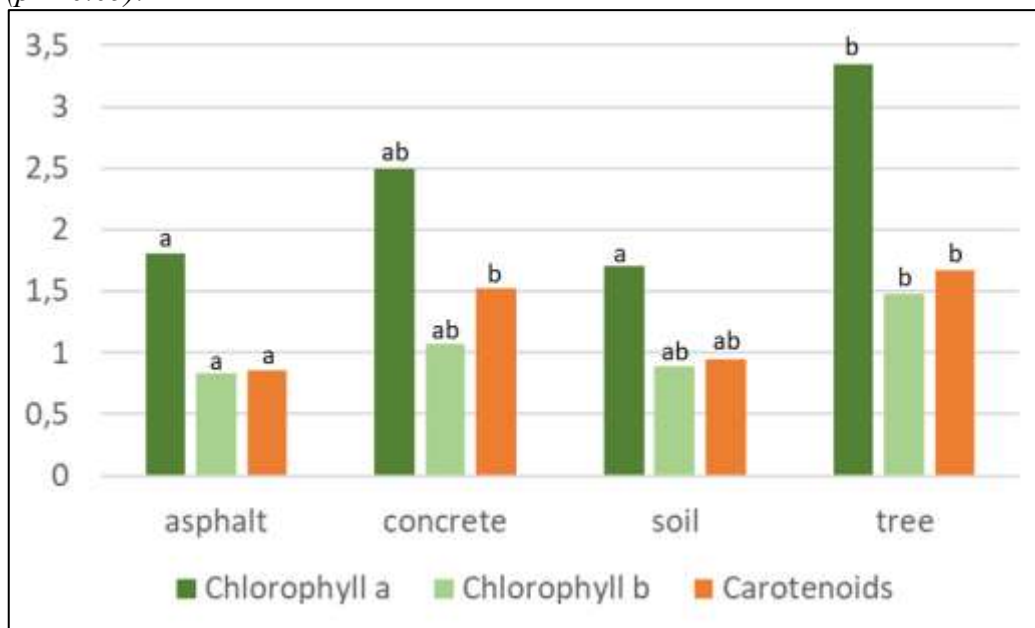


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10 Various statistical analyses (GLM, ordination analysis, and correlation  
11 analysis) did not reveal strong relationships between pigment concentrations and  
12 heavy metal levels. However, light availability was significantly correlated with  
13 all pigment concentrations. Ordination analysis likewise showed that light  
14 explained the largest proportion of variation in moss pigment content.

15 Pigment concentrations differed significantly among growth substrates  
16 (ANOVA,  $p < 0.05$ ), with the highest values recorded on trees and the lowest on  
17 soil and asphalt (Figure 5). Comparisons of pigment concentrations measured at  
18 reference sites across different seasons and years revealed significant differences  
19 (Welch Anova,  $p < 0.05$ ): values collected in spring 2018 were, on average,  
20 approximately twice as high as those collected in autumn 2019.

21

1 **Figure 5.** The pigment content of moss *Syntrichia ruralis* on different growing  
 2 surfaces. Different letters for the same pigment indicate a statistical difference  
 3 ( $p < 0.05$ ).



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## 7 Discussion

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9 The highest heavy metal concentrations from moss were measured near  
 10 major roads, which was expected. Estonian legislation defines target and limit  
 11 values for heavy metal concentrations in soil (Riigi Teataja 2019). Soil data from  
 12 the eleven studied sites did not indicate any exceedances of target or limit values,  
 13 except for Zn concentrations in the Ameerika community garden and near the  
 14 Rõõmutareke educational garden. These sites are also located relatively close to  
 15 major roads. In such areas, it is advisable to use imported clean soil for  
 16 cultivation and to thoroughly wash edible vegetables before consumption. For  
 17 example, an analysis of lead concentrations in fruits from a community garden  
 18 in Tallinn showed that washing reduced Pb levels by more than half on average;  
 19 in several cases, Pb concentrations in unwashed fruits exceeded the threshold  
 20 value above which plant material is considered contaminated (Vacht et al. 2022,  
 21 Vacht et al. 2025). The soil quality in the remaining nine gardens for which soil  
 22 data were available can be considered good. Hg concentrations in moss were the  
 23 best indicator of heavy metal contamination in soil, showing significant  
 24 associations with soil concentrations of Cd, Cu, and Hg. Contamination sources  
 25 of different metals often overlap. Meyer et al. (2015) reported that heavy metal  
 26 concentrations in mosses, including Hg, reflect atmospheric deposition relatively  
 27 well and that, in some cases, metal accumulation can be predicted by population  
 28 density. In one of our previous studies (Rajandu et al. 2025), which included five  
 29 moss species (including *Syntrichia ruralis*), Hg concentrations in moss were  
 30 most strongly correlated with Hg concentrations in soil, whereas relationships

