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# EFFICIENCY OF PHOTOSYNTHETIC APPARATUS OF PLANTS GROWN IN SITES DIFFERING IN LEVEL OF PARTICULATE MATTER

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**Abstract**. Particulate matter (PM) is among the most harmful pollutants inhaled by man. To reduce its concentration in air, plants could be used as biological filters, adsorbing PM on the foliage ($_S$PM) or stabilizing in waxes ($_W$PM). PM has also negative impact on the photosynthetic apparatus, but not much is known in regard to comparison of species responses to PM. In this work, an attempt was made to define the amount of PM and waxes on foliage and to evaluate the efficiency of photosynthetic apparatus in five species grown in two sites differing in level of PM in the air. Obtained results showed, that quantities of PM and waxes on foliage were greater in plants grown in the City centre. These plants had lowered efficiency of photosynthetic apparatus, usually manifested by lower: (1) chlorophyll content, (2) values of chlorophyll *a* fluorescence parameters and (3) photosynthesis rate, which coincides with an (4) increased stomatal resistance. Among tested species *Sorbaria sorbifolia* was the best acclimated to conditions of urban areas with simultaneous highest PM accumulation. Therefore *S. sorbifolia* is best suited for phytoremediation of PM from air in urban areas.

**Key words:** particulate matter, gas exchange, chlorophyll content, chlorophyll *a* fluorescence

## INTRODUCTION

The environment in which people live in is undergoing continuous and often adverse changes. In urban areas, people are exposed to a mixture of air pollutants which, although in particular cases often do not exceed permissible levels, but as a composition may pose serious threats to men health. According to World Health Organization

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(WHO) [2006] one of the most dangerous air pollutants is PM, size of which is lower than 100 µm. PM vary in source of origin, chemical composition, may be suspended in the air for long periods of time and transported over long distances. PM has negative effects on health and it is proven that PM below 10 µm is the most hazardous [Dockery et al. 1993]. It often contains various toxic compounds, including polycyclic aromatic hydrocarbons (PAHs) and heavy metals, which make them more dangerous [Jouraeva et al. 2002, WHO 2006, Yu et al. 2006, Uzu et al. 2010]. European Environment Agency (EEA) reported that the life expectancy of Europeans is on average reduced by 8.6 months and maximum loss of 12–36 months occurs in Benelux, Silesia and Po Valley [EEA 2007].

Plants accumulating PM may perform the function of biological filters, effectively up taking PM from the air, especially in urban areas and close to roads [Beckett et al. 1998, Beckett et al. 2000, Dzierżanowski et al. 2011, Popek et al. 2013]. PM has also negative impact on plants because when accumulated on leaves, it may change their optical properties due to absorption/reflection of PAR or clogged stomata. In both cases it may negatively affects photosynthesis and transpiration rates. PM also carries some pollutants that could penetrate into plant tissue [Vardaka et al. 1995, Beckett et al. 1998, Farmer 2002]. Although negative effect of industry-originated PM on photosynthetic apparatus is reported [Armbrust 1986, Hirano et al. 1995, Vardaka et al. 1995, Heerden et al. 2007, Uzu et al. 2010] data on the effects of PM mainly originating by car traffic and species comparison in that regard is very limited.

In this work, an attempt was made to determine (1) the amount of PM accumulated on foliage and (2) quantity of wax deposition, and to evaluate (3) the efficiency of photosynthetic apparatus of five species grown in two sites differing in levels of PM in the air.

## MATERIALS AND METHODS

**Plant material and experimental locations.** The object of this study were five species: Norway maple (*Acer platanoides* L.), sycamore maple (*Acer pseudoplatanus* L.), false spiraea (*Sorbaria sorbifolia* L.), Boston ivy (*Parthenocissus tricuspidata* L.) and five-leaved ivy (*Parthenocissus quinquefolia* L.). Plants were growing in two sites differing in level of PM in air (tab. 1): (1) city centre of Warsaw (nearby to busy road, polluted urban environment) and (2) campus of Warsaw University of Life Sciences – SGGW (a moderately clean environment) denoted in this paper as City centre and Campus, respectively. As both sites are localised within the Warsaw city area, temperature and precipitation were very similar during the measurements. Attention was paid to perform measurements and collect plant samples from the individuals of similar age and size within given species.

