Model research on the influence of green roofs on environmental parameters in urban agglomerations

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Abstract. This study presents features of green roofs in urban areas with a particular emphasis on the filtration of air pollutants, heavy metals removal, reduction of rainwater runoff from roof surfaces and thermal insulation. To carry out field studies on the influence of green roofs on the environment in urban areas, two green roof models on a laboratory scale were used. The observations of the prepared green roof models made during the summer, autumn and winter confirmed the extremely beneficial effect of this type of roof for the elimination of air pollutant, heavy metals, and particulate matter. The observations also confirmed that plants on a green roof growing on a soil layer absorb an average of 74% of rain water and then allow it to evaporate. The selection of plants for green roofs should mainly focus on how effectively they improve urban environmental parameters and remove air pollutants. The results of the study of the two green roof models on a laboratory scale are necessary to work out the parameters of layers of the roof and select the most appropriate plants for the reference research object on the roof of one of buildings of the University of Opole.

1 Introduction

In recent years, there has been a clear deterioration in air quality in the centres of Polish cities. This is due to several factors, among which the most important are the local heating systems using solid fuels, and the intensively increasing car traffic in urban agglomerations. To counteract the further deterioration of air quality, different actions are taken. In addition to limiting the above mentioned pollution, it is possible to improve the environmental parameters in urban agglomerations by increasing the biologically active areas [1,2]. Unfortunately, due to the rapidly growing prices of land in city centres, it is difficult to markedly increase the share of biologically active spaces in urbanised areas. It is therefore worth noting the roof areas of buildings that can be converted into biologically active areas. This is possible due to the implementation of green roofs, i.e. layered surfaces of flat roofs planted with vegetation [3,4]. Green roofs can only be made on roofs with an inclination of 2% to 30% [5]. Green roofs can be used for recreational purposes, but it should also be

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noted that the vegetation used on the surfaces of the roofs has an impact on the quality of the environment in strongly urbanised areas. Depending on the type of use, structural factors, and maintenance requirements, green roofs are usually divided into extensive, intensive or semi-intensive roofs [6]. A diagram of the layers of the green roof (extensive and intensive types) is shown in figure 1.

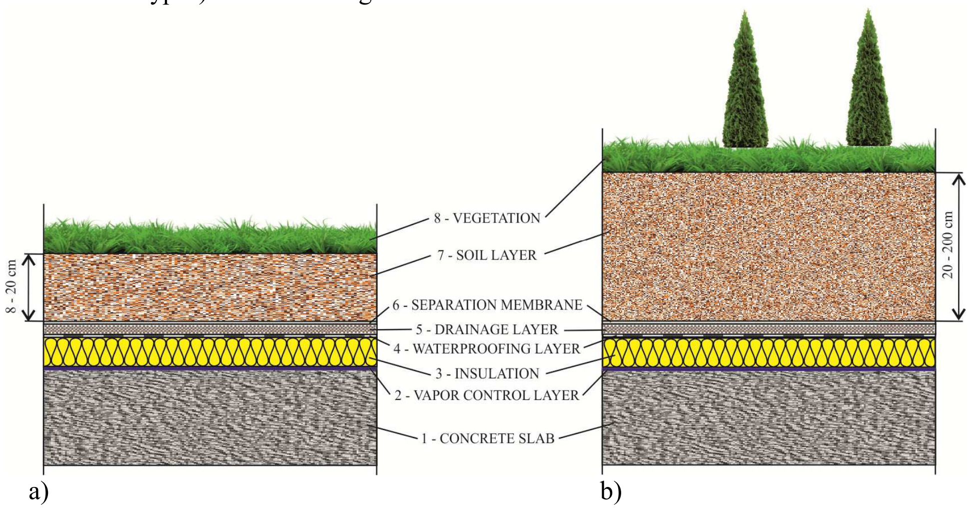

Fig. 1. Diagram of the layers of the green roof: a) extensive, b) intensive.

Extensive roofs with a soil layer thickness of 8 to 20 cm are mainly planted with the sedum, as well as with grasses, and bryophytes. On intensive roofs, where the soil layer is between 20 and 200 cm thick, perennials, shrubs, and even trees can also be planted (this type of roof is most often used for recreational purposes) [7,8].

Numerous researchers stress the impact of green roofs in city centres on not only the architectural values of the urban landscape, but also on the environmental parameters of the surrounding areas. This mainly applies to air pollution filtration, the removal of heavy metals, the reduction of rainwater run-off from roof surfaces and the prevention of urban heat islands [9].