1 with other soil metals were not significant. At the same time, soil Hg  
2 concentrations were strongly correlated with concentrations of other metals,  
3 such as Fe and Cu, in moss. These findings suggest that Hg accumulation may  
4 serve as a useful proxy for broader patterns of heavy metal contamination.

5 Heavy metal concentrations measured in soil and *Syntrichia ruralis* were of  
6 the same order of magnitude. Although no comparable studies directly  
7 comparing heavy metal concentrations in *Syntrichia ruralis* and soil are known,  
8 previous research on *Pleurozium schreberi* and *Hylocomium splendens* has  
9 shown that these moss species accumulate heavy metals at levels reflecting  
10 environmental contamination (Kaasik and Liiv 2007). In our previous study  
11 (Rajandu et al. 2024), which compared heavy metal concentrations among five  
12 moss species, the Fe and Cd contents of *Syntrichia ruralis* were found to be  
13 significantly higher than those of *Sciuro-hypnum curtum*.

14 The measurement of heavy metals in mosses provides an important  
15 complement to soil-based assessments. Response times, particularly for Pb  
16 concentrations in soil, appear to be delayed compared with those observed in  
17 moss. Consequently, the use of mosses as biomonitors may enable more rapid  
18 detection of changes in environmental contamination and support faster  
19 management decisions (Meyer et al. 2015). Temporal variations in heavy metal  
20 deposition may partly reflect changes in the abundance of airborne fine  
21 particulate matter (Bozkurt et al. 2017), which often contains substantial  
22 concentrations of heavy metals (Valavanidis et al. 2008).

23 An unexpected finding was that relatively high heavy metal concentrations  
24 in moss were detected at Põhjala, despite this site having the lowest modelled  
25 PM<sub>10</sub> and NO<sub>x</sub> concentrations. This suggests that pollution at the site is not  
26 directly related to traffic emissions. As Põhjala is a former industrial area, the  
27 observed heavy metal contamination may be associated with past industrial  
28 activities. Kazantzoglou et al. (2016) found that previous land use is an important  
29 factor influencing heavy metal concentrations in urban garden soils, which  
30 subsequently affects the accumulation of these metals in plants.

31 In the present study, concentrations of Cu, Cd, Ni, and Pb in *Syntrichia*  
32 *ruralis* were strongly correlated with each other. Similar patterns have been  
33 reported by Zhou et al. (2025), who found strong correlations among heavy  
34 metals accumulated in mosses, including Cu-Ni and Cu-Pb relationships.

35 Previous laboratory tests have demonstrated a reduction in chlorophyll  
36 content due to heavy metal-induced stress (Shakya et al. 2008, Tuba et al. 2010,  
37 Stanković 2018). We can conclude that the level of heavy metals in the selected  
38 moss species in Tallinn is not high enough to affect chlorophyll content, even  
39 under variable environmental conditions. Tremper et al. (2004) study in field did  
40 not also give any measurable heavy metals negative effect on the chlorophyll  
41 concentrations in moss species *Pleurozium schreberi* and *Rhytidiadelphus*  
42 *squarrosus*. Other factors, such as climatic factors, interaction with other  
43 pollutants or shelter, probably, still had a stronger influence on the chlorophyll  
44 concentrations (Tremper et al. 2004). In a other study (Tuba et al. 2010) where  
45 tested heavy metals effects in field and laboratory, the chlorophyll a fluorescence  
46 remained nearly constant in most of the studied bryophyte species (9) in field

1 conditions and in laboratory at lower concentration (5 mM), revealing that the  
 2 maximal photochemical capacity of the photosynthetic cells remains unchanged  
 3 at lower Pb concentration, but two species were already affected by lower lead  
 4 concentrations.

