

Review

Constructed Technosols: A Strategy toward a Circular Economy

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Abstract: Soil is a non-renewable natural resource. However, the current rates of soil usage and degradation have led to a loss of soil for agriculture, habitats, biodiversity, and to ecosystems problems. Urban and former industrial areas suffer particularly of these problems, and compensation measures to restore environmental quality include the renaturation of dismissed areas, de-sealing of surfaces, or the building of green infrastructures. In this framework, the development of methodologies for the creation of soils designed to mimic natural soil and suitable for vegetation growth, known as constructed soils or technosols, are here reviewed. The possible design choices and the starting materials have been described, using a circular economy approach, i.e., preferring non-contaminated wastes to non-renewable resources. Technosols appear to be a good solution to the problems of land degradation and urban green if using recycled wastes or by-products, as they can be an alternative to the remediation of contaminated sites and to importing fertile agricultural soil. Nevertheless, waste use requires analysis to ensure the salubrity of the starting materials. Moreover, materials produced on site or nearby minimize the cost and the environmental impact of transport, thus the involvement of local stakeholders in the urban land management must be encouraged.

Keywords: constructed soils; land degradation; remediation; waste recycling; organic biowastes



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1. Introduction

Soil, the substrate which we walk on, we inhabit, spend our days on, is fundamental for the survival of a large quantity of plants and living beings of all kinds and it hosts countless geo-bio-chemical reactions.

Due to the very slow processes of its formation and recovery from degradation, soil can be considered as a non-renewable natural resource [1]. However, population growth and urbanization implies an increase in natural resources exploitation and a consequent demand of soil to provide new urban areas and to sustain agricultural production [2]. The expansion of cities and intensive farming have led to a degradation of soil properties and functionalities, resulting in many environmental problems: loss of habitats, biodiversity depletion, soil erosion and ecosystems resilience, with implications for health, food and energy supplies for human beings [3].

Land degradation does not involve only urban areas; there are numerous sites around the world where the land has been exploited extensively, from mining areas to road building sites, from industrial to agricultural sites soil functionality has been reduced if not obliterated. Mining areas and brownfields, in particular, suffer very often from contamination problems affecting the feasibility of their reuse. Brownfields are generally defined as previously built sites that are now abandoned and unused [4]. They may be contaminated, and their reuse often passes through an expensive remediation [5,6]. Only at European level, more than 500,000 contaminated sites needing reclamation had been

estimated in 2018 [7], 16,000 of them in Italy, were the ex-tension of the polluted surfaces roughly correspond to more than 1400 square km, the 0.5% of the total area [8].

The formal, scientific attention toward the soil dates to the 19th century [9,10], but only recently its global environmental role has been recognized with several attempts to attract the consideration of the lawmakers and the public at large. In 1994 the United Nation Convention to Combat Desertification (UNCCD) was established with the aim of creating a future that avoids, minimizes, and reverses the desertification and degradation of land [11]. The 2030 Agenda for Sustainable Development [12], adopted by all United Nations Member States in 2015, provides 17 Sustainable Development Goals (SDG), which are an urgent call for action by all countries in a global partnership. They recognize that ending poverty and other deficits must go together with strategies improving health and education, reducing inequality, and stimulate economic growth-all while tackling climate change and working to preserve oceans and forests. Among the SDG, Goal 15 is to protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. The importance of enhancing inclusive and sustainable urbanization and of human settlement planning is claimed to design more livable, healthy, and resilient cities [12]. This can be achieved also through the creation of green spaces within the city, whose benefits are well-known: microclimate regulation, with the reduction of the urban heat island effect; water regulation that prevents flooding problems; pollutant removal; reduction of the biodiversity loss; improvement of human physical and mental health; economic advantages from restored soil services [13–18].

In 2015 the European Community endorsed the action plan “Closing the loop” [19] to maintain the future provision of natural resources with the development of waste materials reuse and reduction of non-renewable ones. The plan has connections with other European actions for a better management of natural resources, such as the European Green Deal [20], the Roadmap to a Resource Efficient Europe [21], the EU Biodiversity Strategy [22], the EU Soil Thematic Strategy [23], and the CAP strategic plans [24,25]. The ambitious EU program is aimed to apply a holistic strategy to achieve a climate neutral EU by 2050 [26], including actions to protect our soils. The 8th Environment Action Program [27] follows up on the UN Agenda by setting six thematic priority objectives: protecting, preserving, and restoring biodiversity and enhancing natural capital, notably air, water, soil, and forest, freshwater, wetland and marine ecosystems.