**Quantitative assessment of PM and waxes amount on foliage.** Samples for determining PM and wax quantities on foliage were collected at the end of the growing season, from four plants of each species (biological replications), of traffic-exposed side of the plant, at a height of 0.6–2.0 m, depending on plant size. Sample contained 5–20 leaves, with total leaf area ranging between 300–400 cm$^2$. The content of PM was

Table 1. Concentration of $PM_{10}$ in the City centre and on the Campus in the months of running experiment in 2008, according to readings by the Voivodeship Inspectorate of Environmental Protection in Warsaw. Data are monthly means

| Location | Month | | | |
|---|---|---|---|---|
| | July | August | September | October |
| | $PM_{10}$ $\mu g \cdot m^{-3}$ | | | |
| City centre | 38.49 | 42.75 | 47.06 | 63.26 |
| Campus | 20.10 | 23.60 | 24.56 | 37.73 |

examined in two categories: (i) water-washable, which is deposited on the surface of foliage ($_{S}PM$) and (ii) stabilise in waxes ($_{W}PM$). For the fractional division of PM, the following filters were used: paper filters types 91 and 42 and PTFE membrane filters (of 10, 2.5 and 0.2 µm retentions respectively, Whatman, UK). As a result, three-sized fractions of PM were collected: (i) 10–100 µm (large), (ii) 2.5–10 µm (coarse) and (iii) 0.2–2.5 µm (fine). The filters were first dried for 30 min at 60°C (KCW-100, PREMED, Poland), left in the weighing room to stabilise humidity for the next 30 min and then pre-weighed (XS105DU, Mettler-Toledo International Inc., Switzerland equipped with a deioniser gate, HAUG, Switzerland). Each leaf sample was rinsed with distilled water (250 ml, agitated for 60 s) and obtained solution was passed through a metal sieve of 100 µm mesh (Haver & Boecker, Germany) in order to eliminate particles over 100 µm. Then, solutions were filtrated sequentially through the above-mentioned filters using a 47 mm glass filter funnel with a stopper support assembly (PALL Corp., USA) connected to a vacuum pump (KNF Neuberger, Inc., USA). After being rinsed in water, each sample was washed with chloroform (150 ml, agitated for 40 s) in order to determine $_{W}PM$. The filtration procedure was the same as for $_{S}PM$. Chloroform after filtration was collected in pre-weighed beakers and left under hood for evaporation. Before the final weighing, filters were again dried using the same procedure as during pre-weighing. The amount of PM and waxes were calculated from differences in $1^{st}$ and $2^{nd}$ weights of filters and beakers, respectively. The area of leaf samples taken for analysis were measured using an Image Analysis System (Skye Instruments Ltd, UK) and Skye-Leaf software in order to express the amount of PM and waxes as $\mu g \cdot cm^{-2}$ which allowed comparison between species and locations.

**Evaluation of efficiency of photosynthetic apparatus.** During vegetation, once a month, the following parameters of efficiency of photosynthetic apparatus were measured *in vivo*:

(i) plant gas exchange: photosynthesis rate and stomatal resistance using an infra-red gas analyser (IRGA) method (LICOR 6200 Photosynthesis System, Lincoln, Nebraska, USA),

(ii) total chlorophyll content expressed as chlorophyll content index (CCI) (Chlorophyll meter CCM-200, OPTI-SCIENCES, USA),

(iii) based on chlorophyll *a* fluorescence measurements the maximum quantum efficiency of Photosystem II (Fv/Fm) and Performance Index (vitality indicator, PI) (Handy PEA, Hansatech, UK) were calculated.

Simultaneous transpiration rate was measured (IRGA).

Measurements were performed always on sunny days, on the same, fully developed and undamaged leaves. Ten replicates (leaves) were used for measurements (in the case of gas exchange with three independent measurements for each). In October, due to the adverse weather conditions, measurements of gas exchange were performed in the growth chamber (Simez Control s.r.o. Vsetin, Czech Republic). Shoots with leaves were collected and left to acclimate (temp. 20°C, PAR 220–250 μmol $m^{-2}$ $s^{-1}$ on leaf level, photoperiod 8/16 h d/n, RH 60%) for 2 days before measurements.

**Statistical analysis.** Data was subjected to one factorial analysis of variance using StatGraphics Plus 4.1 software (StatPoint Technologies, Inc., USA). The significance of differences between mean values was tested using Tukey's Honestly Significant Difference test (HSD) at $\alpha = 0.05$. The correlation coefficient ($r$) was calculated using Microsoft Excel (Microsoft Corp., USA). The data presented are mean ±SE.

## RESULTS

The amount of total PM accumulated on foliage differed significantly between sites and species and was always higher in plants grown in the City centre (tab. 2). Among species *Sorbaria sorbifolia* was the most effective in total PM accumulation followed by *Parthenocissus tricuspidata*. A relatively low amount of total PM was accumulated by *Acer* species, as in both sites they accumulated between 42.6–73.8% less PM as compared to *S. sorbifolia.* In total PM, $_{W}$PM contributed with smaller amount than $_{S}$PM, except of *A. platanoides* (tab. 2).

