




## Article

# Assessing Soil-like Materials for Ecosystem Services Provided by Constructed Technosols

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**Abstract:** Urbanization results to a wide spread of Technosols. Various materials are used for Technosols' construction with a limited attention to their ecosystem services or disservices. The research focuses on the integral assessment of soil-like materials used for Technosols' construction in Moscow megalopolis from the ecosystem services' perspective. Four groups of materials (valley peats, sediments, cultural layers, and commercial manufactured soil mixtures) were assessed based on the indicators, which are integral, informative, and cost-effective. Microbial respiration, C-availability, specific respiration, community level physiological profile, and Shannon' diversity index in the materials were compared to the natural reference to assess and rank the ecosystem services and disservices. The assessment showed that sediments and low-peat mixtures ( $\leq 30\%$  of peat in total volume) had a considerably higher capacity to provide C-sequestration, climate regulation and functional diversity services compared to peats and high-peat mixtures. Urban cultural layers provided ecosystem disservices due to pollution by potentially toxic elements and health risks from the pathogenic fungi. Mixtures comprising from the sediments with minor ( $\leq 30\%$ ) peat addition would have a high potential to increase C-sequestration and to enrich microbial functional diversity. Their implementation in urban landscaping will reduce management costs and increase sustainability of urban soils and ecosystem.

**Keywords:** urban soil; organo-mineral materials; ecosystem disservices; MicroResp technique; functional microbial diversity; fungi; Moscow megalopolis

## 1. Introduction

Urban ecosystems are to a great extent artificial by genesis and human-driven regarding their functions and services, and therefore highly variable and dynamic [1–3]. Considering the degree of anthropogenic impact, urban soils are identified as man-influenced, man-changed, or man-made [4]. From a variety of urban soils, soil constructions (constructed Technosols) are likely the most attractive and challenging for environmental assessment and modeling. Annually, thousands of tons of organic and mineral materials are imported into a big city and utilized for Technosols' construction [5–7]. The technologies and materials used for Technosols' construction are selected considering the

management purposes, e.g., for reclamation, landscaping, establishment, and maintenance of urban green infrastructures [8–11]. A literature survey shows high diversity of materials used in urban soil engineering, including technic (e.g., rubble, sludge, wastes, and industrial by-products) and natural (e.g., peat, relocated topsoil, biosolids, and dredged (bottom) sediments) materials [9,12–15]. Various commercially manufactured materials are available on the market for landscaping and greening purposes. A variety of materials results in a unique diversity of chemical, physical, and biological properties of the constructed Technosols.

The quality of materials is usually legally regulated by state or municipal standards, which differ between countries and cities. For example, the mixture of agricultural topsoil, silt, clay, and sand is applied for greening public areas in Parma, Italy [16]. A mixture of compost, peat, and sand is recommended for planting trees at the roadsides in Rome [17]. In France, topsoil removed from agricultural and forest lands remains a key material for urban greening [15], whereas reusing the industrial by-products, wastes, and fine sediments is suggested as an environmentally friendly alternative [12,18]. In the United States, particularly in Chicago, biosolids and dredged sediments are implemented for renovation and greening works [9,14]. In Moscow, Russia, there are at least 50 companies, supplying about a hundred of different materials for greening, mainly comprised of peat, sand, compost, and excavated topsoil in different proportions [5,8].

Although the quality standards of materials for the Technosols' construction differ between the cities, most of them are focused on several chemical properties (e.g., pH or content of potentially toxic elements, PTE), whereas their capacity to provide the ecosystem services remains overlooked [19,20]. Soil microorganisms are responsible for such important ecosystem's service as nutrients' cycles [21], pollutants' biodegradation [22–24] and climate regulation [25]. The provisioning of these services can be projected based on the microbial functional indicators, e.g., specific microbial respiration, community-level physiological profile, abundance of metabolic genes or enzymatic activity [26–29]. Microbial diversity contributes to ecosystem resistance to external stress; however, the presence of pathogenic species evokes substantial health risks and shall be considered as an eco-system disservice [30,31].

The research aimed to analyze soil-like materials used for Technosols' construction in Moscow megalopolis (Russia) and assess their quality based on chemical and microbial properties. The study outcomes shall allow re-thinking the existing soil quality standards and regulations from the ecosystem services' perspective to support urban sustainable development.

## 2. Materials and Methods

### 2.1. Materials Used for Technosols' Construction in Moscow

Moscow megalopolis extends over 2500 km<sup>2</sup> and with the population above 12 million people is the largest city in Europe. Moscow is located in the Central part of East-European plain (56° N; 37° E) and has a temperate continental climate. Taiga and mixed forests on the Retisols dominating the natural areas of the region, in Moscow city, are to a great extent substituted by ornamental plants and green lawns on man-changed or man-made soils with a considerable portion of constructed Technosols [32,33]. More than 1 million m<sup>3</sup> of soil-like materials (e.g., organic and mineral components and commercially manufactured mixtures) are annually imported into the city for the needs of civil engineering and green infrastructures' development [5,8,34]. A major part of the commercially manufactured mixtures available on the market composes from the similar components: valley peat, topsoil from meadow or arable lands, urban topsoil, and subsoil excavated before building construction, excavated river valley topsoil, compost, sand, dredged sediments, and sludge from water treatment stations. For this study, the most representative groups of the materials were purchased and collected: valley peats, sediments, urban cultural layers, and commercially manufactured mixtures (Table 1).

**Table 1.** The origin, suppliers, and implementation of the studied materials for Technosols' construction (PTs, valley peat (n = 4); SDs, sediments (n = 2); CLs, cultural layers (n = 4); MIX<sub>LPT</sub>, mixture (n = 3) with low peat content; MIX<sub>HPT</sub>, mixture with high peat content (n = 3)).

