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Review

The Impact of Green Roofs on the Parameters of the Environment in Urban Areas—Review

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Abstract: This study presents the results of a review of publications conducted by researchers in a variety of climates on the implementation of 'green roofs' and their impact on the urban environment. Features of green roofs in urban areas have been characterized by a particular emphasis on: Filtration of air pollutants and oxygen production, reduction of rainwater volume discharged from roof surfaces, reduction of so-called 'urban heat islands', as well as improvements to roof surface insulation (including noise reduction properties). The review of the publications confirmed the necessity to conduct research to determine the coefficients of the impact of green roofs on the environment in the city centers of Central and Eastern Europe. The results presented by different authors (most often based on a single case study) differ significantly from each other, which does not allow us to choose universal coefficients for all the parameters of the green roof's impact on the environment. The work also includes analysis of structural recommendations for the future model green roof study, which will enable pilot research into the influence of green roofs on the environment in urban agglomerations and proposes different kinds of plants for different kinds of roofs, respectively.

Keywords: green roof; environment; urban areas; urban heat island; air pollution; rainwater; roof insulation; plants; noise reduction; modeling

1. Introduction

Over the last 10 years, Poland, as well as all Central and Eastern Europe have experienced extreme weather phenomena, such as hurricane winds or cyclones, which are unusual for the local climate there. This is related to increasingly visible climate changes, causing, for instance, higher average monthly temperatures, longer periods of dry weather (causing steppe formation of soil), followed by torrential rains or violent storms [1,2]. Such climate changes may be caused by intensive forest management (e.g., deforestation), land use changes in agriculture, irrigation, and drainage, regulation of streams and rivers, as well as a reduction in biologically active areas [3–6]. Another factor affecting the parameters of the environment is an intensive economic development of Central and Eastern Europe (following the political changes), which has resulted in an increase in energy demand (both by industry and households). Due to the fact that the power industry in post-communist countries uses mainly hard coal and lignite, air quality is seriously deteriorating. This has been very clearly visible over the last 25 years, with an increase in concentrations of PM2.5 and PM10 particulate matter in urban areas during the heating season (from the beginning of October to the end of April) [7]. Increasing air pollution is particularly harmful in heavily urbanized areas. As the urban agglomerations develop fast in Poland and other European countries, the biologically active areas grow more important for the quality of the urban environment. Taking into consideration the rapidly rising prices of land in city centers, it is worth noting that the vast surfaces of rooftops can make a location for biologically active areas. This solution has been used in some parts of Europe for hundreds of years—turf roofs were used to protect the interior of a building from weather conditions. Since the mid-20th century, there has been a rise in interest in rooftop vegetation, but at present it should be emphasized that green roofs are an important issue, not only in architecture or construction. They are very beneficial for the environment in which the buildings are located. However, to an average Polish person the notion of a green roof would most often be either completely unknown or rather associated with the color of the roofing.

In order to determine the impact of green roofs on the reduction of pollution in urban areas, it is necessary to develop mathematical models that take into account the degree of reduction of various types of environmental pollution and nuisances in the city. Such a model should determine the following: Reduction in gaseous and particulate pollutants (as the most burdensome in the cities of Central and Eastern Europe), reduction of the urban heat island effect, and sustainable rainwater management taking into account the area of green roofs in the city and coefficients determined experimentally. When developing the model, the coefficients of the green roof impact may be used to change various parameters of the quality of the environment as presented in scientific publications or determined during laboratory and field research for specific climatic conditions.

The authors posed a question of whether the research results presented thus far in the publications indexed to the web of science allow creating a comprehensive model of air quality improvement in cities (in the climate of Central and Eastern Europe) through the use of increased green roof area. Such a model should help to determine the degree of reduction of the most important indicators of environmental pollution (gaseous and particulate) depending on the surface of green roofs and vegetation used.

Therefore, a decision was made to review publications on green roofs, which are indexed in the web of science database, in order to assess the impact of this solution on the environment in urban areas. When analyzing the results, particular attention should be paid to their relevance to the climatic conditions of Central and Eastern Europe. This will help to formulate model dependencies and thus determine the total area of green roofs for any location in the analyzed area, which in turn will lead to improvement in the quality of the environment in urban areas. It is essential to determine whether it is possible to use the already determined coefficients of the impact of green roofs on individual parameters of the environment, or whether it will be necessary to conduct laboratory tests in order to determine the coefficients for the specific local conditions within the selected area of Europe.

