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Review

Anti-Smog Building and Civil Engineering Structures

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Abstract: Currently, people worldwide, in the period from September to April, observe with their own eyes and feel the pollution of the air, called smog, in their own breath. The biggest cause of smog and the source of air pollution is burning rubbish in stoves. Other causes include exhaust fumes from large factories, burning coal in furnaces, and car exhaust fumes. Smog is an unnatural phenomenon, directly related to human activity. The weather is becoming worse. On no-wind, foggy days, the smog phenomenon is the most troublesome for city dwellers. Smog persists in European countries from November to April, during the heating season. The harmful effect of smog affects almost the entire human body. Every year, air pollution causes the death of approximately 26,000–48,000 people. At the same time, poor air quality reduces life expectancy by up to a year. The purpose of this article is to present buildings and finishing elements that can help in the fight against air pollution.

Keywords: smog; pollutions; sustainable development

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1. Introduction

Pollution of the natural environment is a state of the environment resulting from the introduction into the air, water, or land or from the accumulation on the surface of the earth of solid, liquid, or gaseous substances or energy in such quantities or in such composition that it may adversely affect human health, living nature, climate, soil, or water, or cause other adverse changes, e.g., corrosion of materials [1].

Sometimes environmental pollution is understood as exceeding environmental quality standards or acceptable emission factors, i.e., the actual occurrence of an unacceptable level of environmental pollution. According to UNESCO experts, currently the most dangerous polluting factors are:

- carbon dioxide (CO_2) one of the causes of the greenhouse effect;
- carbon monoxide (CO);
- sulphur dioxide and nitrogen dioxide (SO_2 and NO_2), causing acidification, phosphorus, and eutrophication;
- mercury and lead, bioaccumulating;
- crude oil;
- DDT and other pesticides;
- radiation [2].

At the same time, many risks arise from the contamination of people's immediate environment, including indoor air (presence of CO_2 and CO, NO_x, volatile organic compounds, radon, cigarette smoke, and oxygen deficiency), drinking water, and food.

Air pollution called smog has increased in recent years. It usually arises in large cities where levels of exhaust emissions and energy consumption are very high [3]. Road transport has a significant impact on the formation of photochemical smog.

Often, due to comfort or lack of other options, people choose to use a personal car over public transport. This results in heavy traffic on the streets. This increases the emission of exhaust fumes from tailpipes and the escape of dust from worn tyres and asphalt into the atmosphere. Passing cars also stir up the pollutants lying on the streets. The problem is the condition of cars. Quite often they do not meet the standards. Rapidly developing countries have a huge problem with air pollution and thus the environment as such [4]. This also has a negative impact on human health [5]. Each component of smog adversely affects human health, but just as the composition of smog can vary and is constantly changing, so too are its effects. The components it contains are very dangerous for humans.

As shown by researchers at the Health Effects Institute (HEI), smog is the fourth most serious risk factor, just behind hypertension, smoking, and obesity. It affects almost all organ systems in the human body, causing many different diseases:

- nervous system (headache, central nervous system disorders);
- the respiratory system (chronic lung disease, lung cancer, asthma);
- the cardiovascular system (ischaemic heart disease, heart attack);
- the digestive system (liver disorders);
- reproductive system (disorders of internal organs);
- the immune system (allergies).

Even small and short-lasting exceedance of nitrogen oxide concentration in the air may worsen the feeling of well-being. At the concentration of only 1.5 mg/m^3, it may cause cough or irritation of the nasal mucosa. When the concentration rises, this leads to sore throat and eyes, a drop in blood pressure, dizziness, and an increase in methemoglobin levels in the blood; prolonged breathing in such air results in shortness of breath and swelling of the lungs. This can lead to inflammation of the airways [6]

2. Smog

The word "smog" is a combination of the words "smoke" and "fog". This newly coined word or word cluster has spread around the world. It seems to define the phenomenon very well. Smog is an artificial fog, an unnatural atmospheric phenomenon consisting of the coexistence of air pollution caused by human activity and natural phenomena: considerable haze and windless weather [7,8]. There are two main types of smog, which are shown in Figure 1 [9].

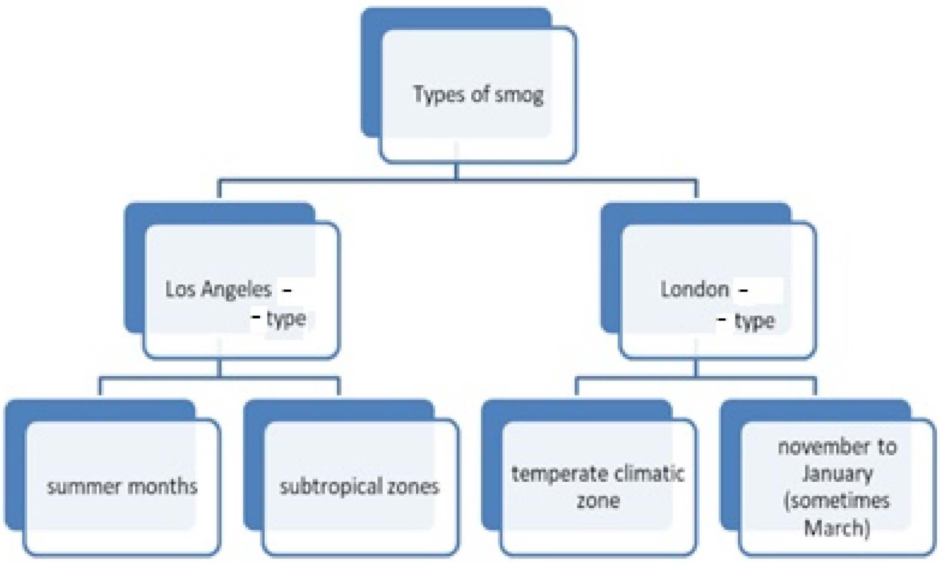

Figure 1. Diagram: types of smog (developed by the author).