Material	Origin	Suppliers	Implementation
PTs	peatlands	peat mining companies	high
SDs	water body	water management companies	low
CLs	urban subsoil		low
MIX <sub>LPT</sub>	man-made	producers of soil mixtures for gardening and landscaping	high
MIX <sub>HPT</sub>			high

The valley peats group included four samples from the major supplying companies. The sediments group was represented by sludge from surface water treatment stations (i.e., solid and non-soluble particles mechanically filtered prior the water supply) and bottom sediments (i.e., dredged sediments excavated from a lake bottom). Cultural layers included subsoil urban sediments accumulated during a long-term residential activity and frequently excavated during building and infrastructure constructing [35,36]. The commercially manufactured mixtures comprised from several components, including valley peat. Based on the portion of the valley peat in the mixtures' composition, they were subdivided to low-peat ( $\leq 30\%$  of peat in total volume) and high-peat ( $\geq 75\%$  of peat in total volume) (Table 2). All the materials are available on the market and were collected from the official suppliers—from two to four materials per group and three mixed samples (50 L bags) for each material. The topsoil (0–10 cm) of Retisols sampled in the four mixed forested parks of Moscow was considered as a natural soil reference.

**Table 2.** The composition of the investigated commercial mixtures.

Mixture	Number	Composition	Volume Portion, %
Low peat content	I	peat/excavated urban topsoil/sand/excavated river valley topsoil	30/30/30/10
	II	excavated urban topsoil/peat/compost/sand	25/25/25/25
	III	excavated urban topsoil/valley peat/sand	50/30/20
	IV	peat/sand	75/25
High peat content	V	peat/compost/sand	80/10/10
	VI	peat/sand	95/5

## 2.2. Integral Assessment of the Materials' Quality

To assess the quality of the materials and project the ecosystem services they can provide, sub-samples (300 g) were taken for each material and the natural soil reference. Sub-samples were sieved through a 2-mm mesh and subdivided into two parts. The first part was air-dried for chemical analysis. The second part was adjusted to 60% water-holding capacity and preincubated (150 g, 22 °C, 7 d) in the thermostat in a plastic bag with air exchange. The preincubation stage eliminated initial variation in materials' temperature and moisture, and excluded possible CO<sub>2</sub> efflux from the preparation procedures [37–39]. After preincubation, the sub-samples were analyzed for microbial properties.

## 2.3. Chemical Analysis

Total carbon (C) and nitrogen (N) contents were determined by spectrometry (CHNS-932, LECO Corp, USA) after oxygen combustion (1100 °C). The pH of peats, cultural layers, high-peat mixtures (the high organic material:water = 1:10) and soil, sediments, low-peat mixtures (material:water = 1:2.5) was measured by pH-meter (Basic Meter PB-11, Germany) [40]. Total contents of nickel (Ni), zinc (Zn), lead (Pb), cadmium (Cd) were measured by X-ray fluorescence spectroscopy (Spectroscan Max-GVM, Russia).

#### 2.4. Microbiological Analysis

In the subsamples, the microbial respiration (MR) was evaluated by CO<sub>2</sub> production rate after its incubation for 24 h at the standardized condition at 22 °C [38,41]. The measurement of CO<sub>2</sub> was carried out by a gas chromatograph with a thermal conductivity detector (KrystaLLyuks 4000 M, Yoshkar-Ola, Russia). Microbial biomass carbon (MBC) was measured by substrate-induced respiration (SIR) method, which is based on the registration of the highest initial microbial CO<sub>2</sub> production after glucose addition [37,38]. The subsamples (1.0 g each) were placed in a vial (15 mL volume) and a glucose solution was added dropwise (10 mg glucose g<sup>-1</sup>, volume was 0.1 mL). The vial was tightly closed and incubated at 22 °C during 3.5 h. The measured SIR was converted to MBC units (μg C g<sup>-1</sup>) by the following equation:  $SIR (\mu L CO_2 g^{-1} h^{-1}) \times 40.04 + 0.37$  [37]. The MBC:C and MR:MBC ratios were calculated to estimate microbial C-availability and specific respiration ( $qCO_2$ ), respectively [25,42].

Community level physiological profile (CLPP) was measured by MicroResp<sup>TM</sup> technique [27,28,43]. Briefly, samples were put to the 96-deep well (945 μL volume each) and solutions of four C-substrates' groups were added: amino acids (glycine, L-arginine, L-leucine, α-aminobutyric, L-aspartic acids), carbohydrate (D-galactose, D-fructose, D-glucose), carboxylic acids (L-ascorbic, citric, oxalic acids), and phenolic acid (vanillic and syringic acids). The response of microbial community was detected by CO<sub>2</sub> production by colorimetric method after 6 h of incubation with detection gel at 25 °C. The absorbance by the detection gel was analyzed at 595 nm wave length (microplate spectrophotometer FilterMax F5, USA) before and after incubation and expressed as μg C g<sup>-1</sup> h<sup>-1</sup> [28]. Microbial functional diversity was assessed through Shannon index:  $H' = -\sum p_i \times \ln p_i$  [44], where  $p_i$  is the ratio of CO<sub>2</sub> response on the addition of single C-substrate to the sum of responses for all studied substrates.

The fungi species were cultivated on Getchinson's and Czapek's solid media, that allowed to cover the widely distributed fungi in materials consuming the cellulose and carbohydrates, respectively [45]. The Getchinson's solid medium consisted 2.5 g NaNO<sub>3</sub>, 1.0 g K<sub>2</sub>HPO<sub>4</sub>, 0.3 MgSO<sub>4</sub>, 0.1 g CaCl<sub>2</sub>, 0.1 NaCl, 0.01 g FeCl<sub>3</sub>, 7.5 g agar L<sup>-1</sup> water. The Czapek's medium included 30 g sucrose, 2.0 g NaNO<sub>3</sub>, 1.0 g K<sub>2</sub>HPO<sub>4</sub>, 0.5 g MgSO<sub>4</sub>, 0.5 KCl, 0.01 g FeSO<sub>4</sub>, 15 g agar L<sup>-1</sup> water. Streptomycin sulfate (100 mg L<sup>-1</sup>) was added to the media for bacterial growth inhibition. Briefly, sterile water (90 mL) was added to each 10 g soil and each subsample materials' group, and shaken for 10 min [46]. Serial dilutions (from 10<sup>-2</sup> to 10<sup>-9</sup>) were prepared by sequentially transferring 1 mL supernatant into glass tubes with 9 mL of sterile water. Subsamples (0.1 mL) at selected three dilutions were pipetted on the surface of three Petri dishes with each solid medium. The Getchinson's medium was covered by filter paper then. The dishes were incubated at 25 °C during 10 d [47]. Fungi genus and species identification was based on their morphological characteristics using the manual [48]. The occurrence of the fungi was calculated as the ratio of the number of Petri dishes with an identified species to their total number for each subsample. Occurrence was measured as follows: >83% is frequent, 33–83% is medium, and <33% is rare. Pathogenic potential was identified according to the atlas of clinical fungi [49].