2. Review of Publications Indexed in the Web of Science

2.1. Method of the Publication Review

The review of the literature was based on publications indexed to the web of science. Advanced search tools were used, and the search terms selected were "green roof", "green facades", etc. The very first search results showed that publications on green roofs began to appear towards the end of the 1980s. For that reason, only the period of the last 30 years, i.e., 1989–2018, was taken into account in the further search for publications. Over 2400 articles, conference proceedings, and chapters in monographs were found. Due to language limitations, an attempt was made at reviewing the works published only in English (about 2370 articles). The authors managed to access almost 70% of the full texts of the publications they were interested in. During the review, it was found that the subject matter of the presented research could be divided into 7 thematic groups, which will be presented in detail in Section 2.2. Given the limitations in the space of this article, only 100 publications were selected (listed in the Bibliography): Representative examples of the results of experimental research conducted around the world, computer simulations, and review articles.

2.2. Results of the Publication Review

Prior to analyzing the impact of green roofs on the parameters of the environment in urbanized areas, first, the concept of the green roof needs to be clearly defined. According to many sources [8–14], the term green roof is to be understood as an open overgrown surface on a multilayer ceiling of a building. Green roofs can only be made on flat or low-slope roofing pitched 2–30%. Depending on the use, construction factors and maintenance demands, green roofs are classified as: Extensive, intensive, and semi-intensive [15]. Extensive green roofs are thin-film systems, typically low weight, and are characterized by low maintenance demands. Intensive roofs, however, have a thick layer of substrate suitable for almost all types of plants and can be used for recreation and other purposes [16–19].

In recent years, there have been a lot of publications on green roofs. According to the web of science, more than 2400 articles, reviews, book chapters, and proceedings papers on green roofs have been published in the last 30 years (1989–2018). The graph in Figure 1 shows a marked increase in interest in research on this issue in the last 10 years, which is clearly reflected in a steady rise in the number of publications.

In the last 30 years, the largest number of research projects, with the resulting scientific publications, has been carried out in the United States (over 20% of all globally published works). The percentage share of scholarly publications in various countries of the world is presented in Figure 2.

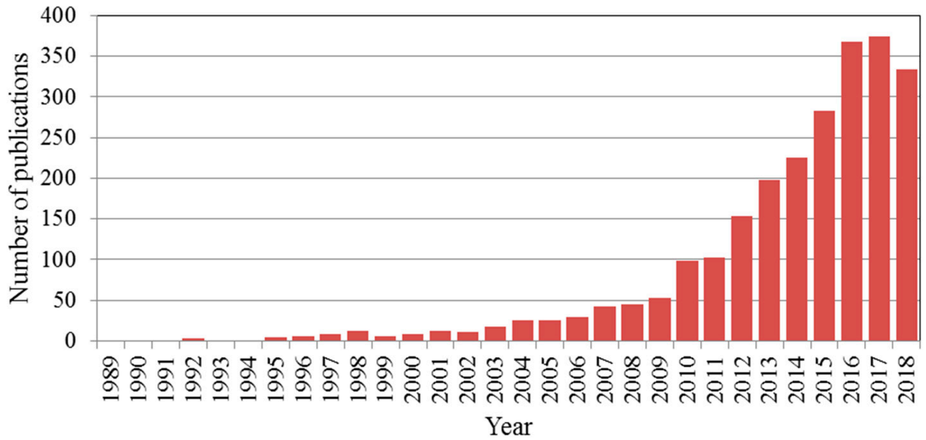

Figure 1. Number of publications on green roofs indexed on the web of science.

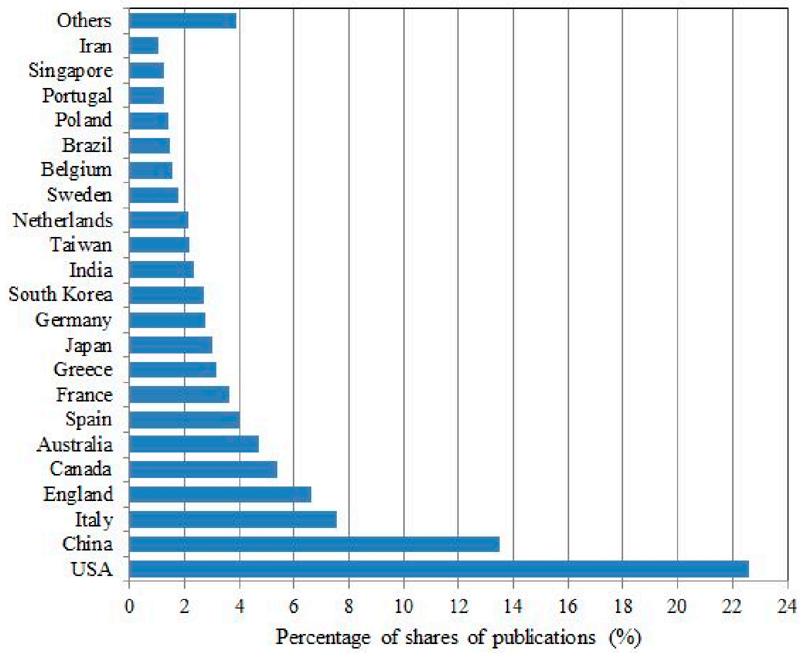

Figure 2. Percentage of academic publications by country.