Los Angeles-type smog [9,10], otherwise known as photochemical smog, occurs during the summer months of the year and usually in subtropical areas. Under such conditions, under the influence of strong sunlight, the chemical compounds contained in car exhausts are strongly transformed and oxidants are formed. It consists of gases including carbon oxides, nitrogen oxides, and hydrocarbons. It also forms a very noxious brown haze. The London type [9,11], on the other hand, is formed in temperate climate zones and occurs during winter periods from November to January and even into March. It consists of different dusts, enriched with sulphur, nitrogen, and carbon oxides, as well as soot. As the smoke from chimneys rises higher, its temperature drops. In normal weather conditions, the air temperature decreases with height and the smoke rises freely into the upper layers of the atmosphere. In autumn and winter, however, a so-called temperature inversion often occurs. This creates the opposite situation. The higher the altitude, the higher the temperature. Under such conditions, the temperatures-of the pollutants from the chimney and the air - quickly equalise. As a result, the pollution stays closer to the ground because it cannot escape into the higher layers of the atmosphere. If, in addition, there is no wind and high humidity, the smog accumulates more and more [12,13].

On the one hand, smog is caused by the air mixing with pollutants and exhaust fumes produced by human activity. Factories, the increasing number of cars, burning coal, and wood and other solid fuels in cookers are responsible for this. On the other hand, weather, climate, and general conditions of the area influence its formation. Pollutants lingering over a city located in a basin, in windless weather, cannot spread and dilute. This causes them to hover over the town in question [13,14].

There is also another type of smog, the so-called influx smog. This involves pollution spreading to other areas. The air clears in one place but becomes more polluted in another [15].

Smog has a negative impact on human health. It has direct and indirect effects. The direct ones are allergies, heart failure, cardiovascular and heart diseases, and lowering of the general immunity of the body. Indirect ones are related to eating smog-contaminated animal or plant meat. Toxins entering the respiratory system also irritate its mucous membranes, lead to inflammation, and cause symptoms similar to those of the common cold—cough, runny nose, and throat irritation. In addition, smog contributes to the formation of acid rain [4].

In Poland and many European countries, there is London-type smog, but also Los Angeles-type smog due to traffic pollution. In Poland, however, particulate smog has yet to be distinguished [15]. Smog comes from different areas of life, as shown in Figure 2.

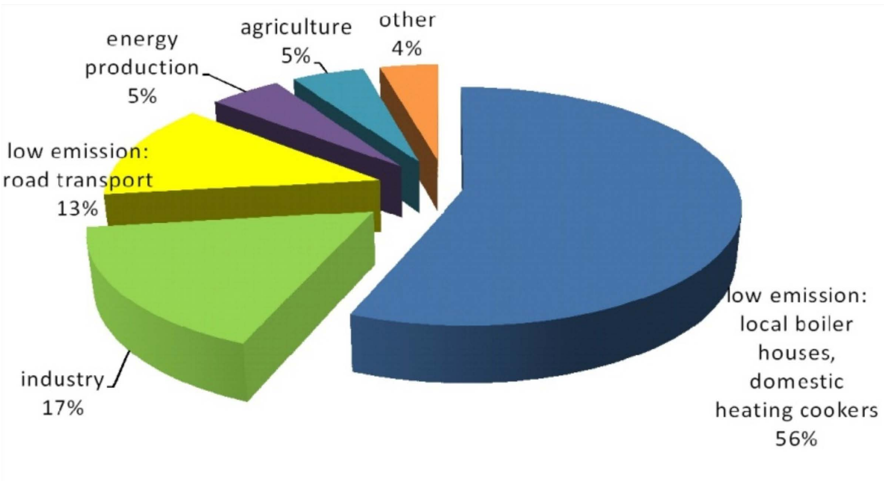

Figure 2. Areas of life with an impact on smog formation (developed by the author).

The largest emissions of smog, including PM10 and PM2.5 particles, are caused by burning low-quality coal in old and often poorly regulated boilers and household furnaces, as well as by various types of waste [16]. PM2.5 are atmospheric aerosols that are less than 2.5 micrometres in diameter. This type of particulate matter is considered to be the most dangerous to human health. PM10 is a mixture of airborne particles whose diameter does not exceed 10 micrometres. It is harmful due to its content of elements such as benzopyrenes, furans, and dioxins, i.e., carcinogenic heavy metals.

Low emission is the emission of harmful substances and dusts from local boiler houses, domestic heating cookers, and car traffic [17]. Combustion products contributing to low emissions include the following gases: carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x; NO_2, NO), polycyclic aromatic hydrocarbons such as benzo(α)pyrene and dioxins, and heavy metals (lead, arsenic, nickel, cadmium) and particulate matter (PM10 and PM2.5). These are point air pollutants. They may occur throughout the year.

"Low emissions" of particulate matter are also caused by industry, especially the power, chemical, mining, and metallurgical industries [18], but due to the height of the emitters and the legislation in force regulating the permissible values of emissions, these sources usually have a much smaller impact on air quality.

Three main air pollutants can be distinguished in European countries: PM10, PM 2.5, and polycyclic aromatic hydrocarbons (PAHs), including benzo(α)pyrene and, to a lesser extent, PM1. PM 2.5 contains particulate matter with a very small diameter of only up to 2.5 m. Due to their size, once they enter the respiratory system, they travel very easily and poison the bloodstream. PM10, on the other hand, consists of grains up to 10 m in diameter. This size allows it to penetrate deep into the lungs. Pollutants from home heating (so-called "low emissions") account for the largest percentage (over 83%) of PM10 concentrations in the air. The situation is very similar for benzo(α)pyran (polycyclic aromatic hydrocarbons). It is emitted in the highest amount during individual heating of buildings, followed by the operation of coking plants and road transport [6].

The building industry is committed to sustainable development. It is defined as a way of farming in which meeting the needs of the present generation will not reduce the chances of meeting the needs of future generations. The breakdown in sustainability is shown in Figure 3.