#### 2.5. Interpretation of Soil-like Materials' Properties from the Ecosystem Services' Perspective

The ecosystem services' assessment was based on the studied microbial properties, which are often used as soil quality indicators [26,50]. The organic matter decomposition rate based on MR was used to assess the nutrients' cycle service. The higher value could indicate a better performance of the service, however, could also show the acceleration of CO<sub>2</sub> production rate. Hence, the  $qCO_2$  value was considered to indicate the balance between CO<sub>2</sub> production and C involved into microbial cells. The ratio of MBC to C determines C-availability to microbes and together with  $qCO_2$  was used as indicators of the C-sequestration and climate regulation service. The microbial response to specific organic acids (e.g., phenolic) was considered as the capacity to biodegradation of organic pollutants, which include a benzene ring. Shannon functional diversity index was considered to

assess the functional biodiversity supporting service. All the selected indicators were standardized to the natural soil reference values, which potential to provide the ecosystem services was considered the highest. The disservices of the materials were assessed based on PTE content compared to the health threshold level and pathogens occurrence in comparison to the natural soil reference. The ecosystem services' performance was ranked from 0 to 1 (where 1 is the best performance). The ecosystem disservices' performance was ranked by the same scale, where 1 means the minimal disservices provided.

## 2.6. Statistical Analysis

All measurements were performed in three replicates and calculated for the dry weight of subsamples. One-way analysis of variance and subsequent multiple comparisons by Tukey's test were performed for comparing the chemical and microbial properties among the materials' groups. The comparison between the materials' groups and the natural soil reference was done based on Dunnett's test. The relationships between chemical and microbial properties were analyzed using Spearman's correlation. Redundancy analysis (RDA) was used to examine the relations of fungal community composition to pH, nutrients (C, N), and PTE (Ni, Zn, Pb, Cd) contents among the studied materials. Data on fungi species occurrence were processed with Hellinger transformation [51]. Prior to RDA, a forward selection was performed to identify the best set of non-collinear explanatory variables with the highest adjusted multiple determination coefficient.

Significance level was accepted as 0.05. Statistical data analysis and visualization were processed in RStudio [52]. Data visualization was done by ggplot2 package [53]. Correlation matrix was visualized with the 'Performance Analytics' package. The RDA was performed using the 'vegan' package.

## 3. Results

### 3.1. Chemical Properties

The pH of all the materials was close to neutral with non-significant difference between the groups or with the natural soil reference (Table 3).

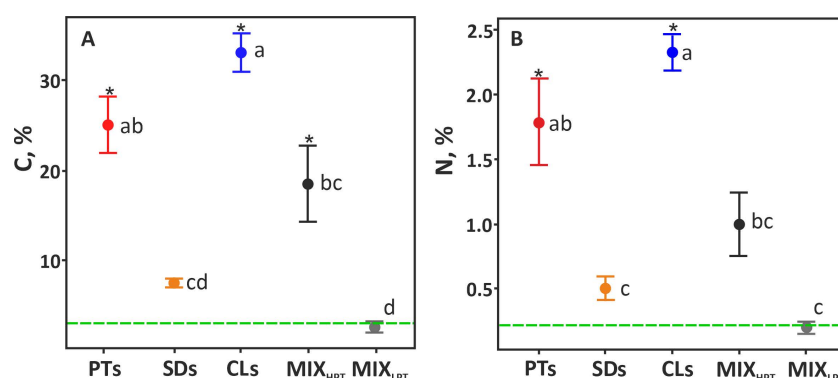
**Table 3.** Average pH and bulk of potentially toxic elements (PTE) ( $\text{mg kg}^{-1}$ ) in the soil-like materials (PTs, valley peat); SDs, sediments; CLs, cultural layers; MIX<sub>HPT</sub>, mixture with low peat content; MIX<sub>HPT</sub>, mixture with high peat content).

PRP	PTs (n = 4)	SDs (n = 2)	CLs (n = 4)	MIX <sub>HPT</sub> (n = 3)	MIX <sub>LPT</sub> (n = 3)	THL
pH	6.4 ± 0.5 a	6.9 ± 0.5 a	7.2 ± 0.0 a	6.5 ± 0.6 a	6.7 ± 0.1 a	6.0–7.5
Ni	23 ± 6 a	23 ± 5 a	12 ± 1 b	29 ± 10 a	27 ± 2 a	80
Zn	215 ± 158 b	140 ± 12 b	<b>563 ± 212 a</b>	54 ± 14 c	53 ± 3 c	220
Pb	9 ± 3 a	12 ± 8 a	22 ± 3 a	15 ± 7 a	15 ± 2 a	130
Cd	0.5 ± 0.1 a	0.3 ± 0.0 b	0.6 ± 0.0 a	0.5 ± 0.1 a	0.2 ± 0.0 b	2.0

PRP, properties. Values are reported as mean ± standard error, different letters indicate a significant ( $p < 0.05$ ) difference between the groups. Bold value represents the exceeding of threshold level (THL) for PTE (HS-514-11 regulation).