Accumulation of the large PM was always higher in the City centre (tab. 2). Large PM were mainly recorded as $_{S}$PM. Only for *A. platanoides* higher amount was noted as $_{W}$PM. *S. sorbifolia* and both *Parthenocissus* species accumulated substantially more large PM than other species, especially *Acer* ones. With exception of *S. sorbifolia*, a higher accumulation of coarse PM was also recorded in the City centre. The adsorption of coarse PM in *A. pseudoplatanus, P. quinquefolia* (both sites) and *S. sorbifolia* (Campus) was greater as $_{S}$PM, while in other cases more coarse PM were $_{W}$PM. Among species, greatest accumulation of coarse PM, similarly to large, was recorded in *S. sorbifolia* plants and the lowest in both *Acer* species. The accumulation of fine PM, when compare to other species, was higher in *P. tricuspidata* and *S. sorbifolia* and no clear trend in regard to sites was noted. Fine PM in *A. platanoides* and *P. quinquefolia* (both sites), was in greater amount stabilised in waxes while in *A. pseudoplatanus* (City centre) more were sPM (tab. 2).

There were also differences in amount of waxes between locations and species (tab. ). Greater amount of waxes was usually noted for plants grown in City centre, except *P. quinquefolia* (tab. 2).

From the correlation coefficient between PM and the amount of waxes it is clearly seen that irrespectively from the PM categories and size fractions, the correlation was moderately positive, especially for large PM and $_{W}$PM (tab. 3).

This study demonstrates that the photosynthetic apparatus efficiency of the examined species was usually, sometimes significantly, negatively affected by PM (fig. 1, 2,

Table 2. Amount of large, coarse and fine PM, and waxes on foliage of examined plant species. Data are means ±SE, n = 4