In particular, in a document produced for the European Commission [28] three pillars are identified to reach the objective of “no land take by 2050”: (i) the conversion of now un-built open space or agricultural land into new developments has to be avoided; (ii) areas with uses that were once active and now exhibit no viable use should be recycled by either introducing new uses or through renaturation and (iii) compensation should be required when construction must take place on previously un-built land. Compensation measures would restore the land quality in a specific site to balance the contemporary use of soil in a near area, in terms of provided ecosystem services. These approaches are frequently invoked for dismissed areas, which, before their reuse, very often require remediation to comply with the legislation requirements and to prevent pollutants diffusion [29]. This can take the form of renaturation projects or de-sealing measures in built areas, where soil sealing is no longer necessary (Figure 1). Mitigation intends to contain the negative effects connected to soil sealing with actions such as the use of permeable materials to reduce water runoff or the building of green roofs [30]. Realization of green spaces after de-sealing procedures, especially in cities, appear to be an adequate solution to restore, at least partially, soil ecosystem services and functions [30]. De-seal procedures involve removing the covering layer (concrete or asphalt) in order to expose the soil which, however, is often polluted [31] or not fertile enough [32], making further actions necessary to restore soil quality.



Figure 1. Layering of a sealed Technosol: artificial and natural materials are superposed to reach the prescribed level (photo F.A.M.).

It is therefore not surprising that several cities in Europe have promoted, in recent years, public intervention programs for degraded urban soils with new integrated approaches at the social, economic, and cultural level as suggested by the URBAN-SMS project [33,34].

In this framework it can be included the development of new methodologies for the creation of specific soils designed to mimic the natural soil and suitable for vegetation growth, known as constructed soils.

2. Constructed Technosols

According to the World Reference Base for Soil Resources (WRB) [35], Technosols include *soils whose properties and pedogenesis are dominated by their technical origin. They contain a significant amount of artefacts (something in the soil recognizably made or strongly altered by humans or extracted from greater depths) or are sealed by technic hard material (hard material created by humans, having properties unlike natural rock) or contain a geomembrane. They include soils from wastes (landfills, sludge, cinders, mine spoils, and ashes), pavements with their underlying unconsolidated materials, soils with geomembranes and constructed soils.*

In recent years, some pedological engineering studies [36,37] showed the ad hoc construction of Technosols (thus the punctual formulation of soils with the correct physical and chemical parameters for the studied or remediated site) as a potential solution for restoration of mined lands and urban greening.

Usually, the demand for restoration of brownfields, dismissed sites, and polluted areas has been met with the development of remediation techniques designed to remove or immobilize the contaminants from the soil. These techniques, although often efficient, are usually very expensive, favoring the removal of the contaminated soil and its replacement with clean soil or soil material. To avoid the use of soil excavated from uncontaminated areas for this purpose, appropriate purpose-designed Technosols have been constructed to be placed on the affected site. These constructed soils are intended to be fertile substrates for plant growth even if their composition is sometimes far from the ideal.

In the urban areas of the developed countries, the demand for green areas is increasing; this is due in part to a change in the way of living and expectations of urban dwellers and in part to the reduction of the industrial framework that left large, dismissed areas behind [38]. If, on the one hand, extensive areas with poor-quality soils are available, on the other hand city transformations produce large amounts of excavated materials—e.g., from the construction of underground lines—that must be disposed of. In addition, more and more frequently municipal organic waste is collected to be recycled as compost. The import of fertile agricultural soil from surrounding areas is becoming less and less feasible from many points of view: agronomic, environmental, and economic. In view of the necessary ecological transition [12], constructed soils appear to be an attractive and modern solution to respond to the urgent request of green areas within the urban fabric, with the aim to obtain a suitable substrate for plant growth [39]. Such solutions are currently studied worldwide; for example, in Roubaix (France) an experimental plot with constructed soils has been placed inside the “Ecoquartier de l’Union” [40], while in New York (USA) technosols made from waste have been tested to be used for urban gardening [41]. In the near future, the development of good quality soils for horticulture in urban spaces may lead to the realization of cultivated urban areas intended for providing food supplies for citizens [42].

3. Designing Technosols

Soil is a dynamic and constantly evolving system. This extremely complex matrix, in which lithosphere, hydrosphere, atmosphere, and biosphere interact, requires continuous and long-term monitoring. There is no unique “recipe” for constructed technosols, but many studies in the literature [43] have aimed to obtain a suitable formulation that is obviously similar to the composition of a natural soil: a structural, inorganic material and an organic material in various proportions [44,45].

A suitable formulation for the construction of a technosol would depend on many variables: (i) the problem to be tackled, as the area to be recovered can have remnants of previous activities such as contamination, rubbles, compaction; (ii) the final aim of the intervention, such as an urban green area or the remediation of a mining site; (iii) the local availability of materials; and finally (iv) the envisaged timespan of the project.

Several materials can be used to construct a technosol (Table 1), but they must show an adequate capability to support plant growth, usually in addition to other components. In recent years, different materials have been investigated to identify their suitability in terms of cost and performance [43], from natural substrates such as coffee grounds [46] to man-made recycled materials like concrete [47]. Some of these materials have already been used as growing media to support containerized plant production and in the creation of green roofs, e.g., a mixture of coco peat and perlite [48], heat expanded shale, slate or clay [49], mineral wool, vermiculite and volcanic rocks. In Europe peat moss is mainly used, often in mixtures with barks, sand, wood products, volcanic products, compost, and manures [50,51]. Unfortunately, very often, the energetic costs and environmental impacts of the production of these materials make their use scarcely convenient.