It needs to be noted that the bar marked as 'Other' included a total of 64 countries, where in total 3.89% of publications on green roofs were made between 1989 and 2018, and none of these countries produced more than 1% of all world publications. The analysis of the individual continents shows that most publications were issued in Europe (37.84%), followed by Asia (29.11%), North America (24.93%), Australia (4.72%), and South America (2.49%), with the lowest number of publications in Africa (0.91%). These numbers should be considered in relation to the differences in climate and vegetation used on green roofs across continents. However, in Central and Eastern Europe (including Russia), only 4.28% of the publications were made, which constituted a small proportion of the European publications. The same applied to review articles, which were mainly based on publications covering the results of research conducted in the US, Western Europe, and Asia. Hence, the authors noted the need to analyze the results obtained in different regions of the world and the possibilities of using them in specific climatic conditions of the central-eastern part of Europe. Publications on green roofs were easily available as 97.23% of the research papers were in English, while just single papers were published in other languages (except Spanish—0.92%, and German—0.38%).

Given the current condition of the environment in urbanized areas of Central and Eastern Europe, more attention should be drawn to the impact of green roofs on the environment quality parameters in cities and to the popularization of this type of roofing solution in both residential and public buildings. It is also essential to extend the scope of research (in the geographic and climate conditions of Central and Eastern Europe) into the vegetation that can be used on roofs, the preservation of roofs in winter, and the resistance of green roofs to stress conditions (torrential rains, periods of drought or strong environmental pollution).

It is also worth noting that several authors have published results of simulations of model behaviors of green roofs [4,20–23]. The adequacy of mathematical models depends strongly on coefficients (frequently determined through experiments), which are characteristic for a specific climate, type of vegetation, or composition of soil layer used on the roof. Due to the fact that most publications are related to laboratory tests or experiments carried out on existing green roofs, the results very often reflect the impact of the environment on the green roof (and vice versa) in specific climatic conditions and a location of research facilities. The results obtained in South-East Asia or in the Southern United States do not relate directly to the conditions in Central and Eastern Europe. There are also significant climate differences between the Mediterranean Basin and Eastern Europe. Therefore, drawing on the methodologies used by various authors in their research, it is essential to plan experiments which will allow for laboratory or field studies to be carried out to determine the impact of green roofs on the quality of air parameters in urban areas specific to the aforementioned part of Europe.

3. Results: Features of Green Roofs in Urban Areas

The results of the different authors' research published in the analyzed articles on the impact of green roofs on the parameters of the environment in urbanized areas have been divided into 7 groups: Thermal effects, drainage of rainwater, architecture and construction, plants (flora), noise reduce, air pollutions elimination, and others [24]. A significant proportion of these publications present test results for single case studies. However, a small number of publications provided proposals for mathematical models of the impact of green roofs on single parameters of the environment. Review articles also constituted a small share of the publications.

Some of these thematic groups were directly related to the green roof layers. Figure 3 shows an example diagram of a green roof with marked layers. The green roof structure consisted of many layers, including a thermal insulation layer (3), a waterproofing layer (2,4), a drainage layer (5), and a soil substrate (7) allowing the plants to grow on the entire area, or a part of the roof surface.

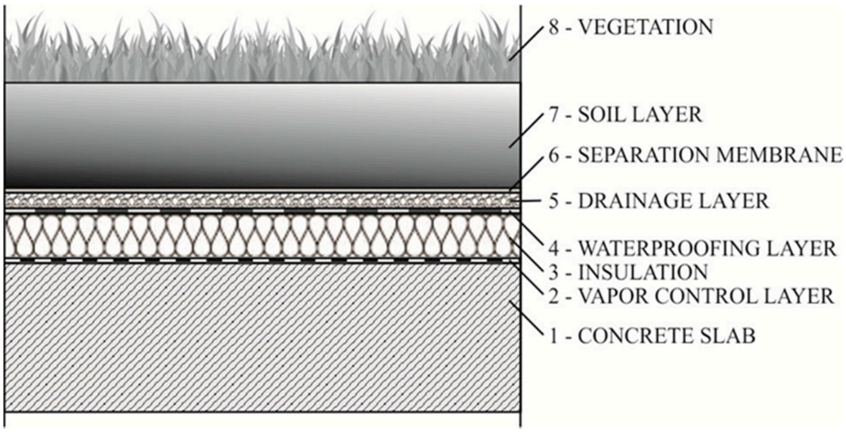

Figure 3. Green roof construction diagram.

Table 1 presents the proposed thematic breakdown of academic publications on green roofs (into 7 thematic groups)—indexed in the last 30 years on the web of science—together with the percentage share of publications covering the particular thematic groups.

Table 1. Subject area of green roofs discussed by various authors.