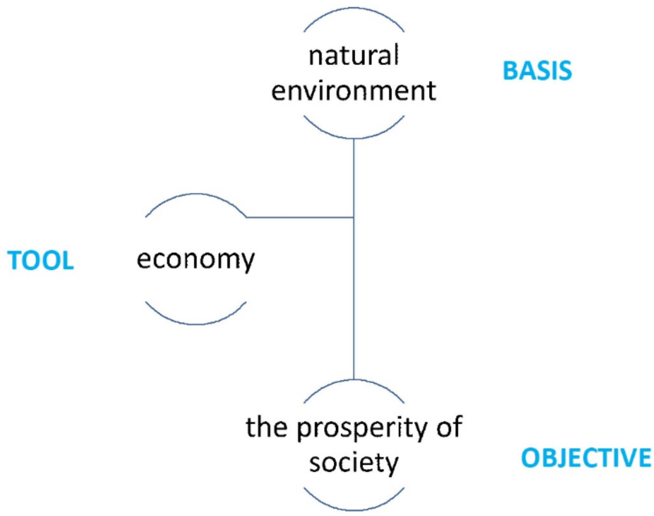

Figure 3. Division in sustainable development (developed by the author).

In order to achieve sustainable development, coherence is needed between three key elements: economic growth, social inclusion, and environmental protection. These are interlinked and all are critical to achieving well-being for individuals and societies as a whole [19].

Sustainable development is implemented in many ways. One of them is the gradual elimination of hazardous and toxic substances from economic processes and keeping emissions within the limits set by the assimilative capacity of the environment. Such actions entail striving to ensure the sense of security and well-being of citizens, understood as creating conditions conducive to their physical, mental, and social health. Sustainable development is implemented through

- restricting the use of renewable resources to the limit of their recovery;
- reducing the consumption of non-renewable resources to a level that allows them to be gradually replaced by suitable substitutes;
- the progressive elimination of hazardous and toxic substances from economic processes;
- keeping emissions of pollutants within the limits set by the assimilative capacity of the environment;
- restoration and permanent protection of biological diversity at landscape, ecosystem, species, and gene levels;
- socialisation of decision-making processes concerning the local natural environment [19].

In the analysis of the above, efforts should be made to minimise the amount of smog. At the same time, the causes of smog should be eliminated, i.e., low-emission cookers and reducing the number of old cars, especially diesels, which emit the greatest amount of pollution. In addition, the effects must be fought. In the circles of city halls, architects, town planners, and builders, the topic of smog removal has been frequently discussed in recent years.

In the following part of this article, different ways of fighting smog in architectural and construction aspects are presented.

3. Building with Nano Additives

Nanoparticles are compounds with at least one dimension below 100 nm. Nanoparticles can be used as nanomodifiers for various materials. The most commonly used nanoparticles include nanosilver, titanium dioxide, nanogold, nanopalladium, nanocopper, nanoplatin, zirconium dioxide, zinc dioxide, graphene, nanotubes, and fullerenes, as well as carbon nanofibers [20].

One of the most commonly used nano additives is nano-TiO_2, which has specific physical and chemical properties. These include photocatalytic activity, hydrophilicity, and strong UV absorption. One solution to clean up the surrounding environment is to apply coatings with nano-TiO_2 to building materials. This additive, after absorbing UV radiation, is able to effectively decompose organic compounds such as VOCs (volatile organic compounds), microorganisms, and NO_x pollutants. The photocatalytic activity of the nano additive requires access to sunlight, and thus thin layers (coatings) of a few millimetres are sufficient to achieve the desired properties [21]. Various applications of nano-TiO_2 are presented in Figure 4.

Titanium dioxide exists in three crystal structures: anatase (distorted tetragonal crystal structure), rutile (also tetragonal), and brucite (rhombic crystal structure). Of these, only rutile and anatase can be of practical use. This is due to the fact that they have a wide semiconductor bandgap [22]. Anatase is more efficient in degrading organic as well as inorganic contaminants in the gas and liquid phases [23]. Rutile and brucite phases are more applicable for selective oxidation of organic syntheses [24]. The simultaneous use of anatase and rutile phase increases the photocatalytic activity compared to each individual component [25]. The high photocatalytic activity of anatase has led to its widespread use as a photocatalytic coating on various substrates under low intensity, i.e., near UV light [26]. Consequently, visible light is not energetic enough to induce photocatalytic activity in anatase [27].

The photocatalytic degradation reactions of pollutants are shown in Figure 5.

The mechanism is based on the generation of radicals as a result of irradiation of the photocatalyst substances, and then transforming the pollutants into harmless compounds [28]. Figure 2 shows the photocatalytic reaction to eliminate NO_x pollution by photocatalysis of concrete pavements.

Figure 4. The use of nano-TiO_2 products (developed by the author).

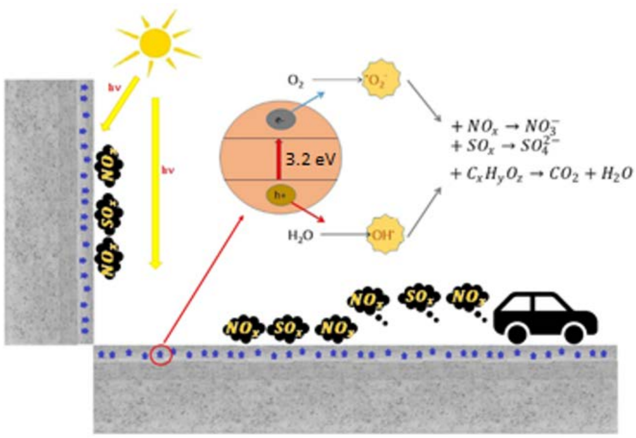

Figure 5. Photocatalytic degradation reactions of pollutants (developed by the author).