The use of alternative materials, such as recycled waste, could lessen the environmental impact of substrate accomplishment. Some of these materials are bricks [52–54], construction and demolition waste material (Figure 2) [54–56], crushed porcelain and foamed glass [57], recycled glass [58], concrete [59], clay and sewage sludge, paper ash, carbonated limestone [55], and sieved waste [60].



Figure 2. An example of urban excavated soil material that can subsequently be employed for constructed technosols (photo F.A.M.).

Table 1. Potential waste materials used for technosols design in literature and in research projects.

Waste	Reference
Inorganic waste materials	
Construction and Demolition Waste	[61]
Excavated subsoil	[47]
Bricks	[47]
Concrete waste	[62]
Dredged sediment	[63,64]
Residual sludge from stone processing	[29,65]
Mining wastes and tailings	[29,66]
Organic waste materials	
Compost from urban bio-wastes (food and garden)	[67,68]
Compost from sewage sludge	[68]
Anaerobic digestate from bio-waste and sewage sludge	[68]
Anaerobic digestate from agriculture and farms	[68]
Green wastes	[39]
Paper mill sludge	[39]
Biochar	[69]
Coffee grounds	[46]

It is fundamental to choose components properly, paying particular attention to the destination of the constructed Technosol: a park in the inner city would require a high global quality whereas, in the restoration of an abandoned mining area, a lesser soil performance might be acceptable. The same holds for the plants expected to host: pioneer, low-demanding plants can be used if a low soil quality is obtained in relation to the availability of materials.

The capacity of the substrate to fulfil soil functions is affected by local conditions, such as the climate, the surroundings surfaces, and the soil use, thus an appropriate design of the Technosol must be pursued [45]. For example, a zone with high precipitation intensity requires a soil with a sandy texture to provide adequate water drainage and to avoid stagnation, flooding, and run-off. On the other hand, if the soil has a very low available

water capacity, it can be improved adding porous additives able to increase the hydraulic conductivity, such as the geogenic coarse porous materials (CPMs). The CPMs are widely used as mineral components for constructed substrates [45]. They derive from natural geological processes, and in most cases, they need to be simply crushed before use; the great availability and low contamination make them a good choice in soil design. Some commercialized CPMs are porolith, tuff, pumice, expanded clay, perlite, and expanded shale mixed in appropriate ratio with sand or silt. These materials have good porosity, lightweight, moderate values of pH, and large grain sizes. Thanks to these properties and their structural stability, they can be added to pure quartz sand or to sandy soils in order to enhance their water retention capacity. Flores-Ramirez et al. [45] tested various commonly used CPMs to establish the best additive for constructed soils in formulation with sand in ratio CPM:sand of 1:4 (*v/v*). Four of the six investigated CPMs (pumice, expanded clay, perlite, and expanded shale) showed low retaining water enhancement, whereas only porolith and, to a lesser extent, tuff increased the available water capacity of sand. The authors suggested an appropriate choice of materials considering the specific purpose, environment and climate conditions and the use of these CPMs in high mixing ratios with sand. Moreover, the use of silt instead of sand, combined with organic matter, increases the water retention capacity of these soils. As regards pumice, a study conducted by Gunnlaugsson and Adalsteinsson [70] attested the low water-holding capacity of this material, suggesting its use in water beds with a water reservoir at the bottom. Despite its water retention properties, pumice is a cheap alternative with a good chemical buffering capacity, that can be easily cleaned and reused, and it has already been successfully employed in horticulture.

Other categories of studied materials to be used in constructed technosols are silicate-based additives. Not many researches have been made on it, but they have been already widely used to improve the water retention of golf courses and vegetable gardens in arid regions. As an example, using this material with sandy soils, the study of Hosseini et al. proved its benefits to increase root biomass of olive seedling by 50% while halving the irrigation frequency [71]. Hydrogels have been also investigated for their use for agricultural, horticultural, and forestry applications in arid regions [53]. They have shown positive effects in reducing irrigation needs [72], increasing the survival of transplanted seedlings [73,74] and of roots under short-term desiccation [75] in reforestation actions.

Biochar and hydrochar are also used to enhance water retention properties of sandy soils, while they also favor carbon sequestration. Several studies have observed an increase in nutrient content and water availability and a reduction of bulk density with the addition of biochar to sandy soils [53,76–80].

The most important benefit of organic components is the input of organic matter that can be readily decomposable or stable, promoting immediate or long-term effects. Organic matter enhances physical, chemical, and biological properties of the soil as it hosts and promotes the development of a consistent microbial biomass and the subsequent cycling of elements [81]. Organic materials used as soil amendments are manure, compost, wood and crop residues, pulp and paper mill sludge and food processing waste. Large addition of these organic amendments may favor the initial reclamation of the soil in a green area and lead to a self-sustaining ecosystem [81]. Furthermore, they can adsorb or foster the degradation (through the development of microbial biomass) of some contaminants promoting the soil restoration and reducing soil hazard.