Item	Subject Area	Research Conducted	Tied to the Roof Layer (as Per Figure 3)	Percentage Share of Publications
1	Thermal effects	Thermal insulation, roof surface heating, elimination of the "urban heat island" effect.	1, 3, 7	45%
2	Drainage of rainwater	Reduction of rainfall runoff, storage of rainwater, humidity in the roof vicinity, filtration of rainwater pollution.	4–8	18%
3	Architecture and construction	Recreational functions of the roof, durability of the roofing, moisture insulation, roof drainage solutions, thickness, and composition of the soil layer.	1–8	11%
4	Plants (flora)	Selection of plants for specific growing conditions, CO_2 absorption, O_2 emission, animal habitats, transpiration, and evaporation, biodiversity in urban areas.	7, 8	7%
5	Noise reduction	Sound insulation of the building interior.	1, 3, 7, 8	5%
6	Air pollutants	CO_2 absorption, suspended particulates capturing, accumulation of heavy metals.	7, 8	5%
7	Others	The costs of a green roof construction and operation, recreational facilities, fire protection, and other related issues.	1–8	9%

Despite the proposed classification of publications into 7 thematic groups in Table 1, it should be emphasized that most of the publications on green roofs are interdisciplinary as they pertain to different structural layers of the roof and often combine the issues of life sciences, environmental engineering, or construction. In spite of the common research areas (e.g., thermal effects, or plants), the studies are conducted in conditions typical of different locations (latitudes) and in the different local climates, and thus they focus on different functions of the green roof, or different species of vegetation used.

In addition to the number of publications on green roofs, this review shows the results of research focused primarily on the impact of this type of roofing solution on the quality of the environment in urban areas. The explanation of the particular areas of impact of green roofs on the city environment was supported by examples of research results from the most representative publications for a given research subject. Publications from climatic zones other than the analyzed region of Europe have been selected as examples in order to substantiate the necessity of determining the impact coefficients characteristic for the area of future model research. A few examples of publications presenting the results of research carried out in Central and Eastern Europe were also given, but they constituted a small proportion (4.28%) of global publications on the impact of green roofs on the environment in urban areas.

3.1. Drainage of Rainwater

Urbanized areas typically have a very low permeability to rainwater. This becomes a serious problem during periods of torrential rains, storms, or snow melting as the drainage systems become inefficient for the peak volumes of runoff in a short span of time. Unfortunately, large areas of impermeable surfaces and high prices of land render the creation of green areas very expensive or virtually impossible [25,26]. Green spots on roofs can offer the solution, for they can absorb and partially evaporate precipitation and thus reduce the discharge of large amounts of water into the sewage system [25–29]. Plants on the green roof growing on the porous substrate absorb rainwater and then evaporate it. The ground also retains some precipitation water, which slows down the discharge of water into the sewage system. Both the substrate and the plants significantly reduce the peak volume of the runoff occurring after heavy rain and storms [28,30]. The test results have, therefore, shown the roof to act as a buffer delaying high peak flows into the drainage system. Studies conducted in the US between 2007 and 2009 on 11 model surfaces showed an average of 63% slowdown and runoff reduction compared to traditional surfaces and in the summer months, even 70% up to 93% [29]. In the case of light rain, green roofs can reduce runoffs up to 100% during 2.5 mm rainfall and up to 45% during rainfall above 15 mm [31]. However, it should be noted that the moistness of the substrates immediately before the onset of rain significantly affects the retention of water, thus it is very important to choose a suitable roof drainage system [26].

Many studies (including the models under development) focused on the process of water evapotranspiration from the vegetation layer and the soil layer. However, most of these studies were conducted under climatic conditions very different from those in Central and Eastern Europe. Experimental studies were conducted in Australia [32], Hong Kong [33], Israel [34], Japan, [35], Singapore [26], or the United States [36]. Therefore, the proposed equations describing the evapotranspiration process and their coefficients cannot be directly used in model studies of rainwater management on green roofs located somewhere in Central and Eastern European countries, e.g., in Poland. Therefore, experimental studies should be conducted for soil mixtures and vegetation used on green roofs in climatic conditions typical of Eastern Europe in order to determine the coefficients characterizing the evapotranspiration process, rainwater accumulation, or the amount of water drained through the drainage layer. At this stage, the results of stormwater management studies conducted in Europe can be used [37–39].

What needs to be noted is the improved quality of the green roof runoff. This effect can be achieved by selecting the appropriate type of soil substrate, the vegetation layer, as well as through the use of appropriate plants, suitable for the local climatic conditions [29]. The green roof generally acts as store-pollutants accumulate in the substrate layers and are only released at high tide. Due to evaporation, some of the components, which are dissolved in soil water, bind with the soil or sediment in the drainage layer [26]. The quality tests of water drained from green roofs were most often based on measurements of total phosphorus and total nitrogen.