NO is considered a primary pollutant that is mainly introduced into the atmosphere directly from high-temperature combustion in transport and industrial activities, while NO_2 is considered a secondary pollutant as it is mainly formed in the atmosphere due to the interaction of NO with O_2 or O_3 and/or sunlight [29].

Concrete pavements and building exteriors are ideal for photocatalytic application of materials because their flat configurations would facilitate exposure of the photocatalyst to sunlight [30].

In photocatalytic cements, the resulting $NO_3{}^-$ reacts with the calcium in the cement to form a water-soluble salt, calcium nitrate, which is easily removed by rainwater. Effective elimination of air pollutants at concentrations in the range of 0.1–10 ppm is possible with such photocatalytic cement materials [31].

3.1. Construction Works

Portland cement modified with nano-TiO_2 has become one of the elements for reducing air pollution. Thanks to its self-purifying properties, i.e., the conversion of organic compounds, sulphur, and nitrogen oxides into harmless substances, i.e., water and CO_2, titanium dioxide makes it possible to clean the air of pollutants [32]. Its use in cement or concrete is already well known. Due to the fact that only a certain thickness of the material with this nano-additive has the possibility to be activated by UV radiation, it is only used on top surfaces. Therefore, these materials are used in the form of façades, coatings, or paints [21].

3.1.1. Façades

There are façade panels on the market from Berlin-based architecture firm Elegant Embellishments that absorb pollutants from the air. The technology is called Prosolve370e [33]. The individual modules are coated with very fine titanium oxide particles. The panels are designed to absorb harmful substances and light over as large a surface area as possible. According to research, the panel system cleans the air of pollution from a thousand cars a day. The technology has been used in many cities around the world, including those in Mexico, the United Arab Emirates, and Australia.

One of the first buildings to be built with a purifying façade is the Jubilee Church in Rome dedicated to the Merciful God the Father, designed by Richard Meier. Self-cleaning and smog-absorbing cast concrete blocks with titanium oxide and white architectural concrete were used in its construction. It was completed in 2003 [33].

Another example is the Hotel de Police building in Bordeaux, France. It was built in 2003, designed by Claude Marty and Lacrouts Massicaults SA Architects. The building is located in the city centre, where there is a lot of traffic and therefore also a lot of pollution. The façade of the Hotel de Police is made of prefabricated concrete panels. There are 750 panels, 700 of which are white, covering a total area of 5400 m^2. In addition to cleaning the air, the technology also has a self-cleaning function so that, even after many years, the original appearance and especially the colour of the building will not change [34,35]. TX Cement Active® technology was also used by Luc Declercq in the creation of The Commodore building in Ostend. In collaboration with E&L Projects, he designed an apartment complex to purify the air in the Belgian town. The first six floors of the building are covered in polished concrete with titanium dioxide to help purify the air. Due to its coastal location, the building is also exposed to organic pollutants, which develop more quickly in a humid environment. The building was constructed in 2005, and tests carried out several years later confirmed the material's self-cleaning properties. This shows that TX Active® technology allows the aesthetic appearance to be maintained for many years, regardless of the location of the building and the pollutants affecting it [33].

Another facility that uses titanium nano-dioxide façades to reduce smog is the Manuel Gea Gonzalez Hospital in Mexico City. The façade has a decorative appearance, i.e., the white openwork panels resemble honeycombs, a spider web, or a coral reef. This increases the photocatalytic surface. The unusual shapes exhibit larger active surfaces, which allow for increased removal of contaminants. A 2500 m^2 façade can reduce pollution from 1000 cars per day. In 1992, the city had only nine smog-free days per year. Today, it is one of the leaders in the fight against smog [34].

The Palazzo Italia designed by Nemesi and Partners for Expo 2015 [36] in Milan is a building that also uses nano modifications. The façade used in this building is designed to resemble growing trees, in which the tree crowns are made of nanocement. The effectiveness of this surface (9000 m^2) measured by the reduction of air pollution has been found to be between 20 and 70%, depending on weather conditions. This refers to the purifying properties of plants, which clean the air of pollutants, as does the façade of the pavilion. The decorative element is made of cement with titanium [35].

3.1.2. Plasters

In buildings with complex shapes, cement-based plasters or paints are used. This is because the low thickness of the coating provides the same performance on concrete surfaces while reducing the consumption of titanium dioxide. An interesting example of paint application is a historical building undergoing renovation is Matrice Church in Italy. A coating product based on natural hydraulic lime with low cement content was applied [2].

Another example is the Umberto I Tunnel in Rome, where plaster was applied to the walls over a length of about 400 m and a width of 8 m. Due to the lack of access to UV rays, dual-function lamps were used, providing normal light and UV radiation. The efficiency of pollution reduction in the tunnel reaches 20 to 70% [37].

Cement paints doped with TiO_2 can be used to create a mural. In Poznań, Poland, a mural depicting Poznań of the future was created on the wall of the "Wiktoria" cultural centre in the Winograd Zwycięstwa housing estate. The painting is 77 sq m in size.

A mural with similar features can be found in Italy in Rome of the Yourban 2030 project called "Pollution Hunt" with an area of 1000 m^2. It depicts the tricoloured heron, an endangered species that is struggling to survive. The mural absorbs as much smog as 30 trees. The creators of the technology ensure that the paint is able to eliminate up to 88.8% of air pollutants and 99.9% of bacteria. Many murals have been created by the Converse City Forests project. They can be admired in Rio de Janeiro, Lima, Belgrade, Sydney, Santiago, Bangkok, Johannesburg, Saigon, Manila, Mexico City, Sao Paulo, Jakarta, Ratchaburi, and Chiang Mai, among others [38].

3.1.3. Paints

Artists have also taken an interest in the use of nano-TiO_2 paints. They create murals to decorate the walls of buildings and neutralise nitrogen dioxide. They can be found in many cities around the world, e.g., in England and Italy, while in Poland they can be seen in Warsaw and Poznań, among others [39].