The selection of parameters for green roofs should focus on how to effectively improve urban environmental parameters and eliminate gas and particulate matter. The roughness of grasses, twigs and leaves makes plants used on green roofs a very effective tool for capturing particulate matter from the air [10].

For the purpose of the future long-term field studies into the impact of the green roof on the environment in urban areas in Poland, it is necessary to create a research object – a garden on the roof of one of the university buildings located in the centre of Opole.

The paper presents the research results of model green roofs on a laboratory scale which are essential in defining the parameters for each layer of the roof, and for selecting the most favourable plant species for the planned research roof on one of the buildings of the University of Opole.

2 Materials and methods

Many researchers, in their experiments, use only model soil layers with vegetation, soil layers with the drain layer, or models of soil layers only [11, 12]. In view of the impact on the environmental parameters in urban agglomerations, for the optimal selection of parameters of each layer of the reference roof and the species of the plants, two model green roofs were made on a laboratory scale (as shown in fig. 2.), set on the balcony located on the top floor of a building located in the centre of the city of Opole. The constructed models accurately represent the actual structures of green roofs and contain all the layers: for model 1 in extensive roofs, and for model 2 in intensive roofs.

Fig. 2. Laboratory models of green roofs: 1 - extensive roof model, 2 - intensive roof model.

Both models were made in glass tanks measuring 35 x 80 x 40 cm for model 1, and 55cm for model 2, and reinforced with a frame of steel angles. The tanks were inclined at an angle of 5% to the level to better reflect the rainwater flow through the roof layers. For both models, the first layer was made of C16/20 class concrete. Then the hydro insulation layer was made in the form of PVC membrane. The next layer was thermal insulation made of polystyrene (in the model 1 - a layer of 8 cm thick extruded -XPS, and in the model 2 – a layer of 10 cm thick expanded - EPS). The thermal insulation was protected with another layer of hydro insulation membrane. Drainage layer was made: for model 1, in the form of drainage pipe, and for model 2, in the form of 2 cm layer of gravel fraction of 1-1.5 cm (allowing excess rainwater to the vertical discharge pipe). In both cases, the drainage layer was protected with an anti-rooting filter membrane made of polypropylene filter fabric. A drainage pipe was laid from the drainage layer to the bottom of the model, allowing rainwater to be drained from the model to the measurement tank. The soil layer was made of silt and clay soil mixtures with the addition of organic material. In model 1, the soil layer which was a mixture of peat and clay soil was 18 cm thick, while in model 2 it was made from a mixture of 50% of silt soil and 50% of clay soil, with a total thickness of 30 cm. The soil layer compositions in both laboratory models were made according to the author's personal idea. In future studies, to be carried out at a reference research facility, the soil layer is to be constructed according to the recommendations of the German Landscape Research, Development and Construction Society (FLL) and DAFA (Association of Flat Rooftops and Façades Contractors) [13]. The following were used for vegetation: for model 1 - grasses (*Poaceae*) and bryophyte (*Bryophyta*), while for model 2 - grasses (*Poaceae*), perennials (*Herba perennis*) and sedum (*Sedum*). These particular plant species were selected for their frequent use in green roofs [14].

Such research models will be used to analyse the impact of various green roof solutions on environmental parameters, such as gaseous and particulate matter, rainwater management and the urban heat island phenomenon [15].

Research on the green roof models was conducted from April 2017 to March 2018, by observation of the models throughout all seasons of the year. The sample plants were examined (grass, bryophytes and sedum), taken from both models in order to analyse their heavy metal contents - Cu, Pb, Ni, Mn, Zn, Fe. Soil samples from the models were also studied in order to determine the accumulation of contaminants in different soil mixtures used on green roofs and with different plants used. The samples of plants and soil were collected from both model green roofs every three months for a period of one year. The analysis of the heavy metal content in the samples was made by the AAS method. The dried samples of plants and soil (0.4 g) were mineralised. For this purpose, the dried plant samples and separately 3 cm^3 of soil were sunk in 65% nitric acid, and then heated to 120ºC and left for 4 hours. The samples were then filtered and the filtrate poured into volumetric flasks and topped up with distilled water to a volume of 20 cm^3. In such prepared solutions the heavy metal content was determined by way of an absorbent nuclear spectrophotometer.