Green roofs can reduce pollution of urban rainwater by filtering out and absorbing pollutants, but they might also release pollutants from soil, plants, and fertilizers into water. The quality of runoff water from the green roof depends on its construction, plants type, roof age, as well as the nature of the surrounding area and the local sources of pollution [40,41].

The results of the studies outlined in the publications imply the need for further research into the green roof impact on the volume of pollution in water drained off its surface. Future research should focus on the roof layers (thickness and materials used), namely the thickness and kinds of substrate layers, and on the care of the roof plants (e.g., fertilization), especially in the intensive green roofs [27]. Further research should also analyze how the retention of rainwater by plants and the soil layer of a green roof affects the relative air humidity in the vicinity of the building during rain-free periods.

3.2. Thermal Effects

One of the best-documented phenomena related to climate change was the occurrence of the so-called urban heat island (UHI) [42]. This means higher air and surface temperatures in urban areas, especially at night-time, compared to the temperatures in suburban and rural areas [43,44]. This phenomenon occurs in particular when the biologically active surfaces are replaced by concrete, stone, or bituminous materials. The temperatures of biologically active areas rise in a moderate manner due to the evaporation of water contained in soil and plants as well as due to the shade, while other objects in urban areas easily absorbed sunlight energy during the daytime and emit thermal energy at nighttime [42,43]. The urban heat island effects can cause health problems such as transient thermal fatigue, heat rash, fainting, and respiratory contractions. This is due to the loss of large amounts of water through perspiration, and possible excessive salt depletion. High temperatures in urban areas cause an increase in power demand for air conditioning systems by almost three times, but at the same time, their efficiency drops by about 25% [43,44]. Absorption of solar radiation and heating up of traditional roof surfaces can be minimized by the use of plants on the green roof [43–53].

The preliminary observation of the green roof model (constructed as outlined in Section 4 following the analysis of the laboratory models used by other researchers) carried out with the thermographic camera over the summer months confirmed outstanding benefits of this type of roof construction to ameliorating the adverse effects of the urban heat island. An example green roof model image made with a thermographic camera at an ambient temperature of 34°C is shown in Figure 4.

As the infrared image shows, the temperature of the concrete roof slab (marked as 2 in Figure 4) is rising to 46.5 °C, and the temperature of the roof frame made of steel (marked as 3 in Figure 4) is rising to 55.8 °C. The vegetation layer on the green roof (marked as 1 in Figure 4) has an average temperature of 39 °C. This is not much higher than the air temperature, thus at nighttime, it does not exacerbate the urban heat island effects. The choice of materials whose temperature was measured in the image was made on the basis of their occurrence in urban areas in Central and Eastern Europe. Concrete is a common material in manufacturing pavers used on the surfaces of roads and footpaths, and also quite common in flat roofs; steel and aluminum are the preferred materials in urban infrastructures, such as fences, railings, road signs, elements of traditional roofs, e.g., flashings, or ventilation chimneys.

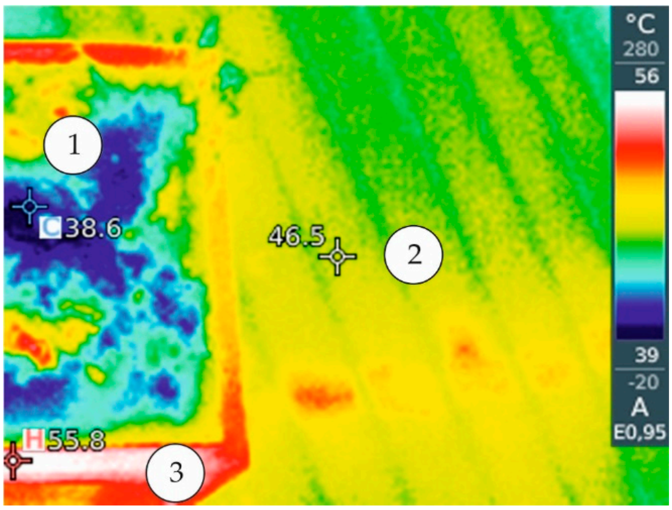

Figure 4. An example image of a green roof model made with a thermographic camera (A—automatic temperature scale, E—emissivity).

Analyses of urban areas with the most representative buildings in Central and Eastern Europe are, therefore, to be carried out using geographical information systems (GIS) in order to identify the areas made of different materials and to determine the roof area for the future green roof construction [54,55]. Such information will make it possible to model the influence of green roofs on the reduction of the urban heat island effect by determining the area of a specific temperature (depending on the material it is made of).