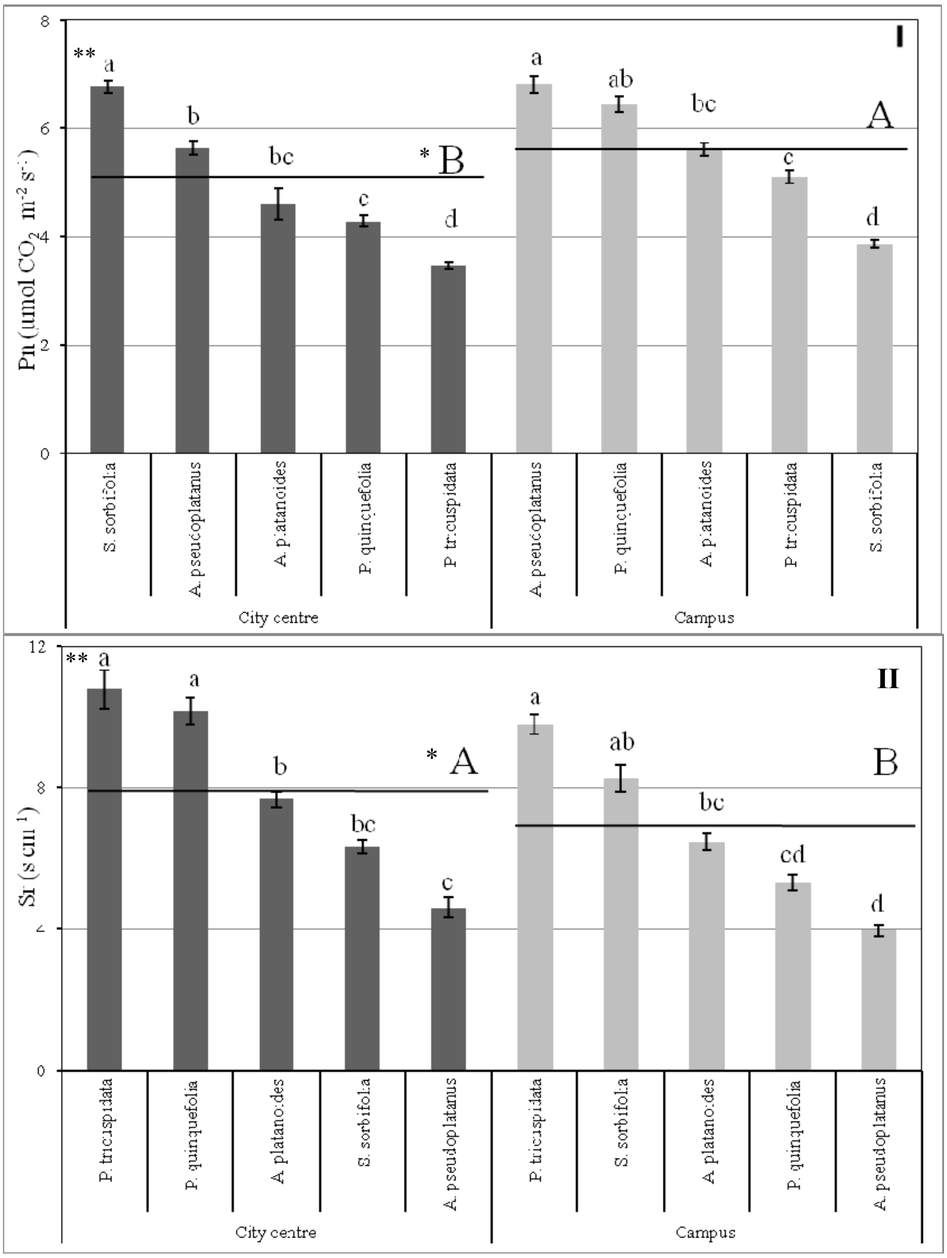
| | Size fractions | PM categories | Species | | | | | $HSD_{0.05}$ |
|---|---|---|---|---|---|---|---|---|
| | | | *A. platanoides* | *A. pseudoplatanus* | *P. tricuspidata* | *P. quinquefolia* | *S. sorbifolia* | |
| City centre (µg·cm$^{-2}$) | Total PM | All | 17.98 (±0.873) | 12.51 (±0.080) | 29.16 (±0.930) | 20.13 (±0.664) | 31.35 (±0.218) | 6.7 |
| | | $_{S}$PM | 7.37 (±0.443) | 8.71 (±0.145) | 20.66 (±0.755) | 13.45 (±0.676) | 17.31 (±0.089) | 5.1 |
| | | $_{W}$PM | 10.61 (±0.439) | 3.80 (±0.081) | 8.49 (±0.349) | 6.68 (±0.102) | 14.05 (±0.148) | 2.7 |
| | Large | All | 14.34 (±0.703) | 9.25 (±0.098) | 21.94 (±1.105) | 15.11 (±0.622) | 24.11 (±0.223) | 4.6 |
| | | $_{S}$PM | 6.35 (±0.304) | 6.91 (±0.140) | 16.89 (±0.870) | 10.81 (±0.558) | 13.94 (±0.115) | 4.9 |
| | | $_{W}$PM | 7.99 (±0.403) | 2.34 (±0.124) | 5.04 (±0.301) | 4.30 (±0.190) | 10.17 (±0.120) | 2.5 |
| | Coarse | All | 3.02 (±0.271) | 2.80 (±0.079) | 5.80 (±0.212) | 3.88 (±0.301) | 5.80 (±0.091) | 2.1 |
| | | $_{S}$PM | 0.96 (±0.159) | 1.62 (±0.035) | 2.89 (±0.148) | 2.13 (±0.153) | 2.60 (±0.040) | 1.3 |
| | | $_{W}$PM | 2.06 (±0.144) | 1.18 (±0.057) | 2.92 (±0.146) | 1.74 (±0.170) | 3.20 (±0.072) | 1.2 |
| | Fine | All | 0.62 (±0.019) | 0.46 (±0.009) | 1.42 (±0.032) | 1.15 (±0.101) | 1.44 (±0.021) | 0.5 |
| | | $_{S}$PM | 0.06 (±0.005) | 0.17 (±0.010) | 0.89 (±0.029) | 0.51 (±0.021) | 0.77 (±0.020) | 0.2 |
| | | $_{W}$PM | 0.56 (±0.023) | 0.28 (±0.014) | 0.53 (±0.024) | 0.64 (±0.117) | 0.67 (±0.009) | 0.4 |
| | Waxes | | 81.69 (±0.985) | 52.37 (±0.885) | 25.96 (±2.063) | 36.55 (±0.904) | 68.21 (±0.703) | 12.4 |
| Campus (µg·cm$^{-2}$) | Total PM | All | 6.39 (±0.351) | 9.92 (±0.098) | 18.32 (±0.672) | 16.52 (±0.387) | 24.40 (±0.614) | 4.8 |
| | | $_{S}$PM | 2.76 (±0.223) | 6.85 (±0.155) | 10.41 (±0.225) | 10.94 (±0.278) | 15.14 (±0.402) | 2.7 |
| | | $_{W}$PM | 3.63 (±0.207) | 3.06 (±0.069) | 7.91 (±0.455) | 5.58 (±0.221) | 9.25 (±0.214) | 2.6 |
| | Large | All | 4.90 (±0.363) | 6.94 (±0.087) | 12.68 (±0.546) | 12.76 (±0.225) | 16.42 (±0.521) | 3.9 |
| | | $_{S}$PM | 2.36 (±0.228) | 5.02 (±0.128) | 7.67 (±0.235) | 9.07 (±0.200) | 10.77 (±0.325) | 2.3 |
| | | $_{W}$PM | 2.53 (±0.227) | 1.92 (±0.059) | 5.02 (±0.382) | 3.68 (±0.088) | 5.65 (±0.200) | 2.2 |
| | Coarse | All | 0.65 (±0.056) | 2.45 (±0.018) | 4.22 (±0.127) | 2.90 (±0.175) | 7.04 (±0.152) | 1.2 |
| | | $_{S}$PM | 0.22 (±0.041) | 1.55 (±0.024) | 1.91 (±0.079) | 1.45 (±0.140) | 3.72 (±0.091) | 0.8 |
| | | $_{W}$PM | 0.44 (±0.025) | 0.89 (±0.038) | 2.31 (±0.094) | 1.44 (±0.129) | 3.31 (±0.091) | 0.5 |
| | Fine | All | 0.84 (±0.086) | 0.53 (±0.008) | 1.42 (±0.061) | 0.87 (±0.065) | 0.95 (±0.097) | 0.7 |
| | | $_{S}$PM | 0.19 (±0.026) | 0.28 (±0.009) | 0.84 (±0.051) | 0.42 (±0.029) | 0.65 (±0.113) | 0.4 |
| | | $_{W}$PM | 0.66 (±0.023) | 0.25 (±0.004) | 0.58 (±0.030) | 0.45 (±0.051) | 0.30 (±0.017) | 0.3 |
| | Waxes | | 37.11 (±2.555) | 19.34 (±0.602) | 17.63 (±0.689) | 64.20 (±1.462) | 60.03 (±5.816) | 16.1 |
| $HSD_{0.05}$ for Total PM | | | 5.31 | 4.34 | 6.49 | 0.71 | 3.69 | |