This is a cheap and simple solution with double benefits. Apart from cleaning the air, the paints also have a self-cleaning function. They remove unpleasant odour and have an antibacterial effect.

3.1.4. Organic Coatings

Nano additives can also be added to organic coatings such as acrylic, fluorinated ethylenetetrafluoroethylene (abbreviated ETFE), and silane polymers. They are also used for hybrid coatings such as silica and polydimethylsiloxane.

3.2. Road Surfaces

Cementitious materials with titanium dioxide additives can also be used in road construction. The first anti-smog road construction projects were carried out at the beginning of the 21st century. The City Park of Antwerp in Belgium built a pavement of about 10,000 m^2 with concrete bricks containing nano-TiO_2 [40]. Along a road in Antwerp, parking lanes have been created with two-layer photocatalytic concrete pavers. Such solutions are still in use, among others in the Netherlands, where some roads are made of air-purifying cobblestones.

3.2.1. Concrete Asphalt

Researchers at the Technical University of Eindhoves in the Netherlands tested concrete asphalt with photocatalytic properties. They obtained efficiencies of between 19 and 45% reduction in airborne pollutants with this material [41]. Very similar studies were carried out in Chicago in the United States. They obtained a slightly higher efficiency, ranging from 20 to 70% reduction of pollutants. Of course, the effectiveness depended on the type of road in question and the weather conditions. However, the implementation of such a system showed that it works better on local roads than on busy roads, i.e., motorways. The reason behind this is cars. When there is a lot of traffic on the road, it is difficult for particles to fall onto the asphalt, and thus the cleaning processes is prevented [42].

3.2.2. Paving Blocks

Paving blocks consist of two layers: the base layer and the surface layer. Only to the surface layer (texture) is nano titanium dioxide added. They are used to make pavements, as well as bicycle paths. This type of solution is used all over the world. Examples include Chicago in the USA, Bergamo in Italy, Nowa Sól in Poland, in the surroundings of a kindergarten in Bietigheim-Bissingen (Germany), pavements in Tatton Park in Knutsford (Great Britain), and pavements in Warsaw and Krakow in Poland. In Bergamo, both the pavement and the roadway are lined with these paving stones. Traffic routes clean the air up to a height of 2–2.5 m. The effect decreases with distance. They are effective in reducing NO_2 by about 30% under optimal atmospheric conditions [40].

Another air-purifying solution for roads are pavements. A frequently used solution, similarly to roads, is paving blocks made of "green concrete". In Poland, such projects are carried out, among others, by Skanska. The solution is able to reduce the concentration of carbon dioxide by 30%, and in laboratory conditions even by 70% [43]. Photovoltaic tiles are also used for the construction of pavements and cycle paths.

3.3. Acoustic Screens

Acoustic screens are photocatalytic coatings that break down nitrogen oxides into harmless compounds when exposed to sunlight. These are then flushed from the facilities by precipitation. Even on a cloudy day, sufficient sunlight is provided for the screen to work effectively. Many factors influence the effectiveness of the photocatalysis process—porosity, particle size, irradiation time, atmosphere exposure, and pollutant concentration. Such a solution has been applied, for example, in the Philippines. In the capital city, concrete noise barriers along a 15 km city ring road have been painted. It absorbs the pollution produced by tens of thousands of cars every year. Such screens can reduce road air pollution by 15–25% [44].

3.4. Roof Tiles

Cement or ceramic roof tiles are also used as anti-smog materials. However, the nano-additive is not applied to the tile itself, but they are coated with an impregnation with photocatalytic properties. The effectiveness of the tiles: a roof of 2000 m^2/foot can oxidise the nitrogen oxides released by driving a car 10,000 miles a year.

Students at the University of California, Riverside, have developed roof tiles that clean the air of harmful nitrogen oxides. They coated ordinary tiles with a layer of anatase (a special variety of titanium dioxide), which has the ability to actively clean the air. Then, by placing them in a special chamber, they tested their photocatalytic properties and air purification function depending on the thickness of the coating. The result showed that the number of TiO_2 layers had no significant effect on the effectiveness, and that the anatase layer, working together with the sun, is able to remove up to 97% of nitrogen oxides from the air. The stronger the UV radiation, the better the effect. A roof covered with such tiles is able to clean the air of 21 tons of harmful oxides per day [45,46].

4. Building with Vegetation

In addition to the nano-additive and its pollutant-reducing properties through the photocatalysis process, there are other methods used in building structures. Plants can help combat pollution by producing oxygen. Large cities suffer from a lack of space to create new squares, parks, and gardens. These include green roofs, green façades, and artificial trees.

Green roofs, green façades, and living walls are elements of sustainable construction [47]. The use of green roofs is used worldwide [48]. Vertical green systems (VGS), i.e., green façades and living walls, are very rarely used. This is due to the fact that the number of plants possible to use is small compared to the number of plants used in green roofs

Living walls differ from green façades in that the plants are rooted in a structural support. This is attached to the wall itself. The plants receive water and nutrients from the vertical support rather than from the ground [48].

4.1. Pollution-Reducing Façades

The growing popularity of green façades has influenced the number of solutions available for placing vegetation on a building. They differ in terms of:

- construction;
- the degree of independence from the façade plane.

Vegetated vertical systems include two main categories: green façades and living walls [49]. These two categories are characterised by different locations of growing media for plant roots. Green façades use plants placed directly on the ground at the base of the building or in pots at different façade heights. Self-supporting plants can grow directly stuck to the wall in the case of direct green façades; climbing or hanging plants can climb onto support structures placed a short distance from the wall in the case of intermediate green façades. In the latter solution, an air gap is created between the wall and the vegetation layer. Some climbing plant species can cause damage to the building surface if cracks are already present [50]. The presence of an air gap in intermediate green façades and the appropriate choice of plants mitigate these negative effects. Living walls are based on the use of a growing medium that is attached vertically to the building envelope or to the frame. Vertical green systems can reduce the frequency of maintenance interventions on the building envelope due to limited temperature fluctuations of the wall surface [51].