## 7 Conclusions

9 In summary, the analysis of heavy metals in *Syntrichia ruralis* provides an  
 10 important complement to information on environmental pollution. Given that  
 11 concentrations of several heavy metals were strongly correlated with one  
 12 another, practical monitoring efforts could focus on detecting heavy metal  
 13 contamination through the measurement of a smaller subset of metals. The study  
 14 revealed that, among the six heavy metals measured in *Syntrichia ruralis*, Cu  
 15 and Hg were the most informative indicators of environmental pollution. A  
 16 practical recommendation is to wash produce from urban gardens, particularly  
 17 when the gardens are situated not far from major roads.

18 The pigment content in moss is not a reliable practical bioindicator for  
 19 detecting environmental pollution in Tallinn's urban gardens, as it varies  
 20 significantly depending on environmental conditions, particularly light, as well  
 21 as factors such as the season and the surface on which the moss grows.

## 24 Refereces

- 26 Aretz B, Janssen F, Vonk JM, Heneka MT, Boezen HM, Doblhammer G (2021) Long-  
 27 term exposure to fine particulate matter, lung function and cognitive performance:  
 28 A prospective Dutch cohort study on the underlying routes. *Environmental*  
 29 *Research* 201: Article 111533. <https://doi.org/10.1016/j.envres.2021.111533>  
 30 Bozkurt Z, Taspinar F, Pekey B, Pekey H, Uzmez OO, Dogeroglu T, Gaga EO (2017)  
 31 Mass concentrations and elemental compositions of PM10 in Duzce, Turkey.  
 32 *Athens Journal of Sciences* 4(2): 87-100.  
 33 Eesti Keskkonnauuringute Keskus (n.d.) *Eesti välisõhu kvaliteet*. Retrieved 10 June  
 34 2026 from <https://www.ohuseire.ee/> (In Estonian).  
 35 Egli V, Oliver M (2016) The development of a model of community garden benefits to  
 36 wellbeing. *Preventive Medicine Reports* 3: 348–352.  
 37 Govindaparyi H, Leleeka M, Nivedita M, Uniyal P (2010) Bryophytes: Indicators and  
 38 monitoring agents of pollution. *NeBio* 1(1): 35–41.  
 39 Hill MO, Preston CD, Bosanquet SD, Roy DB (2007) *BRYOATT: Attributes of British*  
 40 *and Irish Mosses, Liverworts and Hornworts*. Wallingford: Centre for Ecology and  
 41 Hydrology.  
 42 Huq FF, Deacon L (2025) A systematic review of community gardens and their role in  
 43 urban food security and resilience. *Discover Sustainability* 6: Article 696.  
 44 <https://doi.org/10.1007/s43621-025-01628-5>  
 45 Kaasik M, Geertsema G, Scheele R (2017) Validation of Gaussian plume model AEROPOL  
 46 against Cabauw field experiment. *International Journal of Environment and Pollution*  
 47 62(2–4): 369–384. <https://doi.org/10.1504/IJEP.2017.089420>