Table 3. Correlation coefficient (r) between amount of waxes and PM accumulated on leaves

| | Large | Coarse | Fine | $_{S}PM$ | $_{W}PM$ | Total | $_{S}PM$ | | | $_{W}PM$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | large | coarse | fine | large | coarse | fine |
| Wax | 0.91 | 0.73 | 0.79 | 0.85 | 0.89 | 0.89 | 0.86 | 0.57 | 0.72 | 0.90 | 0.82 | 0.80 |

Table 4. Effect of PM on total chlorophyll content, Fv/Fm and P.I. in examined plants species. Data are means ±SE, n = 40

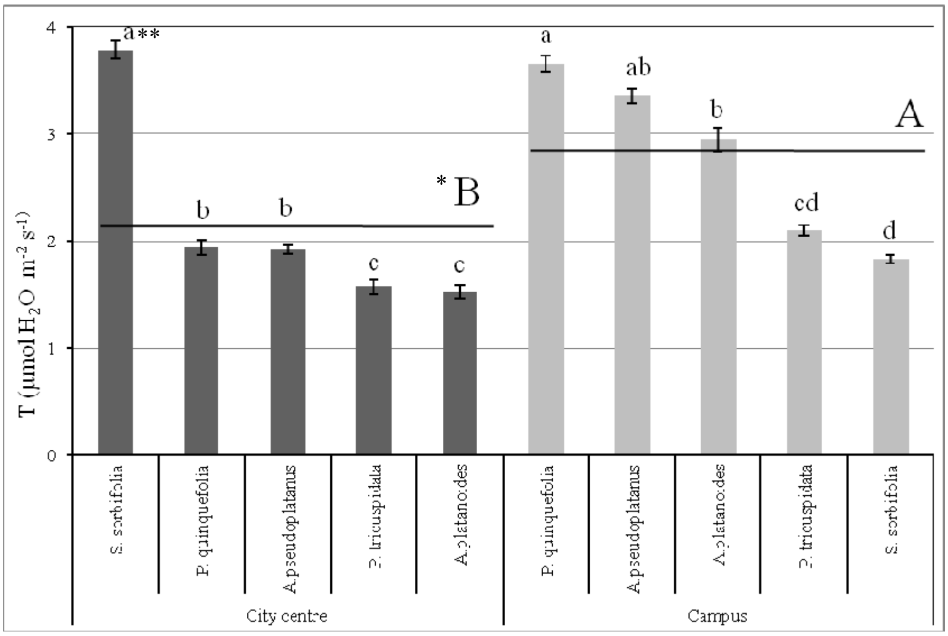
| Species | Chlorophyll content | | | Fv/Fm | | | P.I. | | $HSD_{0.05}$ |
|---|---|---|---|---|---|---|---|---|---|
| | city centre | campus | $HSD_{0.05}$ | city centre | campus | $HSD_{0.05}$ | city centre | campus | |
| *A. platanoides* | 15.6 (±0.29) | 18.7 (±0.37) | 1.33 | 0.77 (±0.006) | 0.78 (±0.004) | 0.02 | 26.0 (±1.61) | 27.7 (±1.73) | 6.51 |
| *A. pseudoplatanus* | 39.7 (±0.59) | 18.9 (±0.25) | 1.66 | 0.79 (±0.005) | 0.78 (±0.004) | 0.01 | 40.7 (±2.39) | 28.8 (±1.07) | 6.01 |
| *P. tricuspidata* | 12.5 (±0.35) | 27.2 (±0.54) | 2.86 | 0.76 (±0.003) | 0.79 (±0.007) | 0.02 | 16.5 (±0.81) | 33.8 (±2.45) | 6.72 |
| *P. quinquefolia* | 14.4 (±0.43) | 18.7 (±0.34) | 2.68 | 0.72 (±0.012) | 0.78 (±0.004) | 0.03 | 10.8 (±1.08) | 14.6 (±0.69) | 5.50 |
| *S. sorbifolia* | 6.1 (±0.19) | 9.6 (±0.23) | 1.04 | 0.80 (±0.003) | 0.81 (±0.002) | 0.01 | 20.2 (±1.17) | 26.8 (±1.03) | 4.01 |