The green roof also benefits the thermal insulation of the building interior [56]. In flats located on the topmost floors, under green roofs, the demand for cooling energy decreases from 10% to 40% (depending on the climatic conditions and the building structure) [53–59]. In buildings without air conditioning, the temperature on the topmost floors may be about 2 °C lower than in buildings with traditional roofs [43,60,61]. In addition, in winter, the heat loss from the inside of the building through the green roof is much smaller than in buildings with traditional roof construction. This reduces the heat energy demand on the topmost floors [62]. Both in the case of cooling and heating of the building, the reduction in energy demand owing to the green roof means a reduction in CO_2 emission from generating power or heat [49,59,61]. However, studies have shown that in the case of energy-efficient or passive buildings, the impact of a green roof on the thermal parameters of the building interior is much lower than in the case of energy-intensive buildings [43,63–66]. Experimental research is required to analyze the permeation of heat through green roofs of different constructions in the climatic conditions of Central and Eastern Europe because there has not been much research on this type done in this region. It is also imperative to study the impact of the humidity in the substrate layer on the thermal insulation of the green roof.

3.3. Elimination of Air Pollutions

Air pollution is a major problem in city centers and heavily urbanized areas [65–69]. Factors such as the concentration of transportation, local boiler houses, and industries in urbanized areas are all responsible for the presence of CO_2, NO_x, SO_2, heavy metals, and suspended particulate matter in city centers [69–71]. Most of the pollutants generated in the cities remain there and are hazardous to the health and life of the citizens. Green roofs can be a way of reducing air pollution [71–73]. For Central and Eastern Europe, it is precisely the reduction of air pollution in urban areas owing to the impact of green roofs that is one of the most important functions of this type of roofing solution [74]. As the analysis shows, only 5% of the publications concerned this aspect of the impact of green roofs on air quality in city centers. Many researchers have confirmed that plants grown on green roofs capture both nitrogen oxides and carbon dioxide [67,69,72,73]. Studies in the United States showed that the aboveground part of a plant collected on average 84 g C/m^2, and roots accumulated 53 g C/m^2 in one vegetation season [9]. On the other hand, research conducted in Singapore, on a 4000 m^2 roof surface, showed that the substrate and vegetation could capture up to 37% of SO_2 from the air. The results of these studies cannot, however, be directly transferred to other locations due to the different meteorological conditions, or the type of plants used. [71]. Large and rough surfaces of branches, twigs, and leaves make the green roof plants a very effective tool for catching dust pollution suspended in the air [71]. Currie and Bass estimated that a green roof could remove between 7.2×10^{-3} kg/m^2 and 8.5×10^{-3} kg/m^2 of pollutants [75]. The plants also lower the ambient temperature, which slows down the photochemical reactions and leads to the reduction of secondary air pollutants such as ozone [71,72]. The substrate layer is instrumental in removing heavy metals from the atmosphere. With the appropriate composition and thickness of the substrate, heavy metals, such as Al, Cd, Cu, Fe, Ni, Pb, or Zn are removed more effectively; the removal efficiency can even go up to 93% [9,75,76].

However, it should be noted that rainwater flowing through green roofs absorbs some of the impurities from the soil and vegetation captured from the atmosphere. The runoff from the green roof, despite the fact that it is smaller in volume than rainfall, will often be laden with dissolved and suspended impurities [69,72]. Research has shown that green roofs neutralize acid rain and raise the pH of rainwater [9,76]. It is far easier to clear the water from the green roof than remove air pollutants directly from the atmosphere (assuming there is no discharge of rainwater from the roofs to the storm sewer or a general sewer).

Green roofs offer many benefits to the environment, e.g., they ameliorate air pollution, or serve as a substitute for a tool for monitoring environmental pollution in urban areas [70]. It is central to study the effect of green roofs on the quality of air in Polish cities, where smog has become such a frequent occurrence in urban areas.

3.4. Plants

Plants protect the roof from direct sunlight, absorb some precipitation water, and cool off the roof surface through evaporation. The use of plants on the roof affects its functionality, aesthetics, and the building's surroundings [51,59–61]. Depending on the type of green roof (extensive or intensive), different types of plants can be used [76]. On extensive roofs, it is best to use sedum plants [13,60]. Sedum are small plants, growing low above the surface of the ground. They are succulents, and because they store water in the leaves, they can survive long periods of dry weather (do not require additional watering), while offering good coverage and protection to the roof surface. Sedum can be used on mats that are laid directly onto the surface of the roof and require minimum care after planting [77–81]. However, as demonstrated through experiments conducted by many researchers, the use of diverse plant species on green roofs is superior to monocultures [82].