In contrast, C and N contents ranged more than one order of magnitude with the highest values in cultural layers and valley peats (Figure 1). Peat soil is widely recognized as the remarkable natural C stock, whereas high C and N content in cultural layers have an anthropogenic origin. They result from a long-term deposition during the residential activity and include organic wastes, wooden cheeps and other artifacts [35,54]. Only the low-peat mixtures contained a similar amount of C and N as a natural soil, whereas in all the other materials C and N contents exceeded the natural reference values 5 to 15 times. The C:N ratio for all the materials ranged between 10 and 20, indicating a balanced of C and N input. Compared to the other materials, cultural layers had higher contents of Cd and Zn, whereas Pb and Ni contents didn't differ significantly among the groups and were lower than the maximal permissible level recommended by Moscow' municipal regulations.

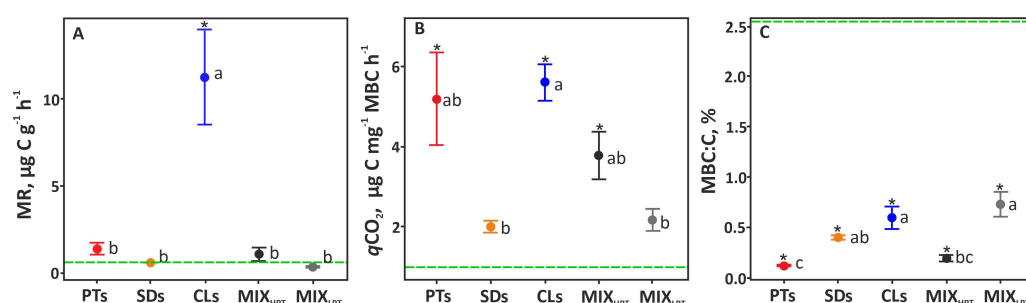




**Figure 1.** Mean (circles) and standard errors (bars) of total carbon (A) and nitrogen (B) in peats (PTs), sediments (SDs), cultural layers (CLs), high-peat (MIX<sub>HPT</sub>) and low-peat (MIX<sub>LPT</sub>) mixtures. Dotted green line represents the mean for the natural soil reference. Letters indicate the significantly different groups (Tukey's test). Means with \* indicate a significant difference from the natural soil (Dunnett's test).

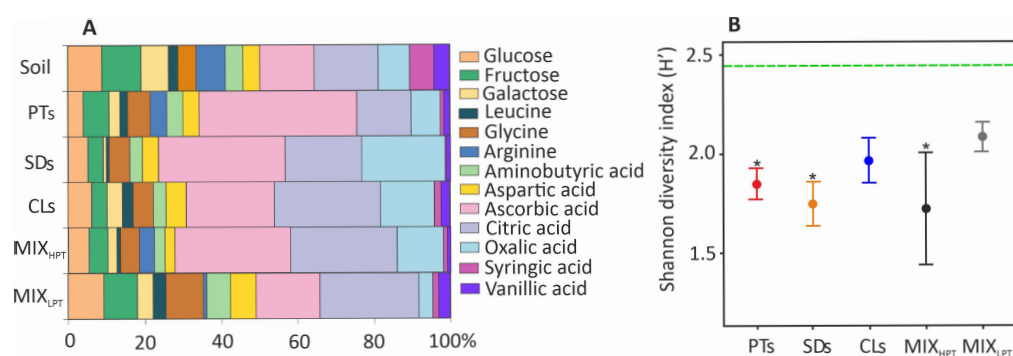
### 3.2. Microbial Properties

An extremely high MR obtained for the cultural layers was two orders of magnitude above other materials and the natural soil reference (Figure 2A). The highest specific respiration was reported for the materials rich in easily mineralizable organic matter (peats, cultural layers and high-peat mixtures), whereas sediments and low-peat mixtures were not significantly different from the natural soil (Figure 2B). Assuming a balanced specific respiration in natural soils as (i.e.,  $q\text{CO}_2$ ), sediments and low-peat mixtures were balanced as well, whereas the other substrates were not. The C-availability in the natural soils was significantly higher than in any soil-like material, and the lowest values were obtained for the peats and high-peat mixtures (Figure 2C). High  $q\text{CO}_2$  and low C-availability in peats and high-peat mixtures indicate their low capacity for C sequestration. Only the small part of C stored in these materials could be consumed by microbes for anabolism and accumulated in microbial cells, whereas the major part was released as  $\text{CO}_2$ .



**Figure 2.** Microbial respiration (MR, A), microbial metabolic quotient ( $q\text{CO}_2$ , B) and ratio of microbial biomass carbon to total carbon (MBC:C, C) in soil-like materials. Dotted green line represents the mean for the natural soil reference. Letters indicate the significantly different groups (Tukey's test). Means with \* indicate a significant difference from the natural soil (Dunnett's test).

The CLPP results showed that microbial structure in the peats was mostly shifted to groups consuming the ascorbic acid, whereas in the cultural layers and sediments, the highest response was obtained on the citric and ascorbic acids (Figure 3A). The response of microbial community on the arginine addition was found only for the peats and high-peat mixtures. For all materials except cultural layers, the capacity of microbial community to decompose complex organic compounds with benzene ring such as phenolic acids (vanillic and syringic) was lower compared to the natural soil. The highest microbial diversity was also reported for the natural soils, for which the Shannon index was considerably higher than in any of the soil-like materials. Among the materials, the index increased in a row: high-peat mixtures, sediments, peats, cultural layers, low-peat mixtures (Figure 3B).



**Figure 3.** Community level physiological profile (A) expressed by contribution of respiration on addition of individual substrates to total substrate-induced respiration in the natural soil and soil-like materials. The Shannon diversity index (B) presents as mean (circles) and standard error (bars) for materials; dotted line represents the mean for the soil. Means with \* indicate significant differences from the natural soil (Dunnett's test).

A more detailed analysis of the fungal diversity in the materials allowed identifying 31 species from 16 genera (Table 4). Between 8 and 11 fungi species were identified in soil, peats, and mixtures, which was 1.6–4.0 times more than in the sediments and cultural layers. The identified species differed between the natural soil and soil-like materials, as well as among the materials' groups. The highest frequency of the opportunistic fungi genera (e.g., *Aspergillus*, *Chaetomium* and *Geomyces*) and plant pathogenic fungi genera (e.g., *Verticillium* genus) were found in cultural layers. These species could cause mycoses in individuals having a weakened immunity. They are also harmful for the plant leaves and stems. Considering the potential risks for human and plant health, the implementation of cultural layers for urban greening purposes is questionable. Some opportunistic fungi genera were also found in low-peat mixtures and in the natural soil reference; however, the frequency of occurrence was less compared to the cultural layers.