* horizontal lines represent averages for all species at given location, capitalized letters indicate significant differences between locations

** lower case letters indicate significant differences between species in given location

Fig. 1. Rate of photosynthesis (I) and stomatal resistance (II) in examined plants species growing in locations differing in level of PM in the air. Data are means ±SE, n = 120 (4 – terms of measurement, × 10 – biological replications, × 3 – measurements)




* horizontal lines represent averages for all species at given location, capitalized letters indicate significant differences between locations
** lower case letters indicate significant differences between species in given location

Fig. 2. Rate of transpiration in examined plants species growing in locations differing in levels of PM in the air. Data are means ±SE, n = 120 (4 – terms of measurement, × 10 – biological replications, × 3 – measurements)

tab. 4). Four months average rate of photosynthesis of plants grown in the City centre was generally lower than in the Campus and this was particularly true for the climber species in which this process was reduced by ca 32% (fig. 1A). Photosynthesis rate in the City centre of *A. platanoides* and *A. pseudoplatanus* plants was reduced to a lower degree (by about 18%). Contrarily to the above photosynthesis rate of *S. sorbifolia* was higher in more polluted site (by 42.9%) (fig. 1A).

The reduced rate of photosynthesis corresponded well with stomatal resistance (fig. 1B), which was usually higher in plants grown in the City centre (by 9.1–47.6%). Again *S. sorbifolia* was on exception, having 30.8% higher stomatal resistance in Campus (fig. 1B).

The adverse effect of PM on total chlorophyll content was also evident (tab. 4). For most species reduced values of this parameter were recorded in plants grown in the City centre (by 16.5–110.0%) while for *A. pseudoplatanus* total chlorophyll content was higher in the more polluted site (by 52.4%) (tab. 4).

Plants grown in the two sites differed in values of the parameters of chlorophyll *a* fluorescence (tab. 4). Values of Fv/Fm in *A. platanoides*, *P. tricuspidata, P. quinque-*

*folia* and *S. sorbifolia* were higher (by 1.2–8.3%) in plants grown on the Campus, in contrast to *A. pseudoplatanus* plants for which values of this parameter were higher in City centre (by 1.3%). Similarly to Fv/Fm, values of P.I. were usually increased (by 6.5–104.8%) in plants grown on the Campus, but not for *A. pseudoplatanus* for which lower P.I. were recorded in less polluted site (by 29.2%) (tab. 4).

In plants grown on the Campus often also transpiration rate was higher (33.3–93.2%) (fig. 2). Higher rate of transpiration in the City centre was only found in *S. sorbifolia* plants (by 51.6%) (fig. 2).

Table 5. Correlation coefficient (r) between selected parameters of photosynthetic efficiency and PM accumulated on leaves

| Parameter | PM | | | | | | Waxes |
|---|---|---|---|---|---|---|---|
| | large | coarse | fine | $_{S}$PM | $_{W}$PM | total | |
| Photosynthesis rate | -0.87 | -0.85 | -0.84 | -0.79 | -0.91 | -0.87 | -0.93 |
| Stomatal resistance | 0.39 | 0.47 | 0.92 | 0.87 | 0.90 | 0.91 | 0.96 |
| Transpiration rate | -0.51 | -0.52 | -0.54 | -0.48 | -0.52 | -0.51 | -0.70 |
| Fv/Fm | -0.42 | -0.52 | -0.53 | -0.38 | -0.51 | -0.45 | -0.38 |
| P.I. | -0.14 | -0.29 | -0.25 | -0.12 | -0.23 | -0.17 | -0.03 |
| Chlorophyll content | -0.67 | -0.58 | -0.60 | -0.61 | -0.69 | -0.66 | -0.58 |

A correlations between the level of PM on foliage and the intensity of gas exchange as well as between PM and chlorophyll content were found. In case of photosynthesis the correlation was negative, moderately strong ($p$ = 0.01), especially clear for $_{W}$PM ($r$ = -0.91) (tab. 5). Between PM accumulation and stomatal resistance, a positive correlation was noted, being strongest in the case of fine ($r$ = 0.92) and $_{W}$PM ($r$ = 0.91). Both photosynthesis rate and stomatal resistance correlated strongly ($p$ = 0.001) with wax content, negatively ($r$ = -0.93) and positively ($r$ = 0.96) respectively. A weak negative correlation was recorded also between amount of PM and chlorophyll content and between PM and parameters of chlorophyll *a* fluorescence (tab. 5).