4. Waste Materials in Technosols Design

Once their harmlessness is ascertained, recycled materials, wastes or by-products can be a viable solution for constructed technosols, employing them as structural or organic components. In fact, the reuse of large quantities of organic and mineral materials that would otherwise be landfilled sustains the transition to a circular and more sustainable economy [82]. The main criteria for the selection of wastes or by-products are easy availability, large quantities, low toxicity, and good agronomic properties [83]. The availability

is often the crucial criteria in the design of the intervention, as, for most of the materials no registers are present at regional or national levels, or they are not publicly available.

A local reuse of sediments entails a reduction of the transport and disposal of materials, with both economic and environmental benefits, cutting down on the consumption of resources, such as natural soil, and the vehicular emissions [41]. The possibility of using such materials in the urban greening has been tested in several studies. Egendorf et al. [63] showed the possibility to use a mixture of clean excavated glacial sediments and a locally produced compost for the realization of urban gardening areas, replacing native contaminated soil. However, a careful monitoring was necessary to exclude the presence of metals at toxic levels in the constructed soils and in crop products. They investigated the metal content of three mixtures intended for raised beds in three New York City gardens, obtained with sediments from the Clean Soil Bank and compost from food scraps and wood chips. All the soil mixtures had metal concentrations below legislative limits and As, Cu, Pb, and Zn had values lower than the control soil (gardening topsoil from a local vendor). After one year from the realization of raised beds, metals concentrations had not changed significantly in the constructed soils. The analysis of metal content in crops grown in the gardens showed a negligible contamination level. Asensio et al. studied the application of three constructed technosols made of wastes to restore the land of a mine in Touro, Spain [84]. They observed the effects of the soils on fertility founding some benefits, such as the development of microbial biomass, improvement of pH, CEC, and content of Ca^{2+} and K^+ , and of inorganic and organic C. However, the constructed technosols presented a high concentration of potentially toxic elements such as Ni, Pb, and Zn [84].

4.1. Waste Materials Employed as Structural Components

To produce fertile Technosols, natural topsoil is often used, but an alternative with a lower environmental impact could be suitable mining and building wastes from the city or the countryside.

Among the recycled mineral materials, the most used are the wastes deriving from construction or demolition building activities (C&DW) (Table 1). Produced in large quantities, they represent about 30–40% of all wastes produced by countries belonging to the Organization for Economic Co-operation and Development (OECD) [85]. The European Union alone, in 2016, produced 374 million tons of C&D waste, excluding excavated soil [86].

Other structural materials have been used as soil matrix for constructed soils: terrestrial or glacially deposited sediments [63], aquatic sand and sediments from lakes, rivers or dams [87,88], bricks [42,47], concrete and demolition rubble [47], sand and recycled ferrihydrites [89], coal waste [90,91], mining wastes [65,69], ashes [92], recycled bentonites [93], crushed rock [94], usually with the addition of natural or native topsoils [90,93,94]. The excavated material from deep soil horizons could be also exploited for this purpose, due to their great availability in every country. At the European level, it has been estimated that more than 500 million tons are produced every year [47], a part of which would definitely achieve the quality to be used in Technosol formulations. Excavated subsoils had already been successfully used in some projects [42,44,47,62], even if not so extensively [95].

The reuse of wastes, incorporating them in constructed technosols, may also be useful to reduce the impact of residues such as mine tailings [65]. Mining wastes represent the 26% of the total wastes produced yearly in Europe [66], a part of which is contaminated while most of the residues is an inert material able to be used as structural material for the reclamation of the closed mines as proposed by Dino et al. [29] or of degraded areas. Also the study by Moreno-Barriga et al. [69] about the use of mine residues in addition to marble waste and biochar showed positive results for the reduction of metal mobility from the starting material to constructed soils. Weiler et al. found that coal mining wastes with high sulfur levels could be used in technosol formulations for the reclamation of mining areas [91]. Similarly, Santos et al. [96] proposed the rehabilitation of mining sites through the combined use of constructed technosols and phytoremediation activities. The solution

allowed the germination and growth of plant species whereas the content of contaminants observed in the plants was below hazardous levels.

Regarding their agronomic properties, these wastes alone cannot be assimilated to a natural topsoil or a substrate for plant growth, even if they present a potential fertility [47]. Nevertheless, these recycled materials contribute to the agronomic properties of the constructed soil even at low use ratios [47,91]. All the reported materials concur to soil structure and texture, water drainage, and nutrient release. Some specific wastes could also provide a consistent contribution of useful elements or substances. For example, steel mill slag, from industrial process of ore-smelting for cast iron, is widely used in Japan and Brazil agriculture not only as structural material but also as amendment. In fact it is a source of Ca, Mg, P, Fe, Mn, and Si and it is a corrective for soil acidity [97]. Also, Fe (hydro)oxides from mining and from goethite production have some use in improving the nutrient content as they can be used to coat sand particles. The result is a substrate whose nutrient retention capacity has been increased, as well as its capability to absorb and retain pollutants [89].