Trees, grass, and bushes filter out air pollution and use a significant proportion of rainwater in comparison with sedum plants, which are commonly used on extensive roofs [69]. Different kinds of herbs, peppers (both hot and sweet) (*Capsicum anuum*), tomatoes (*Solanum lycopersicum*), carrots (*Daucus carota*), fennel (*Foeniculum vulgara*), beetroots (*Beta vulgaris*), beans (*Phasiolus vulgaris*), peas (*Pisum sativum*), pumpkins (*Cucurbita* spp.), courgettes (*Cucurbita* spp.), aubergines (*Cucurbita* spp.), turnips (*Brassica rapa*), broccolis (*Brassica oleracea*), groundcherries (*Physalis* spp.), sweet potatoes (*Ipoema batatas*), artichokes (*Cynara cardunculus*), and radishes (*Raphanus sativus*), etc., can also be cultivated on green roofs [78]. Such diversity may increase the benefits of the green roof both for its utility and recreational purposes, however, the danger of accumulated pollutants captured by the plants from the air must not be overlooked. The selection of plants for green roofs should primarily be made with regards to improving the parameters of the urban environment and on reducing gaseous and particulate pollutants [83–85]. For this purpose, extensive research should be carried out in order to determine which plant species, well adapted to growing on roofs (in temperate climates), are most efficient in carrying out photosynthesis, i.e., absorbing CO_2 and emitting O_2 into the atmosphere around the building. The conducted research shows very divergent results of the influence of particular plant species on the parameters of the environment inside the building as well as in its surroundings. This is very closely related to the climatic conditions and the leaf surface characteristic of a given plant species [86,87].

Some vegetation, such as succulents, are fire-resistive, thus green roofs can also improve the fire safety of the building [18,19].

Another important issue related to the selection of plants used on green roofs is the protection of biodiversity in urban areas. Research should be carried out to determine the possibility of reintroduction of endemic plant species that can be used on green roofs (with resistance to stress: Large temperature differences—summer/winter, long rain-free periods, or torrential rains). This would make it possible to increase biodiversity in urban areas, which is now often reduced by keeping to a minimum the number of plant species used in parks and green areas of cities. Green roofs in cities can also make an excellent habitat for birds (which eliminates troublesome insects), and bees and other insects, which is very important in urban areas as insects help pollinate flowers planted in urban parks and gardens. In addition, the honey produced by bees in cities is becoming increasingly popular. There are hardly any research results in these fields in Central and Eastern Europe.

Future experimental research should focus on the substrate properties of real green roofs, most beneficial for a variety of plant species (typical of the climatic conditions of Eastern Europe), which will be most efficient in capturing air pollutants.

3.5. Noise Reduction

When discussing the impact of green roofs on the urban environment, one should not ignore the building's interior protection against noise. Precipitation, especially rain and hail, is a source of noise when they hit traditional roofing. Covering the building with a green roof practically eliminates this effect while also reducing road, rail, or airborne traffic noise [14,88–92]. The study comparing noise levels penetrating the interior of the building through the traditional and green roofs has shown that, in the case of the green roof, the noise level is reduced by up to 20 dB both for the extensive and the intensive green roofs [14]. The degree of absorption of sound waves by plants depends on many factors, including the size, number, and distribution of leaves on the absorbing surface. Research conducted to date has not covered plants typical of the climate in Central and Eastern Europe, thus it is, therefore, crucial to conduct such studies, especially in the city. Green roofs can also be a good barrier to indoor noise, e.g., coming from underground garages, as they reduce their nuisance to the environment. However, there is little research in this area.

It should also be noted that in Polish conditions, in addition to the above-mentioned effects of green roofs on the environment, the use of green roofs usually allows the coverage of a larger part of the plot than is required by the Building Law. According to §39 of the Regulation of the Minister of Infrastructure on the technical requirements for buildings and their location, "the building plots designated for family housing, buildings for the institutions of health care (except for surgeries), education, and children's care, must reserve at least 25% of the space for biologically active areas" [93]. The green roof can significantly add to and increase the biologically active area.

The results of studies carried out on different continents and in different climate zones show that there are significant differences in both the vegetation used and the impact of green roofs on the parameters of the environment inside and outside the building. Therefore, it is necessary to conduct research on a laboratory scale, as well as on the existing examples of roofs, in order to be able to determine the impact of roof vegetation in given conditions (especially in the analyzed part of Europe) on individual parameters of the urban environment. In the future, this will allow the creation of simulation programs to estimate the impact of new buildings with green roofs on the environment.

It should also be emphasized that the impact of green roofs on the quality of the environment in cities depends to a large extent on the surface area of buildings with this roofing solution. There are no precise breakdowns, analysis, or even estimates of the total area of green roofs in Central and Eastern Europe, let alone the world. The only published Figures on green roof areas are those that are covered by the case studies for individual cities or estimates for individual countries around the world. These present the percentage shares of green roofs in the total rooftops surface, which differ considerably in different analyses; therefore, it is practically impossible to develop an algorithm for the determination of the surface of green roofs in different countries, continents, or globally.

This paper and the future tests results are intended to encourage decision-makers of the analyzed region of Europe to promote the construction of new green roofs as a method of improving the quality of the environment in urban areas.