Several green façade systems can be distinguished. The first is to create wall space for climbing plants, guided along a special structure made of stainless steel or impregnated wood. The plants are then planted at the base of the wall. This eliminates the need to install additional irrigation systems. This is the most commonly used system.

The second one consists in creating a wall on the basis of a system of pots, which are fixed to a special construction made of stainless steel. The advantage of this solution is the possibility to use various types of greenery and integrate it into the appearance of the façade. This method is slightly more advanced than the first system [52].

The third one consists in keeping the vegetation in good condition thanks to an automatic irrigation system, on the basis of the principle of horizontally placed pipes through which water is pumped.

The last solution, the so-called living wall, is the most technologically advanced method. It makes it possible to reduce the construction elements to a minimum. It consists in using ready-made system inserts made of a special material resembling horticultural foam. Plants that are part of the façade are rooted in the inserts and fixed to the frame. This solution, like the previous ones, makes it possible to water the greenery using irrigation systems [52].

The issue of fauna and flora on building façades and roofs does not only relate to how to build a green roof or living wall, but first and foremost to what role they are to play in the natural and social aspect and to what extent they correspond to current trends in shaping urban space.

The environmental performance of green vertical systems can be influenced by different green systems, weather conditions, building types, selected plant species, building orientation, and materials, etc. [53]. A green façade reduces nitrogen oxide by up to 20%, PM10 by 35%, and the temperature drop around the wall by up to 16 °C. The green wall also stores 750 L of water (100 m^2/24 h) and produces oxygen through photosynthesis (155 m^2 of green wall provides enough oxygen for one person for a whole day). It absorbs carbon dioxide and works with great efficiency. Only 100 m^2 will absorb 250 kg CO_2 per year, a figure comparable to a row of street trees [54].

The façade greening of building walls, known as vertical green systems (VGS), requires the use of climate-appropriate and non-allergenic vegetation. Trees that have a positive and significant impact on air quality include maples (*Acer* spp.). In addition to native species such as Norway maple, sycamore, and field maple, North American sugar maple (*A. saccharum*), silver maple (*A. saccharinum*), and red maple (*A. rubrum*) are particularly valuable for cities. Some authors also mention that the most effective pollutant-absorbing plants include common yew (*Taxus baccata*), lime trees (*Tilia* spp.), Sabine juniper (*Juniperus sabina*), Meyer lilac (*Syringa meyeri*), and Siberian microbiota (*Microbiota decussata*), and from American reports, in addition to some already mentioned are black walnut (*Juglans nigra*), ash (*Fraxinus excelsior*), common beech (*Fagus sylvatica*), Lawson's cypress (*Chamecyparis lawsoniana*), and Chinese metasequoia (*Metasequoia glyptostroboides*) [52].

Some species that retain their leaves for a long period of time in autumn, such as the shrub Ligustrum vulgare and the climbing Akebia quinata or the evergreen Hedera helix, which starts flowering in autumn, are also important for improving air quality. Ivy can be planted in roadside screens, but not on the street side, because unlike akebia it is much more sensitive to salt spray. In Prof. B. Wolverton's research, ivy was also found to be one of the more effective plants in purifying indoor air.

Evergreen trees are more effective at removing pollutants because the leaf activity period is longer. The size of the tree is important, as it determines the amount of CO_2 absorbed, retained, and stored in the biomass, as well as the total leaf area ready to absorb pollutants from the air, including particulate matter [51,52].

An example of a building with air pollution removal properties is the Bosco Verticale skyscraper designed by Boeri Studio in Milan [54,55]. Part of the building is shown in Figure 6. Its façade is formed by a vertically planted forest. The 9000 m^2 of terraces are planted with trees, 11,000 selected plants such as perennials and ground-cover plants, and 5000 shrubs. Such façades have another function, i.e., they regulate the indoor temperature [56].

Figure 6. This is a figure. Schemes follow the same formatting. Photograph of part of the Bosco Verticale building. Polina Chistyakova z Pexels (common creative).

Another example of a similar façade is the Tao Zhu Yin Yuan Tower building (Taipei, Taiwan), designed by Vincent Callebaut Architectures based in Paris. The skyscraper is in the form of a DNA double helix. This signals the unity of people with nature. A total of 23,000 trees are planned to be planted on balconies, terraces, and in the immediate vicinity of the skyscraper. The efficiency of this facility is 130 Mg of carbon dioxide per year. Construction of the Tao Zhu Yin Yuan Tower in Taipei, Taiwan, was completed in 2018. It was designed and built by Paris-based Vincent Callebaut Architectures. The building contains 42 flats, spread over 21 floors. Its design is inspired by the structure of the double helix of DNA, twisted from base to top by 90°, the source of life, the harmony of man with nature. The main idea behind the project is to fight global warming by absorbing carbon and saving energy. The building has wide balconies and is to be planted with a total of 23,000 trees and shrubs, whose light is to be facilitated by the unusual shape of the building. They are to absorb 130 tonnes of carbon dioxide emissions annually. It has many other green features: systems for recycling organic waste and used water, a 4.5° horizontal rotation of the floors provides natural lighting, and a photovoltaic solar roof to provide additional power. The construction materials and equipment used to make Tao Zhu Yin Yuan Tower were recycled and/or fully recyclable. The design combines the concepts of energy conservation, carbon reduction, and human–ecosystem harmony [57].

According to *Business Insider*, Boeri Studio is currently in the process of building a similar project, but on a much larger scale. In China, a "forest city" is being built along the Liujiang River, on an area of 175 hectares. It is to be a district that will contain 40,000 trees and almost 1 million plants of over 100 different species.

In addition to housing, there will be hotels, schools, and hospitals, and thus it will be fully self-sufficient. It will be connected to the city of Liuzhou by an electric railway. The district will annually absorb 10 thousand tonnes of carbon dioxide and 57 tonnes of pollution and produce about 900 tonnes of oxygen. The project is to incorporate many other green features, including the use of geothermal energy and solar panels. When completed, it will be able to house up to 30,000 people [58].