### 3.3. Relationships between Microbial and Chemical Properties

The difference in microbial properties between the investigated materials was partly driven by C and N contents and the polluting level by Cd and Zn (Figure 4). A positive significant strong correlation was shown between MR, C, N, Zn, and Cd contents, whereas a significant negative effect of contaminants on microbial properties was not shown.

The negative effects of the PTE on the microbial community (reflected in high MR) were reported for urban soils before [54,55] and indicated stressful conditions for microbiome; however, the opposite effect of C and N input was expected. Apparently, C and N contents in some materials (e.g., in valley peats and high-peat mixtures) were so high that they could not be taken due to the exceeded capacity of their assimilation by microbial community, and therefore resulted in a  $q\text{CO}_2$  increase. The most optimal microbial functional capacity (low  $q\text{CO}_2$ ) was found at a range of 1.6 to 8.0% for C and 0.1 to 0.6% for N (Figure 5A,B).

Based on the RDA ordination of fungi species in the studied materials (Figure 6), the forward selection indicated that the best fitted model included Pb and Ni as factors, which explained 51.3% of the variance in fungal composition. Among these factors, Pb content was significant, explained 30.2% of variance, and was considered as gradient for RDA1 (pseudo  $F = 1.7$ ,  $p = 0.006$ ; 999 permutations). The ordination showed that fungi of cultural layers were more exclusive and less diverse compared to the other studied materials. The occurrence of *Verticillium* and *Aspergillus niger* pathogens increased along the Pb contamination gradient and associated with cultural layers.

**Table 4.** The occurrence of the fungi in the natural soil and soil-like materials and the potential health risks from the pathogenic fungi. Bold font represents the opportunistic fungi according to risk groups 1, which indicates the dangerous of fungi's impact on immunocompromised people (de Hoog et al., 2019).

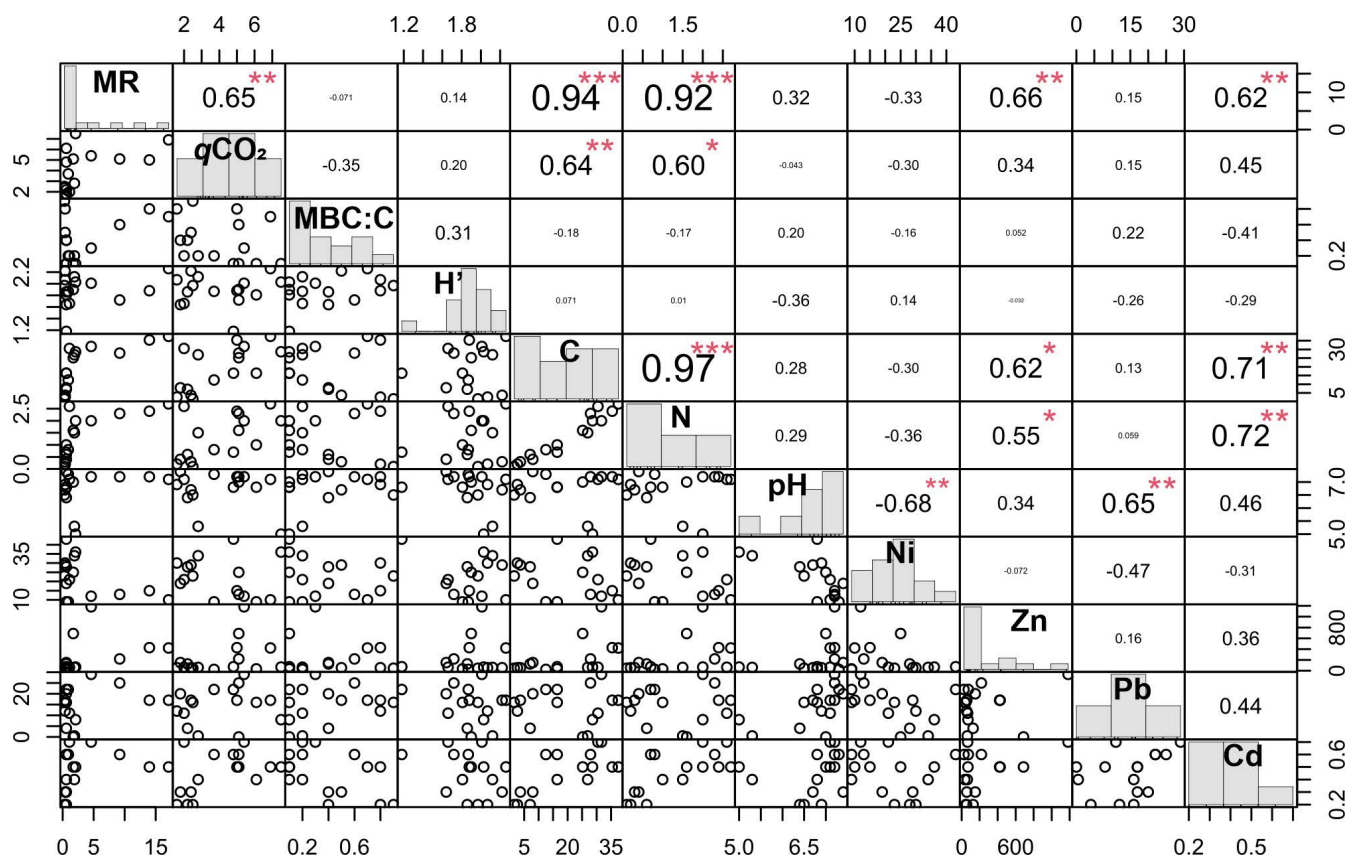
Fungi	Abbreviation	Health Risks	Soil	PTs	CLs	SDs	MIX <sub>HPT</sub>	MIX <sub>LPT</sub>
<i>Acremonium strictum</i> Gams	Astr	pulmonary, pleuritis, fungemia	-	-	-	-	-	++
<i>Aspergillus niger</i> Tiegh.	Anig	otomycosis, aspergillosis	-	-	++	-	-	+
<i>Aspergillus</i> sp.	Asper		-	+	-	-	-	-
<i>Acremonium charticola</i> Lindau	Achar		-	-	-	-	-	++
<i>Chaetomium globosum</i> Kunze	Cglob	onychomycosis, cutaneous lesions	-	+	-	+	-	-
<i>Chaetomium indicum</i> Corda	Cind		-	+	-	-	-	-
<i>Chaetomium spiralliforme</i> Bainier	Cspi		-	-	-	+	-	-
<i>Chaetomium spirale</i> Zopf	Cspir		-	-	-	+	-	-
<i>Chaetomium</i> sp.	Csp		++	+	-	+	-	-
<i>Geomyces pannorum</i> Link	Gpan	onychomycosis	++	-	-	-	-	-
<i>Gliocladium catenulatum</i> Gilman & Abbott	Gcat		-	-	-	+	-	-
<i>Gliocladium roseum</i> Bainier	Gros		-	-	+++	-	-	-
<i>Monocillium</i> sp.	Mon		-	+	-	-	-	-
<i>Monocillium pygmaea</i> Chalab.	Mpyg		++	-	-	-	-	-
<i>Mortierella polycephala</i> Coem.	Mpol		+	-	-	-	-	-
<i>Mortierella</i> sp.	Mor		+	-	-	-	-	++
<i>Mucor</i> sp.	Muc		-	+	-	-	-	-
<i>Paecilomyces farinosus</i> Holm	Pfar		-	-	+++	-	-	-
<i>Penicillium islandicum</i> Sopp	Pisl		-	-	-	-	+	-
<i>Penicillium steckii</i> Zaleski	Pst		-	-	-	-	+	-
<i>Penicillium sclerotiorum</i> Beyma	Pscl		-	-	-	-	-	++
<i>Penicillium rubrum</i> Stoll	Prub		-	-	-	-	++	-
<i>Penicillium terlikowskii</i> Zaleski	Pter		-	-	-	-	++	-
<i>Penicillium</i> sp.	Pen		-	+	-	-	-	++
<i>Stachybotrys parvispora</i> Hughes	Spar		-	-	-	-	+	-
<i>Stachybotrys lobulatus</i> Berk.	Slob		-	+	-	+	-	-
<i>Trichoderma</i> sp.	Trich		++	-	-	-	-	-
<i>Verticillium</i> sp.	Vert	plant diseases	-	-	+	-	-	-
<i>Moniliaceae</i> sp.1	Mon1		+++	+++	-	+	+	-
<i>Moniliaceae</i> sp.2	Mon2		+	++	-	+	+++	+++
<i>Micelia sterilia</i> dark-colored	Msdcd		-	++	-	-	-	+