## DISCUSSION

The results of this research show that the total amount of PM accumulated on foliage of all examined species was always higher in plants grown in the City centre and this is in the agreement with data of Beckett et al. [2000] and Freer-Smith et al. [2005]. Both $_{S}$PM and $_{W}$PM were found on foliage of every species, with $_{W}$PM contributed in smaller amount to total, except of *Acer platanoides*. Such a relationship has also been found in studies of Dzierżanowski et al. [2011] and Popek et al. [2011, 2013], but not in those of Nawrot et al. [2011]. $_{S}$PM, as washable with water, can in nature be washed off foliage by rain or removed by wind, while $_W$PM as immobilised in waxes can be considered as phytostabilised, which reduces the risk to human health during longer time. Armbrust [1986], Beckett et al. [2000] and Heerden et al. [2007] also pointed out that rain and wind remove some of PM from foliage. Out of all size fractions, in both sites, in the greatest amounts were found the largest PM, followed by coarse and in lowest amount were fine PM. This relationship was also reported by Dzierżanowski et al. [2011] and Popek et al. [2011, 2013]. The accumulation of large and coarse PM was higher in plants grown in City centre, but for fine size fractions no clear tendency was found in regard to the site. Among the species tested *Sorbaria sorbifolia* is the most efficient in PM accumulation what confirmed results of Popek et al. [2013]. It can be explained by the fact that leaves of *S. sorbifolia* are composite, with small leaflets. The air turbulence between these leaflets may increase the accumulation of PM, as suggested by Farmer [2002] and Popek et al. [2013]. It is known that leaf structure, presence of waxes and trichomes (morphological features) affect the capture of PM [Bakker et al. 1999, Dzierżanowski and Gawroński 2011, Popek et al. 2013].

Species and sites to some extent determine the amount of waxes on foliage, which was usually higher in the City centre. Studies revealed that the amount of accumulated PM on foliage correlates positively with the amount of waxes, which as shown by Dzierżanowki et al. [2011] and Popek et al. [2011, 2013] is rather rare.

Results of this work showed that conditions in the City centre usually have a negative impact on the efficiency of photosynthetic apparatus. Plants grown in the more polluted site photosynthesised with lower rate, but the level of this reduction depends on the species. The highest reduction was recorded for both climbers. An exception was in case of *S. sorbifolia* which in City centre had higher intensity of photosynthesis, despite that this species accumulated highest amount of PM. The moderate negative correlation between photosynthesis rate and the level of accumulated PM prove that the efficiency of photosynthetic apparatus depends, at least to some extent, on the level of PM. These results confirmed findings of Armbrust [1986], Hirano et al. [1995], Vardaka et al. [1995] and Heerden et al. [2007] who demonstrated the negative effects of PM on rate of photosynthetis due to leaves shading by dust. Hirano et al. [1995] reported that the photosynthetic rate of cucumber and kidney bean decreased in parallel with the increase in the amount of dust. They pointed out that the effect depends on PM size and was greater when particles were smaller. In contrast to the above, in our study PM size has no influence on the correlation between photosynthesis and PM adsorption. However, it has to be taken into consideration that above mentioned authors mainly studied industrial dust, while in our case PM was generated mostly by car traffic. Recorded in this work higher intensity of photosynthesis in City centre by *S. sorbifolia* can be explained with possible protective role of PM through the avoidance of photoinhibition and/or with greater mitigation, in this species, of negative effects of oxidative stress and/or other stressors present in city conditions. Similar phenomenon was noted by Takagi and Gyokusen [2004] who showed that the photosynthetic rate of *Ilex rotunda* trees grown in the more polluted urban core was higher than in suburban areas. In their study, the rate of photosynthesis was negatively correlated with sunlight conditions and positively with air pollutant concentrations. Authors suggest that poor sunlight conditions and higher concentrations of air pollutants could protect plants against photoinhibition.

Lowered photosynthesis rate well corresponded with changes in stomatal resistance, which were usually lower in plants grown in Campus. We demonstrated that there is a significant positive correlation between stomatal resistance and fine PM and a moderate for $_S$PM, $_W$PM and total PM. Lowered stomatal conductance (parameter opposite to stomatal resistance) in plants after dust deposition on foliage was also noted by Vardaka et al. [1995] and Heerden et al. [2007]. It is worth mentioning that higher stomatal resistance, because of PM accumulation of leaves, makes the $CO_2$ flow to chloroplast more difficult and, in addition to lower light access, at least partially explains the decreased rate of photosynthesis in plants grown in the City centre. Vardaka et al. [1995] reported effect of limestone dust on greater blockage of leaf stomata and subsequently on photosynthetic rate. Beckett et al. [1998] suggested stomata clogging by PM as possible mechanism for reduction of photosynthesis rate. According to the authors, smaller PM with a diameter similar to stomata may result in them becoming clogged, making gas exchange difficult. Hirano et al. [1995] found that dust decreased stomatal conductance in the light and increased it in the dark by clogging the stomata if the stomata were open during dusting.