One of the aims of the study by Rokia et al. was to predict the main agronomic properties of a constructed soils using mathematical models starting from the properties of the constituting wastes [47]. They realized several binary and ternary combinations of eleven different wastes from the European wastes catalogue [98]. This list included excavated earth material, bricks, compost, concrete, demolition rubble, green wastes, paper mill, street sweeping wastes, sewage sludge, and track ballast. To model the characteristics of the mixtures, the authors used second order polynomial models without interaction terms. Eleven factors, descriptive of the composition of each waste, were included in the models to predict the agronomic characteristic of the mixtures (C_{tot}, P_{Olsen}, CEC, pH, WC-10 KPa, and bulk density). The initial characteristics of the wastes were given as input data to estimate the properties of the mixtures. The prediction capability was validated for models for bulk density and WC-10 KPa, not for C_{tot} and pH, whereas the models for Olsen P and CEC showed intermediate prediction capability. Therefore, the model can be considered as a tool to guide the design of constructed soils.

4.2. Growing Material from Wastes

Organic waste materials could be a potential source of nutrients that could be reintroduced to natural cycles [99]. Recycling organic wastes, which allows the organic matter and the nutrients to be returned to the soil, has already been introduced in agricultural practices to save the costs of fertilizers and amendments and to avoid waste disposal [42].

Various types of organic materials are added to the inorganic matrix (Table 1) and (Figure 3), mostly compost from aerobic digestion of urban or green wastes [42,47,63,88,90,91,93], but also sewage or paper mill sludge [47,90,94], street sweeping wastes [47], green waste [42], furfural residues [92], peat [100], and biochar [101,102]. As for the inorganic structural materials, it is difficult to assess the a priori availability of each material but the recent legislative actions leading to greener industrial practices will probably tend to increase the available feedstocks for compost and digestate, as an example. Compost is now estimated to be the second most important organic waste, with estimated quantities of 15 million ton recycled each year [67,68]. Digestate, both from agriculture and from bio-waste and sewage sludge is probably the most available material, although mostly used directly in agricultural practices, with estimated productions of 120 and 60 million tons, respectively, in agricultural and urban settings [68].

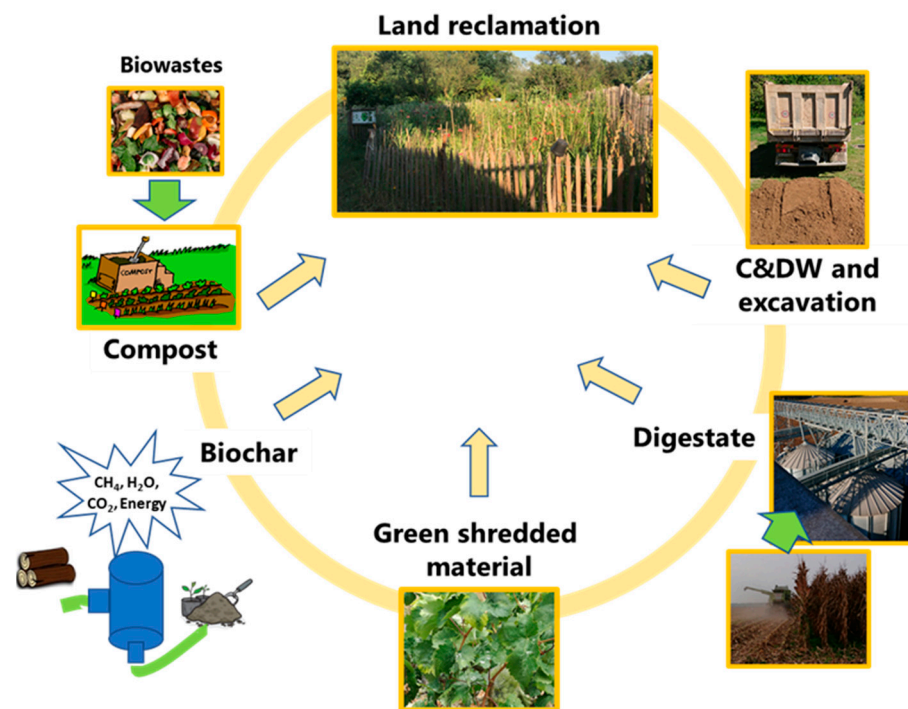


Figure 3. Schematic representation of the organic and inorganic materials mostly used in constructed soils. C&DW: Construction and demolition wastes.

The characterization of waste materials is fundamental and has to be conducted a priori before realizing constructed soil in order to control the suitability of these substrates, excluding heavily polluted materials, and to predict agronomic quality of final mixture.

Despite the benefits of adding organic materials are widely recognized, the optimal percentage of organic matter cannot be established in general terms for constructed soils, as it strictly depends on the type of organic waste, soil matrix, and plant species selected for the site.