Occurrence was measured as follows: +++, frequent (>83%); ++, medium (33–83%); +, rare (<33%); –, no.

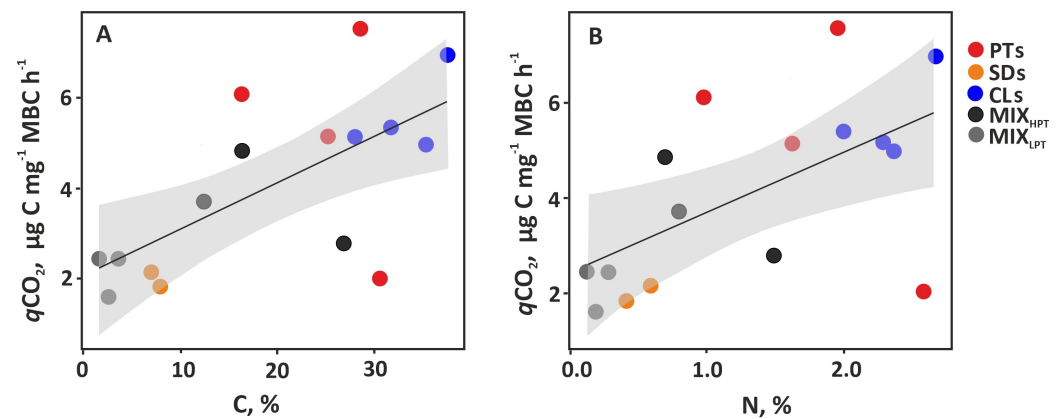
### 3.4. From Properties towards Ecosystem Services

Chemical and microbial properties of the analyzed soil-like materials were integrated and interpreted to assess the ecosystem services or disservices, which they can provide. A high capacity to provide functional biodiversity and nutrient cycles' services was shown for all the materials. For the cultural layers, however, the biodiversity service was hampered by the health risk disservice induced by the occurrence of the pathogenic fungi. At the same time, only a few materials (sediments and low-peat mixtures) had the potential to provide C-sequestration and climate regulation services. For all the other materials with very high contents of easily mineralizable organic matter, the risks of CO<sub>2</sub> emissions were much higher than in the natural soils, considered as a reference for the ecosystem services' assessment. In result, the capacity of cultural layers, peats, and high-peat mixtures to provide the service was assessed 20% lower than for sediments and low-peat mixtures and 80% lower than for the natural soil. An opposite pattern was shown the pollutants' biodegradation services, which was performed by peats and high-peat mixtures 20 to 30% better than by the sediments with low C and N contents. For cultural layers, an optimal performance of the pollutants' biodegradation services coincided with the disservice evoked by PTE pollution; therefore, cultural layers can be considered quite an ambiguous material for Technosols' construction. Services' and disservices' assessment aggregated on Figure 7 clearly illustrate the multi-functionality of the materials. Likely, the preliminary idea of the target service to obtain (or disservice to avoid) shall be developed prior to selecting the particular material for Technosols' construction.