Citicape House in London is a project to be completed in 2024. It includes, among other things, a five-star hotel, offices, a spa, and a restaurant. The façade of the corner 11-storey building in central London will be largely covered with vegetation. Its surface area is 24,500 m^2. It was designed by the British design studio Sheppard Robson. On the roof of the building, apart from the bar, there will be a terrace with a meadow, decorated with native endangered flower species. In addition to improving air quality, the designers want to raise public awareness of this issue. The building is located in a busy area and is full of hustle and bustle. An estimated 400,000 plants will cover the façade, producing 6 tonnes of oxygen per year. The flowers will be placed in special frames and then fixed to the façade. They will be watered by rainwater collected in special tanks. According to estimated calculations, the amount of pollution will be reduced by 8 tonnes per year and about 500 kg of particulate matter will be absorbed. It will also lower the temperature by 3–5 °C. It will be the largest green wall in Europe [59].

4.2. Green Roofs/Inverted Green Roofs

Green roofs are a common nature-based solution [60]. They carry numerous benefits such as reducing building energy consumption, rainwater management, mitigating the urban heat island effect, improving air pollution, and enhancing the green aesthetics of buildings [61].

Green roofs are most commonly constructed on inverted roofs. This is due to the fact that they are more durable and less prone to mechanical damage. The plants present on them are permanently attached to the structure. Such a roof may be designed as a roof over an underground garage, or a terrace on top of a skyscraper.

The division of green roofs is related to the way they are used. There are

- extensive roofs;
- intensive roofs.

The first group of roofs is non-utilised. It has a decorative function and is used to reduce the amount of rainwater discharged into the sewage system. Plants used in this system must have a flat root system and low vegetative requirements. This means that they do not need to be nurtured. They can maintain and grow themselves, such as grass, herbs, sedums, and succulents. Systems for extensive green roofs are lightweight roof structures that are ideal for bus shelters and buildings that cannot take a heavy load.

The second group of roofs is suitable for use and can play the role of a private garden in the city centre. They are comparable to green areas on the ground, such as gardens and parks. They are planted with lawns, shrubs, and trees, and are used in the building of a gazebo and in the making of ponds. Such compositions are representative. Plants planted on them require more care, and in some cases additional irrigation is also needed. Intensive green roofs can be installed on buildings such as detached houses, blocks of flats, or public buildings, as well as on underground structures such as car parks [62].

Green roofs involve higher production and maintenance costs. This is because a more complex structure must be designed to simultaneously store water and drain excess water.

Extensive and intensive green roof systems, which can be used to roof almost any structure, give it a green appearance while reducing harmful substances in the air. Green roofs on bus shelters provide shade for passengers on hot days, while on the roofs of buildings, they replace traditional gardens for residents. When used on underground structures, they allow a piece of developed space to be reclaimed. In addition, they provide bus stops and buildings a green and positive appearance, improving the living environment for city dwellers [63].

However, whether it is an extensive or intensive type of green roof, they are more expensive than the classic ones, being more complicated to install and possibly to repair.

Pollution in the park can be 20–40% lower than in other areas of the city. An area of about 1.5 m^2, covered with uncut grass, produces as much oxygen per year as the annual demand of one person. Therefore, the use of green roofs offers great opportunities.

Another solution is the use of green roofs. They are planted with flower meadows as well as low trees and shrubs. The roofs can be used in an inverted system.

However, green roofs are also arranged on residential roofs. Of course, there must be sufficient moisture insulation and a layer in which plants can grow. A thickness of 5 to 10 cm is suitable for grasses and lower plants, such as shrubs, whereas a thickness of 30 to 50 cm allows for the growth of taller, more strongly rooted trees. Of course, the roof structures in these cases must be reinforced [63].

4.3. Anti-Smog Towers

Anti-smog towers mostly work by using ionisation. They suck in polluted air from above and release it in a purified form at the bottom.

The hexagonal tower called Smog Free Tower, an idea by Daan Roosegaarde [64], is 7 m long. It is made of aluminium and has two storeys. It filters 30,000 m^3 of air per hour. The operation of the tower is based on ionisation technology, i.e., capturing harmful particles. It is powered by solar panels. It is completely environmentally friendly. The Smog Free Tower was first presented on 4 September 2015 in front of the Roosegaarde design studio in Rotterdam. However, it has no fixed location. In accordance with the vision of the originator, it travels the world, cleaning the air in the most polluted cities. In 2018, a second tower was constructed, which could be seen for two months in Krakow [38]. However, research by scientists from the AGH University of Science and Technology did not confirm the possibilities declared by the designer. The concentration of suspended dust at a distance of 10 m from the facility decreased by 12%, but no improvement was recorded within a radius of 50 m. This was confirmed by tests conducted in China [38].

Another tower was developed in India. India’s Symbiosis Studio has developed a system of two types of pollution-absorbing towers. Larger, 60 m high towers are to be set up along the city boundary to absorb pollution coming from the suburbs. Each tower will clean the air in an area of about 2.5 km^2 and operate within a radius of 900 m. Smaller, 18 m high towers will be placed in different parts of New Delhi. They are to clean the air during atmospheric silence, i.e., when there is no air circulation. One is able to purify 30 million m^3 of air. Additionally, 60–70% of the surface of each tower is to be covered with vegetation, which will further reduce harmful substances, and inside them there will be docks for drones to monitor the state of pollution in the city [65,66].

Another country with a major smog problem is China. The Chinese city of Xi'an is home to the world's largest anti-smog tower [67]. There is also a coal mine there with low prices, which makes the air very polluted. The biggest problem arises in winter when the heating season starts. The tower is 100 m high and is able to clean 10 million m^3 of air per day from an area of 10 km^2. It works by drawing air into greenhouses of about 3.5 thousand m^2 on its surface. The air is then heated by UV rays, causing it to rise. This is how it gets inside, where it is filtered several times and, after being cleaned, is released. After confirming that the tower meets the claimed properties, Chinese engineers plan to build other, even larger towers [65].