The research by Weiler et al. [91] focused on the constructed soil mixtures obtained with fine coal waste and compost from urban wastes for *Medicago sativa* growth, and in particularly the mixtures with 2.5% and 5% of organic matter showed a biomass production equivalent and superior, respectively, compared to the agricultural soil. On the basis of these results, they suggested the addition of 550 t of compost per hectare of constructed soil.

The type of organic matter, which is provided to the soil, plays an important role, because it can interact with inorganic particles and leads to the formation of long-term stable aggregates [103,104]. The presence and stability of aggregates affect significantly soil fertility, e.g., the availability of phosphorus [42], but it is not easy to predict these physical parameters for constructed soils, because the characteristics of technogenic starting materials, which influence soil formation and evolution, are often unknown. Furthermore, many other factors influence the aggregation of soil particles, such as the activity of plant roots and macrofauna [105]. To increase aggregates stability, biochar can also be used as binding agent between minerals and organic matter, with the formation of stable macro-aggregates [69].

The nature of the organic matter affects the delivery and transfer of nutrients, in constructed soils as demonstrated by Vidal-Beaudet et al. [42]. Four mixtures obtained from the combination of excavated subsoil or bricks with green waste or compost were investigated and the biomass growth on these matrices was evaluated comparing it to that obtained from an agricultural soil. The characteristics of investigated materials affected the constructed soils significantly: compost contain mature organic matter, mostly mineralized, whereas green waste is constituted of vegetable residues subject to fast degradation. Therefore, the mineralization rate in mixtures with compost was higher than in soils with green

waste. Moreover, in the compost N and P were associated to stable organic matter and not easily available, representing a long-term reserve, whereas in the green waste these nutrients were associated with labile organic matter and thus releasable easily.

The quantification and qualification of the fungal biomass may be also taken into account when organic wastes are selected as active biomass. Fungal flora, especially, is often correlated with the formation of stable aggregates [106,107]. However, the fungal biomass present in organic matter could lead to problems of water repellence in the constructed technosol. Abel et al. demonstrated that, although biochar and hydrochar are suitable to improve available water capacity in sandy soils with a decrease of bulk density, in case of hydrochar an enhanced hydrophobicity was observed due to fungal colonization [108].

On the other hand, to identify the most suitable materials and mixtures for Technosols made for specific purposes, it is also important to consider the plant species chosen for the site, as each species has different growing needs. Barredo et al. [93] studied different plant species on a constructed soil obtained from construction and demolition wastes, a topsoil, bentonite, and bio-stabilized compost. For grass and legumes, as well as for crop rotation cultures (rape, wheat, sunflower), they observed that high compost percentages support biomass growth. Conversely, forestry species (trees, bushes, shrubs) and willow trees showed lower survival rates in the mixtures with greater compost percentages.

Similar results were obtained by Pruvost et al. [109]. They tested mixtures of excavated subsoil, crushed concrete, and green waste compost to identify the most suitable composition for tree growth, assess soil fertility by macrofaunal colonization and determine also the most tolerant tree species. The investigated constructed soils were [109]: excavated subsoil, excavated subsoil and concrete (30:70 v/v), excavated subsoil and compost (90:10), excavated subsoil with both concrete and compost (20:70:10 v/v/v). The tree species *Acer campestre*, *Acer platanoides*, *Acer pseudoplatanus*, *Carpinus betulus*, *Prunus avium*, *Tilia cordata* were chosen for the study. Although the total annual tree mortality rate was higher than in other studies, due probably to the planting method, the best substrate resulted the mix of subsoil, concrete, and compost with a plant survival percentage of 89% and a good tree growth. The best adapted species were *Acer campestre* and *Prunus avium* that showed a survival percentage of 100%, whereas *Carpinus betulus* was not well adapted, with a high mortality [109].

Another advantage brought by the organic matter addition is the possibility of pollutants removal. In fact the organic fraction could have effects on the bioavailability of contaminants, as it is able to adsorb or biodegrade organic pollutants by indigenous microorganisms [100]. A study by Hofman et al. compared the loss of phenanthrene in natural and artificial soils, made from 70% quartz sand, 20% kaolin clay, and 10% Sphagnum peat. After 84 days from exposure to phenanthrene, they observed a reduction both of pollutant content in soil and of the uptake by worm (*Enchytraeus albidus*) in artificial soils. This behavior can be justified by the presence of microfauna in the peat able to mineralize and reduce the bioavailability of PHAs.

4.3. Issues Related to the Use of Constructed Soils

4.3.1. Contamination

The use of recycled materials is subordinated to the verification of their non-toxicity or non-contamination. Materials such as compost, digestate, sewage sludge, and sediments can be contaminated by inorganic (Cd, Cr, Hg, Pb, Cu, Zn, As) or organic pollutants such as byphenyls, pesticides, and PAHs [110,111]. Contaminants legal threshold values depend on national legislations; however, it is important to maintain a low content of pollutants or, at the very least, to ensure their low bioavailability in constructed soils and their components. In fact, these substances can accumulate in the food chain and result in hazards to human health or interfere with soil functions and services.