The volume and composition of the rainwater filtered through the layers of the roof green was also studied. The total phosphorus and total nitrogen were measured, as well as the pH of the waters drained by the model drainage systems. The total phosphorus and total nitrogen were determined using the spectrophotometric method. The pH of the rainwater and the drain water of the model roofs were measured using a PH VOLTCRAFT-100 pH-meter. During the tests, precipitation was also recorded at the locations of the green roof models in order to determine the percentage of rainwater retained by the green roofs in the proposed design. Precipitation was measured with a self-registration rain meter, and water drainage from the models was measured with the use of 1 dm^3 tanks, placed under both models.

Using a thermal imaging camera, experimental studies of heat transfer through green roofs of various designs were carried out. Observations with the use of a thermal imaging camera of the heating of the surface of green roof models in the event of high sun exposure were also aimed at determining the effect of green areas in urban areas in the occurrence of the urban heat island phenomenon [16].

Analyses of particulate matter retention (PM2.5 and PM10) by plants and soil on the green roof were also performed, based on analyses conducted by various researchers [17-19]. Throughout the whole period of research, particulate matter was measured at the location of green roof models using a Holdpeak 5800D particulate matter meter.

3 Results

Throughout the whole period of research, rainfall was recorded and the average rainfall for each month was determined (dm^3·m^{-2}). At the same time, the total volumes of runoff were recorded for both models of green roofs. The monthly values of precipitation and total runoff from the model roofs are presented in fig. 3.

Summed up over the period of measurement (from April 2017 to March 2018), 628 m^3/m^2 of precipitation was retained by the plants and the soil layer at an average rate of almost 74%. In the case of model 1, the total outflow during the entire testing period was 174.6 m^3/m^2, while in the case of model 2 - 164.4 m^3/m^2. During the tests, daily outflows from green roof models were also recorded in the case of sudden and torrential rains.

The retained water is used by plants for the growth of biomass, and in large part it also evaporates. The graph in fig. 3 shows that the larger volumes of water are retained in the period of strong growth of the plants, and also at times of higher average monthly temperatures.

In the case of short-term rainfall, almost 100% of rainwater was retained by the plants and the soil layer of the green roof. The studies of runoff on the two models confirm that the impact of both the soil and the plants growing on the green roof significantly reduce the volume of runoff, which always follows torrential rains and storms. It also helps to reduce the large volumes of rain water which is discharged to the sewer in highly urbanised areas.

By comparing the volume of runoff from both models of green roofs, it was also possible to conclude that the drainage layer solution applied in a given model of green roof does not significantly affect the reduction of rainwater runoff. During the studies, it was also observed that, compared to the application of plant monocultures, the use of various species of plants in green roofs increases the reduction of runoff.

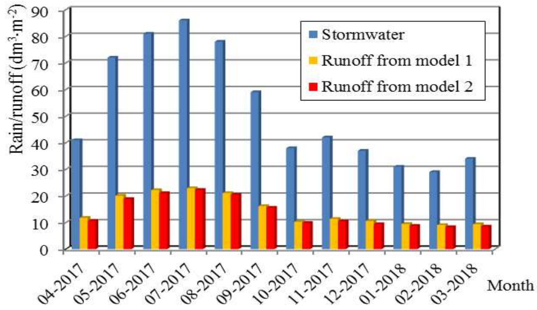

Fig. 3. Monthly values of precipitation and monthly volumes of runoff for the two models of roofs.

Determined throughout the whole experiment, the average nitrates and phosphates concentrations in the runoff from the two roof models are shown in table 1.

Table 1. The average concentrations of nitrates and phosphates in runoff.

Research objects	**Nitrates concentrations**		**Phosphates concentrations**	
	average [mgN·dm^{-3}]	standard deviation	Average [mgP·dm^{-3}]	standard deviation
Model 1	0.331	0.272	0.216	0.363
Model 2	0.372	0.214	0.238	0.376

The different concentrations of nitrates and phosphates in runoff in various months of the year are closely correlated with the periods of growth of different plants used in the two models of roofs. This is evidenced by significant standard deviations in the measurements of concentrations, which indicates a high fluctuation of concentrations - higher for phosphates than for nitrates.

In the course of studies, the pH level was measured, both for the rainwater and for the runoff from the model roofs. The values of the pH measured, determined over the duration of the studies conducted are shown in table 2.

Table 2. The pH of the rain water and the runoff from the two models of roofs.

pH	**Minimum**	**Average**	**Maximum**
Rain water	7.3	7.5	7.9
Runoff from model 1	7.9	8.2	8.6
Runoff from model 2	7.8	8.1	8.5

After completion of the whole test cycle, it was observed that the pH of runoff waters from the green roof was higher than that measured in rainwater collected in the rain meter. This proves that the acidity of rainwater decreases when it flows through the soil layer of the green roof. This confirms the results of the studies carried out by numerous researchers who stress that an increase in the pH value of the green roofs runoff can be of particular importance in areas where acid rain occurs [8,20-21].