5. Concrete with Activated Carbon

A major challenge is the use of anti-smog materials based on concrete in tunnels or underground car parks [68]. Currently, research is being conducted in Poland and worldwide on the effectiveness of concrete with activated carbon in absorbing and cleaning air of NO_x oxides. Researchers have looked into activated carbon. Activated charcoal is an adsorbent of NO_x compounds [69]. Worldwide literature [70] reports that it shows significant chemical affinity to nitrogen oxides in terms of adsorption and reactivity. The material owes its strong adsorbent capacity to its very high specific surface area per unit mass. It is almost 3300 m^2/g. This surface area is so large due to the highly porous internal structure of this material, which consists of micropores and mesopores [71]. Activated carbon starts its action when it comes into contact with pollutants, acting as a particle-catching filter. By means of chemical reactions, the pollutants are converted into harmless nitrate ions.

NO_2 can react in alkaline aqueous solutions to produce nitrite and nitrate ions [72]. Therefore, NO_2 reduction may be related to calcium hydroxide content. The authors of [73] hypothesised that NO_2 first dissolves in the adsorbed aqueous layer that covers alkali cement-based hydrates at 60% relative humidity [74]. According to the authors of [73], the course of reaction for activated carbon modified concrete is as follows:

$$2\,Ca(OH)_2 + 4\,NO_2 => (Ca^{2+}, 2\,NO_3^{-}) + (Ca^{2+}, 2\,NO_2^{-}) + 2\,H_2O$$

Due to the low weight of the activated carbon particles, it flows to the surface of the slurry and settles right at the mashing surface. In order to increase the effectiveness, the expansion surface of the activated carbon particles is sought. This is done by increasing the roughness of the surface and texturing the face layer [68].

The authors of [68] created a garage from concrete containing AC (activated carbon). As a result of experiments, the authors found that a garage made of concrete modified with activated carbon had a NO_2 absorption of 20–25%.

The performance of activated carbons towards NO_2 has been reported by several research groups [75–77]. It is known that the major part of NO_x from power plants and car engines is NO. Removal of NO_2 by activated carbons has become a potential technique.

6. Results

The solutions outlined above will not immediately clean the air of harmful substances. However, one has to start somewhere, according to the proverb/sentence "Rome was not built in a day". Material/plant solutions are the way forward for designing sustainable buildings that will have a positive impact on the environment.

Biophilic design [78] helps to reduce urban heat islands, improving outdoor air quality. It provides a better indoor climate through shading. It reduces the need for air conditioning, which helps to create more sustainable cities by reducing energy consumption. There is a reduction in greenhouse gas emissions and gaseous reactive nitrogen compounds.

To conclude the above examples, it is important to look at them in the right way. Usually, the amount of CO_2 and NO_x absorbed in the case of buildings with vegetated façades or green roofs are given as conversion figures, i.e., a given amount of plants will absorb a certain amount of harmful compounds. There are no measurements or tests to check how far the designers' predictions agree with reality.

In the case of concretes with nano-TiO_2 and activated carbon, tests were performed. In the case of nano-TiO_2, field studies show that the absorption of NO_x was around 65–70% [38]. Laboratory conditions showed 80–90%. For activated carbon, field conditions showed 20–25% NO_x absorption capacity.

Solutions using vegetation or nano-added TiO_2 or activated carbon can be considered in terms of advantages and disadvantages. As any solution will have both. The advantages are presented in the text. The biggest disadvantage by far will be the cost of producing or constructing and planting the vegetation. If these types of buildings were built only to absorb pollutants (NO_x), the profitability of such investments would be low. However, they do have other advantages that outweigh the disadvantages that may still arise. The solutions presented in the article are definitely better than using an anti-smog tower of one of the companies, which worked on the principle of air ionisation (capturing harmful particles). It is powered by solar panels. However, the designer's research was not confirmed. The concentration of particulate matter at a distance of 10 m from the facility reduced by 12%, but there was no improvement within a 50 m radius.

Facilities with vegetation should be looked at through the prism of large, built-up cities, where there is no space for vegetation and green zones. These types of buildings (with vegetated façades or green roofs) are the answer to fast-growing cities and cramped buildings.

Of course, the buildings themselves will not help in the fight against smog, but they can be a good start to the changes that large cities must undergo in order to be able to breathe fresh air in a few years' time.

7. Conclusions

This article presents an overview of solutions that can be applied to buildings and infrastructure to reduce smog and other pollutants. Several solutions are given. The first is the use of plants as a biophilic solution in the form of green façades and green roofs. The second is the use of anti-smog towers with different mechanisms of action. The next two are solutions related to concrete and the use of surface-modifying admixtures. These include nano additives in the form of nano titanium dioxide and activated carbon.

The awareness of states, cities, and even the public allows for the introduction of new, feasible, and usable solutions. Of course, buildings, facilities, and infrastructure alone will not bring about complete clean-up. Changes in other areas are also needed. It is not enough to build anti-smog buildings to reduce smog. Nor is it enough to change heating systems. It is also necessary to phase out cars that produce a large amount of pollution and switch to hybrid and electric cars. Renewable energy sources should be used, waste should be reused, and filters should be installed on chimneys. We should begin to eliminate the causes of pollution, which to a large extent include low emissions. Then, it will be much easier to fight their effects, including smog.

The examples mentioned in the article and those that are still a vision of the future, such as the appearance of Paris in 2050, where buildings consisting of traditional buildings will be complemented by green towers are technological innovations or solutions that already exist, but gain new functions. However, they show the direction for designing new buildings for the future. They set a new direction for researchers, designers, and architects to create new materials or use existing solutions to create new architectural designs that preserve fresh air.

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