- 1 Kaasik M, Liiv S (2007) Spatial and temporal variability of trace metals in mosses in  
2 Estonia. *Forestry Studies | Metsanduslikud Uurimused* 46: 35–44.
- 3 Kaur S, Rao A, Kumar SS (2010) Studies on the effect of heavy metals on the growth  
4 of some bryophytes (mosses). *International Journal of Pharmaceutical Sciences*  
5 *Review and Research* 5(3): 102–107.
- 6 Kazantzoglou A, Argyraki A, Papageorgiou S, Fadel D (2016) Interaction of heavy  
7 metals in the soil-plant system of urban gardens in Athens, Greece. *Bulletin of the*  
8 *Geological Society of Greece* 50: 2090–2099. <https://doi.org/10.12681/bgsg.14274>
- 9 Künn S, Palacios J, Pestel N (2023) Indoor air quality and strategic decision making.  
10 *Management Science* 69(9): 5354–5377. <https://doi.org/10.1287/mnsc.2022.4643>
- 11 Leblanc F, Rao DN (1974) A review of the literature on bryophytes with respect to air  
12 pollution. *Bulletin de la Société Botanique de France* 121(Suppl. 2): 237–255.  
13 <https://doi.org/10.1080/00378941.1974.10839310>
- 14 Li H, Qian X, Wang Q (2013) Heavy metals in atmospheric particulate matter: A  
15 comprehensive understanding is needed for monitoring and risk mitigation.  
16 *Environmental Science & Technology* 47: 13210–13211.
- 17 Mallen-Cooper M, Rodríguez-Caballero E, Eldridge DJ, Weber B, Büdel B, Höhne H,  
18 Cornwell WK (2023) Towards an understanding of future range shifts in lichens  
19 and mosses under climate change. *Journal of Biogeography* 50: 406–417.  
20 <https://doi.org/10.1111/jbi.14542>
- 21 McDonald JH (2014) *Handbook of Biological Statistics*. 3rd ed. Baltimore, MD: Sparky  
22 House Publishing.
- 23 Meyer M, Schröder W, Pesch R, Steinnes E, Uggerud HT (2015) Multivariate  
24 association of regional factors with heavy metal concentrations in moss and natural  
25 surface soil sampled across Norway between 1990 and 2010. *Journal of Soils and*  
26 *Sediments* 15: 410–422. <https://doi.org/10.1007/s11368-014-0999-9>
- 27 Naszradi T, Badacsonyi A, Keresztényi I, Podar D, Csintalan Z, Tuba Z (2007)  
28 Comparison of two metal surveys by moss *Tortula ruralis* in Budapest, Hungary.  
29 *Environmental Monitoring and Assessment* 134: 279–285. <https://doi.org/10.1007/s10661-007-9617-2>
- 30  
31 Oishi Y, Hiura T (2017) Bryophytes as bioindicators of the atmospheric environment in  
32 urban–forest landscapes. *Landscape and Urban Planning* 167: 348–355.  
33 <https://doi.org/10.1016/j.landurbplan.2017.07.010>
- 34 Orru H, Maasikmets M, Lai T, Tamm T, Kaasik M, Kimmel V, Orru K, Merisalu E,  
35 Forsberg B (2011) Health impacts of particulate matter in five major Estonian  
36 towns: Main sources of exposure and local differences. *Air Quality, Atmosphere &*  
37 *Health* 4: 247–258. <https://doi.org/10.1007/s11869-010-0075-6>
- 38 Pindus M, Orru H, Maasikmets M, Kaasik M, Jõgi R (2016) Association between health  
39 symptoms and particulate matter from traffic and residential heating – results from  
40 RHINE III in Tartu. *The Open Respiratory Medicine Journal* 10(1): 58–69.  
41 <https://doi.org/10.2174/1874306401610010058>
- 42 Plášek V, Łuczak K, Kusza G, Režnarová H, Nowak A (2026) Selecting suitable moss  
43 indicators for routine bioindication of roadside air pollution. *Scientific Reports*  
44 16(1): Article 10275. <https://doi.org/10.1038/s41598-026-40922-8>
- 45 Porra RJ, Thompson WA, Kriedemann PE (1989) Determination of accurate extinction  
46 coefficients and simultaneous equations for assaying chlorophylls a and b extracted  
47 with four different solvents: Verification of the concentration of chlorophyll  
48 standards by atomic absorption spectroscopy. *Biochimica et Biophysica Acta*  
49 (BBA) – *Bioenergetics* 975(3): 384–394.