The examination of plants samples taken in the course of the study from both roof models helped in determining the variability of heavy metal content - Cu, Pb, Ni, Mn, Zn, Fe. Plants and soil were sampled from both roof models every 3 months. The content of selected heavy metals was determined for the samples taken. The graphs of heavy metal content variability in soil and in plants sampled from both roof models are shown in Fig. 4.

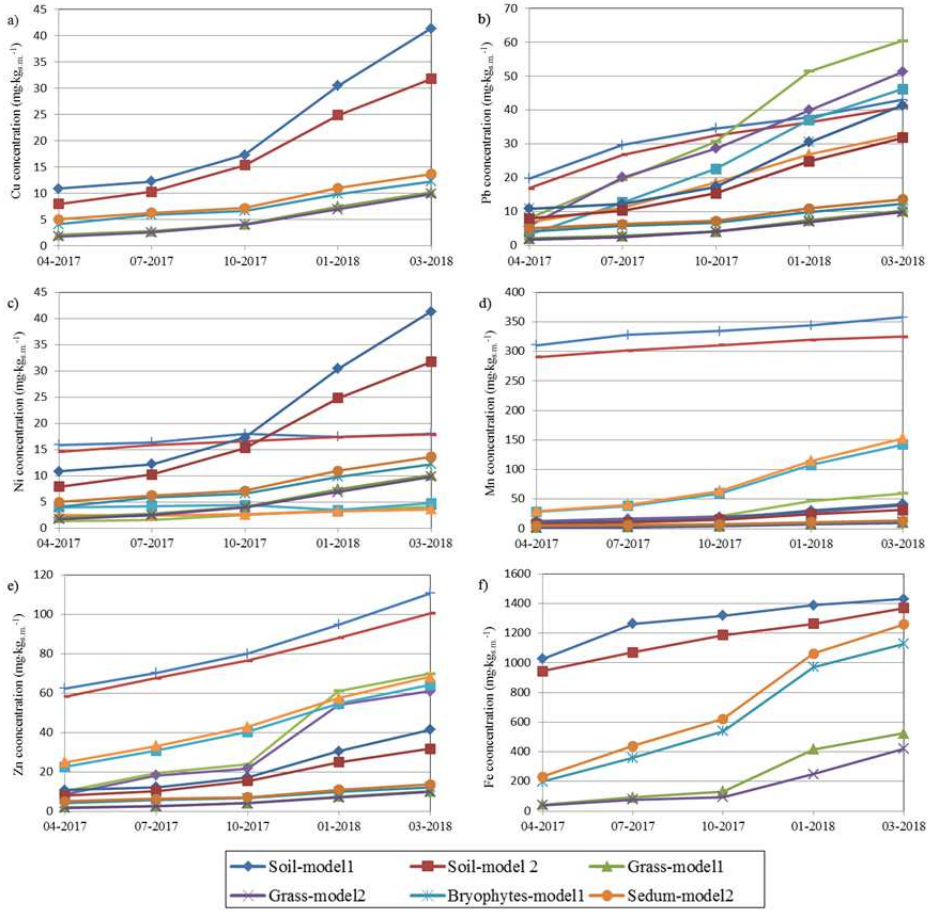

Fig. 4. Graphs of heavy metal content variability in soils and plants sampled from the roof models in the study: a) Cu, b) Pb, c), d) Mn, e) Zn, f) Fe.

As can be seen from the graphs in Fig. 4, a higher accumulation of heavy metals is present in the soil layer of the models than in the plants growing on its surface. Therefore, a decision was made that during further studies of the models, the content of heavy metals in the runoff flowing out of the models should also be examined in order to determine the share of metals accumulated in the soil layer that is washed away by rainwater.

It was also observed that the highest accumulation of lead was found in grass, whereas in the case of other heavy metals the best accumulation properties were observed in stonecrop and bryophytes. Therefore, when planning a full-size reference roof in the future, it is necessary to ensure biodiversity of the plants used in the vegetation layer of the roof.

Further studies are planned on the accumulation of heavy metals in the soil layer and the plants used in green roof models. Further research will also measure heavy metal content in the runoff from the roof models and in the ambient air.