Wu et al. showed that the use of sewage sludge as amendments could cause metals contamination suggesting thus the co-planting of different species of trees for a phytoremediation of the soil [110]. Feng et al. found chromium contamination during pot experiments

on some constructed technosols obtained with furfural residue and fly ash. In particular, the fly ash was found to have Cr concentrations near the critical limit for harmful substances, however the content of this metal decreased significantly after 6 months [92].

A study by Vincent et al. [112] investigated biotic, abiotic, and functional parameters of six derelict soils, comparing native soils from industrial French plant sites and artificial soils. One of the examined artificial soils was constructed with a bottom layer of paper mill waste, a layer of remediated former PAH-contaminated soil, and a topsoil layer of compost. The soil was placed on the site of a former coking plant and planted with grass. Among all the six investigated soils, this mixture displayed the highest quality in terms of fertility and functional parameters, with suitable values of organic matter, water holding capacity, CEC and phosphorous content. The pollutants concentrations in this soil were similar to others from industrial sites, with a content of Cd, Pb, Zn above geochemical backgrounds, but lower than the metal-polluted soils. However, unexpected high PAHs concentration were detected (170 mg kg^{-1}), probably due to the aerial deposition or an accumulation from the remediated soil to the topsoil. These results encourage the use of constructed soils but remark the need to monitor them after their application.

The addition in constructed technosols of components such marble waste and biochar allows using structural material arising from contaminated soil or containing naturally high concentrations of metals. In the study of Moreno-Barriga et al. [69] the mobility of metal(loids) in matrices made from mine tailings was strongly reduced (75–99%) with the addition of marble waste, due to the pH increase and to biochar adsorption.

4.3.2. Inhibition of Plant Growth

The addition of organic matter could help containing contaminations, but it could also represent a source of potential issues, so a careful identification of most suitable types and amount in mixtures is necessary. In the study of Haraldsen and Pedersen [94] about mixtures of crushed rock, natural forest soils, and sewage sludge, the plant growth was initially inhibited presumably due to toxic levels of ammonium-N in sludge organic matter. Despite limits of concentration given by local regulations were higher than those observed in constructed technosols, they recommended a maximum of 10% *v/v* of sludge added to the mixture, to avoid an excess of nutrients and consequent nutrient leaching or plant disorders. Similarly, during the first six months, Fourvel et al. [88] observed symptoms of leaf end yellowing and a low biomass production for ryegrass growth. Usually, the addition of a growing material allows a better air and water flow than in pure sediments, but in this case, it could have enhanced soil waterlogging conditions, limiting the nitrogen uptake. The organic matter may have promoted a reorganization of the pore space and the formation of macropores, reducing the available water. This problem was more intense in some sediments than in others owing to the differences in terms of texture. Nevertheless, after twelve months the yellowing was no more visible, probably due to the mineralization of organic matter. Therefore, it can be useful to provide for a preliminary stage of stabilization of sediment-compost mixtures to obtain a more stable organic matter, less liable to fast mineralization.

4.3.3. Compaction

The problem of soil compaction strongly involves urban soils, and it must be considered when a constructed technosol is placed in urban spaces. Compaction affects the capability of root penetration and nutrient availability, reduces air and water flow and water holding capacity, and promotes the formation of toxic forms of many substances [103]. When soil is compacted, the total pore space, the mean pore size, and the connection between pore of the soils are reduced [113]. The less intense air flow causes reductive conditions that may promote the formation of toxic forms of substances and alters nutrients availability [113]. Compacted urban soils are often remediated with the addition of compost, biochar, or tillage practices [101,114,115].

However, it is preferable to prevent compaction through appropriate design of the Technosols, for example using crushed concrete in soil mixture. The addition of this material in tree plantation holes, in appropriate quantity, provides a mineral and solid skeleton, preventing compaction phenomena with no observed negative effects on soil fertility [109]. Another possibility is the creation of sand-based rootzones to support a green area, exploiting the excellent compaction resistance of sand [116] that can be amended with organic materials [102].

4.4. Aging

The chemical-physical properties of the soil can evolve over time modifying the plant growth and ecosystem functions. Porosity in a soil depends on packing density, particle shape, and size distribution and cementing, and it can change in the early stages of soil evolution [117], particularly due to climate and biological activity [118]. A study by Jangorzo et al. [105] reveals the importance of studying the pedogenesis of Technosols, and in particular the soil structuration. They investigated for two years the pore system evolution of a constructed soil obtained by stratifying green-waste compost, paper-mill sludge, and thermally treated industrial soil. They quantified macro- and micro-porosity parameters with image analysis techniques: pores number, their surface area, perimeter, distance, volume, eccentricity, index of connectivity, equivalent diameter, and shape factor. After two year of experimentation, the percentage of macro-porosity and the mean pore surface area decreased significantly, whereas the pore number raised, indicating soil compaction. This phenomenon causes some negative effects, such as a reduction of water infiltration and drainage and an increase in bulk density. To develop accurate models to predict the evolution of soil structure, the authors proposed also to consider in addition the biological parameters, such as biodiversity, fauna abundance, plant and microbial activity [105].