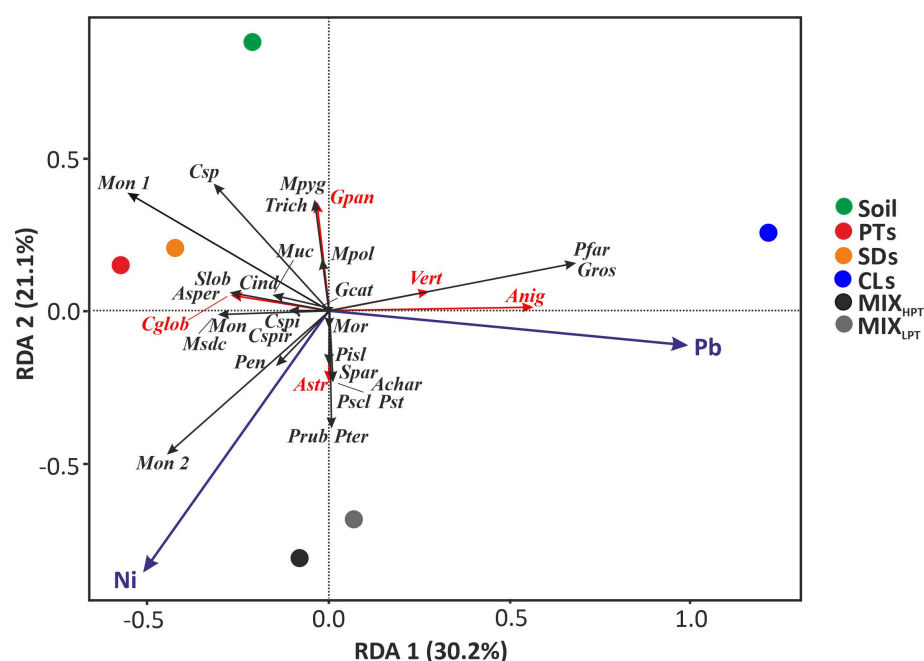




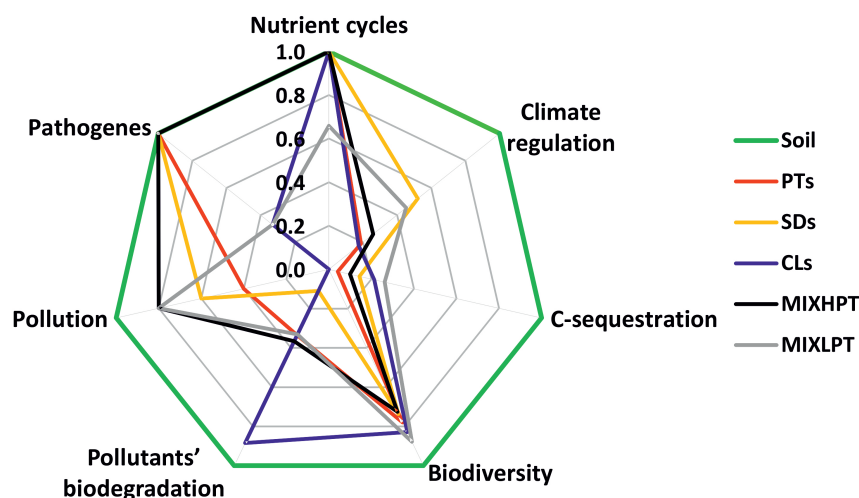
**Figure 4.** Relationships between microbial (MR,  $q\text{CO}_2$ , MBC:C,  $H'$ ) and chemical (C, N, pH, Ni, Zn, Pb, Cd) properties of the soil-like materials ( $n = 16$ ). Significant correlation coefficients are indicated with \*  $\alpha \leq 0.05$ ; \*\* 0.01; \*\*\* 0.001.



**Figure 5.** Scatter plot for microbial ( $q\text{CO}_2$ ) and carbon (A) and nitrogen (B) of the soil-like materials. The gray 'bands' represent the standard error of the regression line.



**Figure 6.** Ordination biplot of redundancy analysis for the fungi composition explained by Pb and Ni contents for the natural soil and soil-like materials. Non-pathogenic and pathogenic fungi are plotted as black and red arrows, respectively (fungi species abbreviations see in the Table 4).



**Figure 7.** Estimation of ecosystem services (1 is the highest) and disservices (1 is the lowest) provided by different groups of materials: peats (PTs), sediments (SDs), cultural layers (CLs), high-peat (MIX<sub>HPT</sub>), and low-peat (MIX<sub>LPT</sub>) mixtures in relation to soil.

#### 4. Discussion

##### 4.1. Advantages and Disadvantages of the Soil-like Materials from the Ecosystem Services' Perspective

A comprehensive analysis of chemical and microbial properties of the materials projected into the ecosystem services' /disservices' assessment allowed ranking their quality and applicability for Technosols' construction. A high rank of the sediments, which balanced most of the analyzed services, is one of the principal and unexpected research outcomes. So far, dredged sediments are frequently used in agriculture as amendments [56–58], but in urban greening and landscaping, preference is traditionally given to C-rich 'dark' materials, which are supposed to be more fertile [5]. In fact, dredged sediments combined with biosolids can considerably improve soil fertility and support plant growth as it was shown for Chicago [9]. Technosols constructed from water treatment station sediments

and composts had high nutrient contents and showed a positive dynamics in formation of stable aggregates [18,59]. Mixing sediments with clay loam, sand, and peat in volumetric proportions 25/30/40/5 or 15/40/40/5 at the pilot project in Moscow allowed constructing Technosols, whose quality satisfied governmental ecological and health standards [59–61]. These examples confirm our conclusion that non-polluted sediments could make a good alternative for the excavated natural and arable soils in composed mixtures for Technosols' construction, especially in the regions where the sedimentation in the water reservoirs is an important problem and dredging activities are needed.