Impairment of the efficiency of photosynthetic apparatus by conditions in City centre could be also due to the often lowered content of chlorophyll, which as shown in this work negatively correlated with the amount of PM accumulated on foliage, though usually not strongly. These results are in line with those on *Zygophyllum prismatocarpum* plants exposed to limestone dust [Heerden et al. 2007]. On the other hand, Vardaka et al. [1995] noted that the average concentration of total chlorophyll ($a$ + $b$) did not vary significantly between the sampling sites close to and further away from (between 300–3000 m) the limestone quarry. Interesting is the fact that in our work between rate of photosynthesis and chlorophyll content only weak correlation was recorded (data not shown).

In this study parameters of chlorophyll *a* fluorescence were negatively affected by conditions in the City centre. The values of Fv/Fm and P.I. were usually lower in plants grown in more polluted site. Similarly to our results, significant decrease of Fv/Fm with increasing dust deposition on leaves are reported also for *Quercus coccifera* [Vardaka et al. 1995] and *Z. prismatocarpum* [Heerden et al. 2007].

The discussed earlier effects of PM on stomatal resistance well corresponds with transpiration rate, which in most cases was lower in plants with greater PM accumulation.

It is important to note that despite of significant differences in examined processes and found correlations PM is not the only factor negatively affecting efficiency of photosynthetic apparatus in plants grown in urban areas. Together with PM also PAHs and heavy metals can penetrate in to plant tissues, making airborne contaminations points of interest of growing number of researches [Jouraeva et al. 2002, Yu et al. 2006, Uzu et al. 2010]. Limited access to sunlight, drought, limited space for growth and soil compaction, high salinity and other pollutants i.e. derived from vehicle exhaust also have great negative impact on photosynthetic apparatus [Woo and Je 2006].

In summary, it can be concluded that plants grown in the City centre with higher level of PM in the air accumulated more PM on foliage and have usually decreased efficiency of photosynthetic apparatus. This negative effect of PM on photosynthetic apparatus was manifested by a decrease in (i) chlorophyll content, (ii) photosynthesis rate, which coincides with an increase in (iii) stomatal resistance and (iv) lowered values of fluorescence *a* parameters. Species differ both in the ability of PM accumulation and range of response of photosynthetic apparatus. Results show that out of the species tested *S. sorbifolia* is least negatively affected by PM despite the highest capturing PM. Therefore, this species is best acclimated to the city conditions and among examined species is most suitable for cultivation in urban areas and of best ability for PM phytoremediation from air.

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## SPRAWNOŚĆ APARATU FOTOSYNTETYCZNEGO U ROŚLIN ROSNĄCYCH NA STANOWISKACH RÓŻNIĄCYCH SIĘ POZIOMEM PYŁU ZAWIESZONEGO W POWIETRZU

**Streszczenie**. Pył zawieszony (PM) należy do najniebezpieczniejszych zanieczyszczeń wdychanych przez człowieka. Aby obniżyć jego stężenie w powietrzu, można użyć roślin jako biologicznych filtrów akumulujących PM na powierzchni liści lub stabilizujących je w woskach. PM ma negatywny wpływ na aparat fotosyntetczny, ale nie ma badań oceniających wpływ PM na różne gatunki. W pracy tej badano ilość akumulowanych PM i deponowanych wosków na powierzchni liści oraz sprawność aparatu fotosyntetycznego u pięciu gatunków roślin rosnących w dwóch lokalizacjach różniących się poziomem PM. Uzyskane wyniki pokazały, że rośliny rosnące w centrum miasta charakteryzowały się większa akumulacją PM i wosków oraz obniżeniem sprawności aparatu fotosyntetycznego. Negatywny efekt PM na aparat fotosyntetczny wyrażał się obniżeniem: (1) zawartości chlorofilu, (2) parametrów fluorescencji chlorofilu *a* oraz (3) intensywności fotosyntezy, co korespondowało z podwyższonymi oporami dyfuzyjnymi aparatów szparkowych. Wśród badanych gatunków tawlina jarzębolistna (*Sorbaria sorbifolia*) okazała się najlepiej zaaklimatyzowanym gatunkiem do warunków miejskich i najbardziej efektywnym w fitoremediacji PM z powietrza.

**Słowa kluczowe**: Pył zawieszony (PM), wymiana gazowa, zawartość chlorofilu, fluorescencja chlorofilu *a*

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