4. Discussion

The review of the literature led to the conclusion that the results obtained by researchers in various regions of the world differ significantly, thus it would be difficult to choose the results that could be considered as a reference (regardless of the scope of the test exposure, e.g., water runoff, as well as its storage and evaporation from the green roof). Therefore, field research has been proposed (in the laboratory, and on the existing facilities) in conditions typical of the region under analysis. In order to carry out the planned field studies on the impact of green roofs on the environment in urban areas (in Polish conditions), it was necessary to create a reference research object—a garden on a flat roof of one of the buildings of the University of Opole. Prior to the construction of the reference roof, we decided to construct a research model of green roofs in the laboratory scale in order to work out the parameters of each layer of the roof and select the most appropriate plants. The green roof models (the layers and the plants used) are presented in Figure 5. While working out the thickness and materials for each layer, we took into account the construction solutions for this type of model design in the laboratory scale used by various researchers [25,94–96]. The soil substrate layers composition in the laboratory model were made according to the author's own idea. In future studies, which will be carried out on the reference research facility, the soil substrate layer is to be made according to the recommendations of the German Landscape Research, Development and Construction Society (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau-FLL) and DAFA (Association of Flat Rooftops and Façades Contractors) [74,97] with certain adjustments to accommodate the specificity of the climate of the tested region.

Figure 5. Green roof models on a laboratory scale [74].

Based on the results of research on green roofs carried out by different researchers [29,50,51,63,92,94,97–100], a methodology for testing green roofs on a laboratory scale (in the climatic conditions of Central and Eastern Europe) has been developed; a decision was also made to build three other research models of varying structures, and various substrate layers in particular. The set of research models, thus developed, will allow for an analysis of the impact of various green roofs on the parameters of the environment, such as particulate and gas pollution of the air, utilization of rainwater, as well as the elimination of the phenomenon of the urban heat island. The literature review confirmed that in order to conduct research on the impact of green roofs on the parameters of the environment in city centers, it is necessary to create an interdisciplinary research team. This is due to the multitude of problems that occur in the course of research on roofs of this type and which pertain to various disciplines of science.

The proposed research should help to formulate a model defining the following: Reduction of gas and dust pollution, reduction of the urban heat island effect, as well as sustainable rainwater management taking into account the area of green roofs in the city and experimental coefficients determined in the course of the research. Drawing on the findings of various researchers [7,20,21,48,75,101–103], the research should be carried out using geographic information systems (GIS), EnergyPlus software, computational fluid dynamic (CFD) models, and modeling with the use of a neural network.

5. Conclusions

As demonstrated in the work of many authors, the increase in the number of buildings equipped with green roofs in urban areas contributes to the increase of biologically active areas and lowers the average ambient temperature. This ameliorates the effects of the urban heat island.

The high efficiency of green roofs as an insulating layer for heat, humidity, and acoustics of the building has also been demonstrated. Most published studies confirm the potential of green roofs for sequestration of CO_2, NO_x, SO_2, and heavy metals in plants and soils. The positive impact of green roofs has also been shown in reducing the rainwater runoff from roof surfaces. Due to the fact that most publications are related to laboratory tests or experiments carried out on existing green roofs, the results very often reflect the impact of the environment on the green roof (and vice versa) in specific climatic conditions and a location of research facilities. The results obtained in South-East Asia or in the Southern United States do not relate directly to the conditions in Central and Eastern Europe.

In Polish conditions, the use of green roofs in cities will also be conducive to the protection of biodiversity in urban areas (threatened by the current trends in city-planning).

To ensure that green roofs significantly impact the quality of the environment in urban areas, the highest possible percentage of roofs on all buildings in the city should be turned into green roofs. This will only be possible by providing landlords and local authorities with the benefits of this type of solution.

Nevertheless, the implementation of green roof systems entails problems that must not be overlooked. The costs of implementation, maintenance, and upkeep are higher than in the case of conventional roofing. In addition, the relatively great weight needs to be accounted for in the building design, and special care and attention must be given to the execution of the thermal and moisture insulation of the ceiling of the top story of the building.

The literature analysis has allowed the systematization of the advantages of green roofs and their impact on the quality of the environment in urban areas. The results of research obtained by the majority of authors conducting laboratory or field research on the impact of green roofs on the parameters of the environment in urban areas allow us to hope that this type of solution will minimize air pollution (particularly burdensome in city areas of Central and Eastern Europe), and improve the comfort of living in buildings fitted with roofs of this type. The only way to model and design green roofs in urban areas and their impact on the parameters of the environment is to examine carefully the various structural solutions of green roofs (and their impact on the environment) in conditions characteristic for the location (latitude) and climate of Central and Eastern Europe.

The literature analysis has led to the preparation of a research plan, which takes into account the methodologies used by a number of scientists in their research done in temperate climates. The research proposed should make it possible to formulate a model defining the following: Reduction of gaseous and particulate pollutants, reduction of the urban heat island effect, as well as sustainable rainwater management based on the area of green roofs in the city and experimental coefficients determined in the course of the research. The model will facilitate the process of planning the course of action that will lead to improved air quality in urban areas.

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