In comparison to sediments, a considerably lower capacity to provide climate regulation and C-sequestration services was shown for the valley peat and high-peat mixtures, which so far dominate the greening markets of Moscow [5,34] and many other cities in Europe [62]. Although the nutrient content in peat materials is high, their vast implementation for Technosols' construction can result in a dramatic increase in CO<sub>2</sub> release to the atmosphere due to intensive mineralization of easily mineralizable organic matter [63,64], which can be even more facilitated by urban heat island effect [65]. We do not appeal for a complete ban for peat implementation in Technosols' construction; however, the proportions shall be thoroughly verified. Based on the research outcomes, a minor addition ( $\leq 30\%$ ) of peat in the mixture composition didn't have a negative impact on the climate regulation and C-sequestration services and contributed to microbial functional diversity, which is in agreement with the previous studies [66].

Urban cultural layers were probably the most “exotic” group of materials we tested, due to specific genesis, properties, and limited implementation for greening and landscaping needs. Cultural layers include various deposits that reflected the anthropogenic activity in the past: wood chips, wastes, excavated bedrock, bricks, and gardening traces [67]. We are not aware of a widely spread practical application of the cultural layers in soil engineering; however, the nutrients' richness could make them attractive for this purpose. Urban cultural layers showed high microbial activity and C-availability indicated by a high potential to accumulate C in microbial cells. As a result, the high capacity in pollutants' biodegradation, C-sequestration, and functional biodiversity was also observed. However, the intensive mineralization of organic matter increases the risks of CO<sub>2</sub> emission and depletes the climate regulation service. Presence of pathogens (*Aspergillus niger* and *Verticillium genera*) and pollution by PTE (copper, zinc, lead), likely inherited from the historical land-use [35] are the principal disservices of cultural layer, which limit their application for Technosols' construction and urban greening.

#### 4.2. Microbial Properties of the Materials in Relation to Nutrients and PTE Contents

Chemical and microbial properties in the studied materials were interrelated, and therefore, the variation in microbial indices and the values of corresponding ecosystem services were partly explained by nutrients' and PTE contents. Commonly, soil C and N contents stimulate microbial biomass growth [68,69]; however, in our study, a positive correlation between C and N contents and  $q\text{CO}_2$  was shown. Apparently, the energy costs for microorganisms to maintain their biomass under intensive input of C and N are too high. There is a threshold level of saturation, above which an additional input of organic matter doesn't stimulate microbial activity [70]. Apparently, in peats, cultural layers and high-peat mixtures this threshold was exceeded. This outcome doubts existing municipal regulations, which allow or even recommend the high content of organic matter in the materials used for soil construction. For instance, the permissible content of organic matter in materials used for landscaping in Moscow range from 10 to 25% [60], which is completely unsustainable and can result in intensive CO<sub>2</sub> emission.

Soil microbial properties are quite sensitive to pollution by PTE. However, in our study, such a negative effect was not evident, that is likely due to relatively low concentrations of the pollutants (for most of the materials, their contents were below health thresholds, Table 3). Moreover, based on the correlation analysis, MR was positively related to Cd and Zn contents. This unexpected outcome is likely explained by the specific properties of the

cultural layers, where considerable contents of heavy metals coincide with a very high C and N contents, and correspondingly, which a high microbial activity.

#### *4.3. Perspectives of Microbial Indicators for the Materials Quality Control*

Existing material quality standards often ignore the fundamental view on soil quality and ecosystem services [71,72]. For instance, Moscow government regulates the permissible values of organic matter, pH, nutrients, as well as pollutants' content, pathogens, and weed seeds in the soil-like materials used for Technosols' construction and urban greening [60]. City of Evans municipality (Colorado, CO, USA) regulates pH, nitrogen, phosphorus, organic matter contents, bulk density, texture, moisture, and soluble salt concentration in the amendments used in landscaping [73]. The British standard for topsoil cut and translocated in building construction considers texture, nitrogen, phosphorus, potassium, organic matter contents, and a wide range of pollutants for quality control [74]. None of these and other reviewed regulations consider microbial properties as an important criteria of urban soil quality. Today, even a shortlist of microbial indicators within the standardized protocols includes microbial (basal) respiration [41], microbial biomass [75], enzymes activity [76], nitrogen mineralization, and nitrification in soils [77]. Partly, implementation of these microbial indicators in urban soils' assessment is constrained by high temporal dynamics, especially during the first years after Technosols' construction [78,79]. From the other perspective, monitoring dynamics of these indicators can reflect the evolution and pedogenesis processes in the constructed soils. For instance, a positive dynamics of microbial biomass carbon in Technosols constructed from the mining wastes to remediate an industrial barren indicated their effectiveness for the ecosystem restoration [11]. Assessing microbial properties of soil-like materials could be a promising tool to project functions and ecosystem services of the constructed Technosols' and therefore shall not be ignored in urban landscaping, planning, and management.

### **5. Conclusions**

An artificial origin of the constructed Technosols gives a unique opportunity to project their functions and ecosystem services based on selecting soil-like materials with particular chemical and microbial properties. Assessment of the materials used for Technosols' construction in Moscow showed the highest performance for the sediments, which so far are almost completely ignored in urban greening. Regarding nutrient contents and balanced microbial functioning, they can be recommended as a promising replacement of native soils in organo-mineral mixtures used in soil constructions. Much lower ranks were given to peats due to very high risks of CO<sub>2</sub> emissions. Their implementation in Technosols' constructions shall be limited to minor ( $\leq 30\%$ ) amendments to mixtures composed from the sediments or native soil. Cultural layers were exposed to high biological (pathogens) and chemical (PTE) pollution, which was considered an ecosystem disservice. Therefore, they shall not be recommended for urban greening and landscaping. Although the research outcomes and recommendations are based on the analysis obtained for Moscow megapolis, they are applicable for many other world cities since most of the investigated materials (e.g., peat, sediments, and organo-mineral mixtures) are universal and widely spread. Our study showed the efficiency of microbial properties for testing the quality of materials and their potential to contribute to the ecosystem services provided by constructed Technosols already at the planning stage. Assessment of microbial functional capacity can be an important factor for developing recommendations on materials and technologies to enhance ecosystem services of urban soil constructions and support urban sustainable development.

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