This approach has been used in the study by Burrow et al. [40], focused on the evolution of fauna colonization in constructed technosols. Macro and meso fauna plays an important role in the evolution of the structure of soils, as it is considered one of the main actors in the ecologic rehabilitation of disturbed soils [119]. They applied two different constructed technosols in the urban area of Roubaix, France. One prepared with a top horizon of silt, a middle layer of fine backfill and a bottom layer of coarse backfill; in the second one, green waste compost was added to the top layer. Different management practices were conducted to establish the most favorable for the fauna development. In all soils, the colonization by macrofauna was observed to be relatively slow, as expected in disturbed soils. The taxa abundances and specific richness increased over the time and the establishment of herbaceous cultures, such as flowering meadow and lawn, showed a positive effect on the fauna development, with a greater abundance and richness of taxa. The closeness of one plot with a railway hedgerow (a potential ecological corridor) involved a more intense fauna colonization, with an abundance of Collembola and earthworms. Such models, able to describe and predict the evolution of the soils, surely have extreme utility in designing sustainable strategies for soil regeneration and assess pollutants spreading in restored sites.

Unfortunately, there is still a lack of competence in the area. For this reason, Legu dois et al. [120] conducted a study to define a framework to develop models focusing in particular on pedogenetic processes. Technosol evolution plays an important role also in the better understanding of the soil pedogenesis in general. The study revealed that the evolution of these artificial soils is very similar to the natural soils, but pedogenetic processes occur faster in unusual assemblages with very high spatial heterogeneity. To model the Technosol evolution, they proposed to couple tridimensional, multi-scale, and dynamic representation with mathematical model approaches (like partial different equations) with the addition of plant related processes [120].

4.5. Instruments for Land Management

In recent years, the research on constructed soils has provided instruments to guide land management and greening practices to local authorities.

In Italy the EU-funded project “Save Our Soil For Life” (SOS4Life, LIFE15ENV/IT/00225) proposed guidelines for the reuse of topsoil from construction sites to develop urban green areas. The study highlights that it is fundamental to know the characteristics of the site to be regenerated and the quality of organic material to be used. To provide this information they considered the soil ecosystem services for urban and peri-urban areas. Soil data from qualitative and quantitative analysis inform about functions and quality of urban soils, in order to orientate green spaces management in cities [121].

A study of Buondonno et al. proposed a protocol for environmental reclamation of limestone quarries [122] in the Campania region (Italy). They showed the weakness and ineffectiveness of regional legislation on quarry environmental reclamation, due to the lack of guidelines to properly manage these lands. The proposed protocol indicates the steps that should be followed developing pedo-engineering projects: site and surrounding survey, future land-use planning, design of the proper Technosol for the specific geo-pedoclimatic environment, identification of potential components, and reshaping the site for the constructed soil implementation.

In Europe, the SITERRE-ADEME research program by the French Environmental Agency promotes a pedological engineering approach to the land restoration [123]. The program proceeded testing 11 wastes for soil construction. The objectives were several: to identify the expected soil properties optimal for the land-uses of the area, to define soil fertility indicators and expected quality, to propose a design coherent with land-use for soil profiles, to identify appropriate wastes for soil construction, to examine the evolution of soil agronomic properties, and assess the safety of constructed soils.

In New York City a program to reuse sediments, derived from construction sites within the city, was established by municipal OER (Office of Environmental Remediation) [41]. The program, known as CSB (Clean Soil Bank) was developed to transfer clean sediments to nearby sites where they can be reused, reducing imported materials from the city surroundings. The CSB obtained great results improving urban sustainability and reducing the ecological footprint for New York City, with about 600,000 tons of soil recycled and transport reduction of 1.6 million miles [124].

5. Conclusions

The construction of artificial soils with recycled wastes or by-products has proven to be the most sustainable choice for the development of constructed technosols in view of the circular economy approach. Considering the case-specific needs they appear also as a possible solution to the problems of land degradation and urban green as they can be an alternative to the remediation of contaminated sites and to importing fertile agricultural soil. However, the use of wastes requires analysis to ensure that the starting materials are not contaminated excluding toxic effects for plants growth and living being's health. In this framework, tools such as the Clean Soil Bank of New York or the local management of sediments recycling can be very useful. Constructed technosols made with materials produced on site or nearby to urban green areas minimize the cost and environmental impact of transport. For this reason, the involvement of local stakeholders in the urban land management must be encouraged.

These artificial soils demonstrated their capability of supporting plant growth as they have been shown to be as fertile as natural soils or more. However, it is necessary to carry out further in-field studies to obtain the most suitable formulations considering the intended use of the Technosol and the plant species that will grow there.

Evidence from the available literature points to the need to consider a number of variables in the adequate design of a constructed technosol. Considering the scope of the project, the state of the area, the availability of materials demand for an iterative process of testing different solutions toward the optimal recovery of a degraded area. It cannot be

excluded that the final result would be different from what expected after due consideration of the variables involved.

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