- 1 Rajandu E, Kaljuvee K-L, Kulp M, Kaasik M, Elvisto T, Küttim M (2024) *Syntrichia*  
 2 *ruralis* as a suitable bioindicator for urban areas – the case study of Tallinn city.  
 3 *Folia Cryptogamica Estonica* 61: 25–34. <https://doi.org/10.12697/fce.2024.61.03>
- 4 Rajandu E, Kaljuvee K-L, Kulp M, Kaasik M, Elvisto T, Küttim M (2025) Assessment  
 5 of air pollution by the contents of potentially toxic chemical elements in  
 6 bryophytes. In Bibri SE, Resta G, Papa D, Magnaye D (eds) *Sustainable Cities:  
 7 Pioneering Approaches to Green Urbanism and Climate Resilience*. Advances in  
 8 Science, Technology & Innovation. Cham: Springer. [https://doi.org/10.1007/978-3-031-86095-9\\_15](https://doi.org/10.1007/978-3-031-86095-9_15)
- 10 Riigi Teataja (2019) Ohtlike ainete sisalduse piirväärtused pinnases. RT I, 04.07.2019,  
 11 6. <https://www.riigiteataja.ee/akt/104072019006> (In Estonian).
- 12 Saare K, Kabral N, Maasikmets M, Teinemaa E (2019) *Välisõhu kvaliteedi seire 2018*.  
 13 Eesti Keskkonnauuringute Keskus. (In Estonian).
- 14 Salemaa M, Mäkipää R, Oksanen J (2008) Differences in the growth response of three  
 15 bryophyte species to nitrogen. *Environmental Pollution* 152(1): 82–91.  
 16 <https://doi.org/10.1016/j.envpol.2007.05.019>
- 17 Shakya K, Chettri MK, Sawidis T (2008) Impact of heavy metals (copper, zinc, and  
 18 lead) on the chlorophyll content of some mosses. *Archives of Environmental  
 19 Contamination and Toxicology* 54: 412–421. <https://doi.org/10.1007/s00244-007-9060-y>
- 21 Stanković JD, Sabovljević AD, Sabovljević MS (2018) Bryophytes and heavy metals:  
 22 A review. *Acta Botanica Croatica* 77(2): 109–118.
- 23 Świsłowski P, Nowak A, Rajfur M (2022) Comparison of exposure techniques and  
 24 vitality assessment of mosses in active biomonitoring for their suitability in  
 25 assessing heavy metal pollution in atmospheric aerosol. *Environmental Toxicology  
 26 and Chemistry* 41(6): 1429–1438. <https://doi.org/10.1002/etc.5321>
- 27 ter Braak CJF, Šmilauer P (2012) *Canoco Reference Manual and User's Guide:  
 28 Software for Ordination (Version 5.0)*. Ithaca, NY: Microcomputer Power.
- 29 Tims K, Haggerty M, Jemison J, Ladenheim M, Mullis S, Damon E (2021) Gardening  
 30 for change: Community giving gardens and senior food insecurity. *Journal of  
 31 Agriculture, Food Systems, and Community Development* 10(4): 85–101.  
 32 <https://doi.org/10.5304/jafscd.2021.104.030>
- 33 Tremper AH, Agneta M, Burton AS, Higgs DE (2004) Field and laboratory exposures  
 34 of two moss species to low metal pollution. *Journal of Atmospheric Chemistry* 49:  
 35 111–120. <https://doi.org/10.1007/s10874-004-1218-7>
- 36 Tuba Z, Saxena DK, Srivastava K, Singh S, Czobel S, Kalaji HM (2010) Chlorophyll a  
 37 fluorescence measurements for validating the tolerant bryophytes for heavy metal  
 38 (Pb) biomapping. *Current Science* 98(11): 1505–1508.
- 39 Vacht P, Kaldma KK, Barbo L, Suitso M (2022) *Vormsi roheala mulla- ja taimeproovide  
 40 analüüs*. Tallinna Ülikooli loodus- ja terviseteaduste instituut, Tallinna Strateegiakeskus. (In  
 41 Estonian).
- 42 Vacht P, Koff T, Kaldma KK (2025) Peamised toiduohutuse mõjutajad: muld, õhk ja  
 43 inimkäitumine. In Plüschke-Altöf B, Kopra H, Tähti Toom I, Derlõs M, Küünal A  
 44 (toim) *Söödav Linn 2. 15 aastat Eesti linnaaianduse arengut*, 121–136. Tallinn:  
 45 Tallinna Raamatutrükikoda. (In Estonian).
- 46 Valavanidis A, Fiotakis K, Vlachogianni T (2008) Airborne particulate matter and  
 47 human health: Toxicological assessment and importance of size and composition  
 48 of particles for oxidative damage and carcinogenic mechanisms. *Journal of  
 49 Environmental Science and Health, Part C* 26(4): 339–362. <https://doi.org/10.1080/10590500802494538>
- 50

- 1 Vanderpoorten A, Goffinet B (2009) *Introduction to Bryophytes*. Cambridge:
- 2 Cambridge University Press.
- 3 Zhou X, Li J, Yan P, Lu N, Lu L, Ni Q, Zhang J, Fang Y (2025) Mosses as biomonitors
- 4 of atmospheric trace metal and nitrogen deposition: Spatial distribution and temporal
- 5 trend in Yancheng, China. *Plants* 14(9): 1315. [https://doi.org/10.3390/plants140](https://doi.org/10.3390/plants14091315)
- 6 [91315](https://doi.org/10.3390/plants14091315)
- 7

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