The studies carried out with the use of a thermal imaging camera in the summer of 2017 confirmed the high thermal insulation power of the green roof. It was also found that the surface heating of green roof models was lower than in the case of ceramic or bituminous materials. This is due, among other things, to the fact that a part of the solar radiation energy (reaching the roof surface) is used to evaporate water from the ground layer and the plants growing on it. Example photographs of the green roof models taken with a thermal imaging camera taken at the ambient temperature of 34°C are shown in fig. 5.

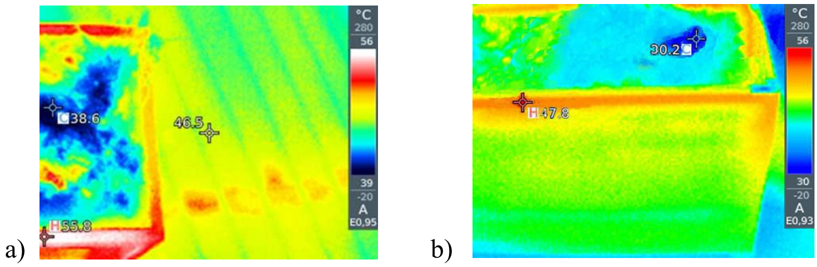

Fig. 5. Examples of thermal images of the green roofs : a) model 1, b) model 2.

As can be seen from the infrared photos, the concrete roof slab was heated to 46.5°C, the roof frames made from steel were heated to 55.8°C, while the vegetation layer on model 1 had an average temperature of 41°C, while the vegetation layer on model 2 had an average temperature of 39°C. This temperature is not much higher than the temperature of the air, so during the night the green roofs in city centres will not increase the effect of the urban heat island. In order to precisely determine the influence of the green roof on the effect of the urban heat island, it will be necessary to determine the emissivity of roofs covered with various plant species. Some authors report emission values for green roofs in the range of 0.9 - 0.95 [22]. Follow-up studies on the two green roofs models are planned in order to determine the value of the heat emissivity for different plant species.

During the experiment, particulate matter (PM2.5 and PM10) was measured in the location of the green roof models. The average monthly pollution with particulate matter PM2.5 and PM10 in the location of the green roof models is shown in fig. 6.

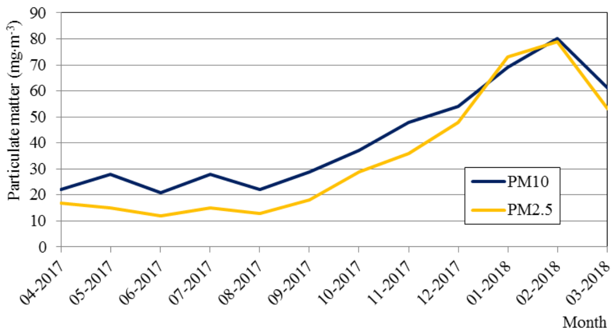

Fig. 6. The average monthly pollution with particulate matter.

The results of measurements of particulate matter in the area of the green roof models confirmed the observations of other researchers [19], that the roughness of biologically active surfaces (especially after rainfall) intensifies the reduction of the concentration of particulate matter PM2.5 and PM10. Research will be continued to precisely determine the impact of various types of plants on the reduction of particulate matter contamination. This is particularly important during the winter months, when (as shown in Fig. 6) contamination with particulate matter is particularly high.

4 Summary

Observations of the two green roofs models carried out over a full annual cycle confirmed the very positive effect of this type of roof on the elimination of air pollutants, including heavy metals and particulate matter in urban agglomerations.

In the course of the research, it was determined that the reduction of rainwater runoff from the surface of the green roof models reaches a maximum value of 74% of precipitation by volume. The value of the reduction of the runoff is not affected significantly by the solution of the drainage layer used in the green roofs models.

The green roof runoff can be contaminated with compounds of nitrogen and phosphorus. Contamination with nitrates and phosphates in runoff waters mainly results from pollutants washed out from the soil layer of the green roof and directly depends on the composition of the mixture of which it is made and also on used plants.

Graphs of heavy metal content variability in soils and plants sampled from both models during the full annual cycle clearly indicate the accumulation of these metals in the soil substrate layer and in plants used in green roof models, with a higher accumulation of heavy metals being observed in the soil layer of the green roof than in plants growing on its surface. It was also observed that the highest accumulation of lead was found in grass, whereas in the case of other heavy metals the best accumulation properties were observed in stonecrop and bryophytes. Therefore, when planning a full-size reference roof in the future, it is necessary to ensure biodiversity of plants used in the vegetation layer.

The research carried out on two models of green roofs, prepared on a laboratory scale, resulted in the preparation of a research plan, which will be continued at the reference research facility made on the roof of one of the buildings of the University of Opole.

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